AI-Driven Smart Homes: Challenges and Opportunities

Waleed Abd Elkhalik[1]
[1]Faculty of Computers and Informatics, Zagazig University, Zagazig, Sharqiyah, 44519, Egypt
Email: waleed.abdlekhalik@zu.edu.eg

Abstract

As AI-based smart homes become increasingly popular, there is a need to better understand the benefits and challenges of this emerging technology. A survey on AI-based smart homes can provide valuable insights into user needs, adoption rates, user satisfaction, barriers to adoption, and opportunities for innovation. This research overviews the cutting-edge literature on smart home development with an emphasis on the utilization of artificial intelligence (AI) approaches in this application area. We begin with a review of AI technologies and the smart home necessities needed to implement AI. Then, we introduce several applications of AI for smart homes and describe the most popular approaches already present in literary works. The open Issues (e.g., security and privacy, data collection and sharing, data analytics, and latency) meeting the development of smart homes are also discussed in this work. Finally, the paper suggests some directions for future study that could be fruitful.

Keywords: Artificial Intelligence; Smart Home; Intelligent Systems; Machine Learning

1. Introduction:

Artificial Intelligence (AI) has revolutionized the way we interact with technology, making it easier for us to automate everyday tasks and make our lives more convenient. One area where AI is making significant advancements is in the realm of smart homes. A smart home is a house that is equipped with various devices and appliances that can be controlled remotely via a smartphone, tablet, or computer. With the help of AI, these devices can learn our habits and preferences and adjust themselves automatically to make our lives more comfortable and convenient. From thermostats that adjust the temperature based on our schedules and preferences, to voice-activated assistants that can turn off lights and lock doors, smart home technology has come a long way. AI algorithms can even analyze our energy usage and suggest ways to reduce our consumption, ultimately saving us money on utility bills.

Despite the many benefits of AI-powered smart homes, there are also concerns about data privacy and security. With so much personal data being collected and analyzed, it's important to ensure that smart homes are secure and that our privacy is protected. As AI continues to advance, it's likely that smart homes will become even more sophisticated, providing us with even greater levels of convenience and automation. However, it's important to be mindful of the potential risks and to take steps to protect our privacy and security as we embrace these exciting new technologies.

Machine learning (ML) is a powerful tool that can be used to improve smart home applications. By analyzing data from various sensors and devices, ML algorithms can learn our preferences and habits and adjust smart home systems accordingly to provide a more personalized and comfortable living environment. For example, ML can play a crucial role in smart home energy management, helping homeowners optimize energy usage and reduce costs. By analyzing data from sensors, smart meters, and other devices, machine learning algorithms can learn about household energy consumption patterns and make predictions about future usage. ML can also be applied to smart home security, helping homeowners to identify potential security threats and take proactive measures to protect their homes. Anomaly

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detection, Facial recognition, Intrusion detection, Personalized security, and Fraud detection are all applications of different ML in the security of smart homes.

ML is a promising tool to enhance home automation, helping homeowners to create a more personalized and efficient living environment. In particular, ML algorithms can be used to learn about a homeowner's preferences for lighting, temperature, and other factors, and adjust smart home systems accordingly. For example, the algorithm could adjust the lighting in a room based on the homeowner's preferred brightness and color temperature. In addition, ML algorithms can analyze data from smart home devices and predict when maintenance is needed. This information can be used to proactively schedule repairs or replacements, reducing downtime and improving the lifespan of devices. further, ML algorithms can learn about a homeowner's daily routine and adjust smart home systems accordingly. For example, the algorithm could adjust the temperature and lighting based on the homeowner's schedule, ensuring a comfortable and efficient living environment.

Through the growing interest in this area, the current body of work on AI for smart homes is dispersed across many different fields of study. This opportune study is performed to fulfill this gap and give valuable intuitions into AI approaches and their application in smart homes. The major contributions of this study are listed bellows:

- Offering a thorough analysis of the current state of artificial intelligence (AI) implementations for smart homes. The review's importance lies in the groundwork it lays for incorporating blockchain technology into a market where change is occurring rapidly. In contrast to prior research, our review is succinct and focuses on why blockchain technology and smart homes make a good match. Inspiring further study, this overview also highlights recent developments in the field and the novel approaches being taken to old problems.

- Bringing a fresh take on various applications (for instance, data sharing for smart homes) backed by cutting-edge research. This article seeks to assist achieve that goal by highlighting some design practices that take advantage of the special characteristics of both smart homes and AI.

- Highlighting the most pressing problems (such as cost, security concerns, and technical issues) and drawing attention to fresh areas of research that require attention from academics and industry professionals. In particular, this analysis sheds light on the range of possible future research, offering pointers for the wider implications of artificial intelligence's use in the smart home IoT ecosystem.

The remaining of this work is debated in four main sections. Section 2 provides background on AI and its application in the smart home. Section 3 reviews the related literature. Section 4 charts out the road map for future works. Section 5 concludes this review study.

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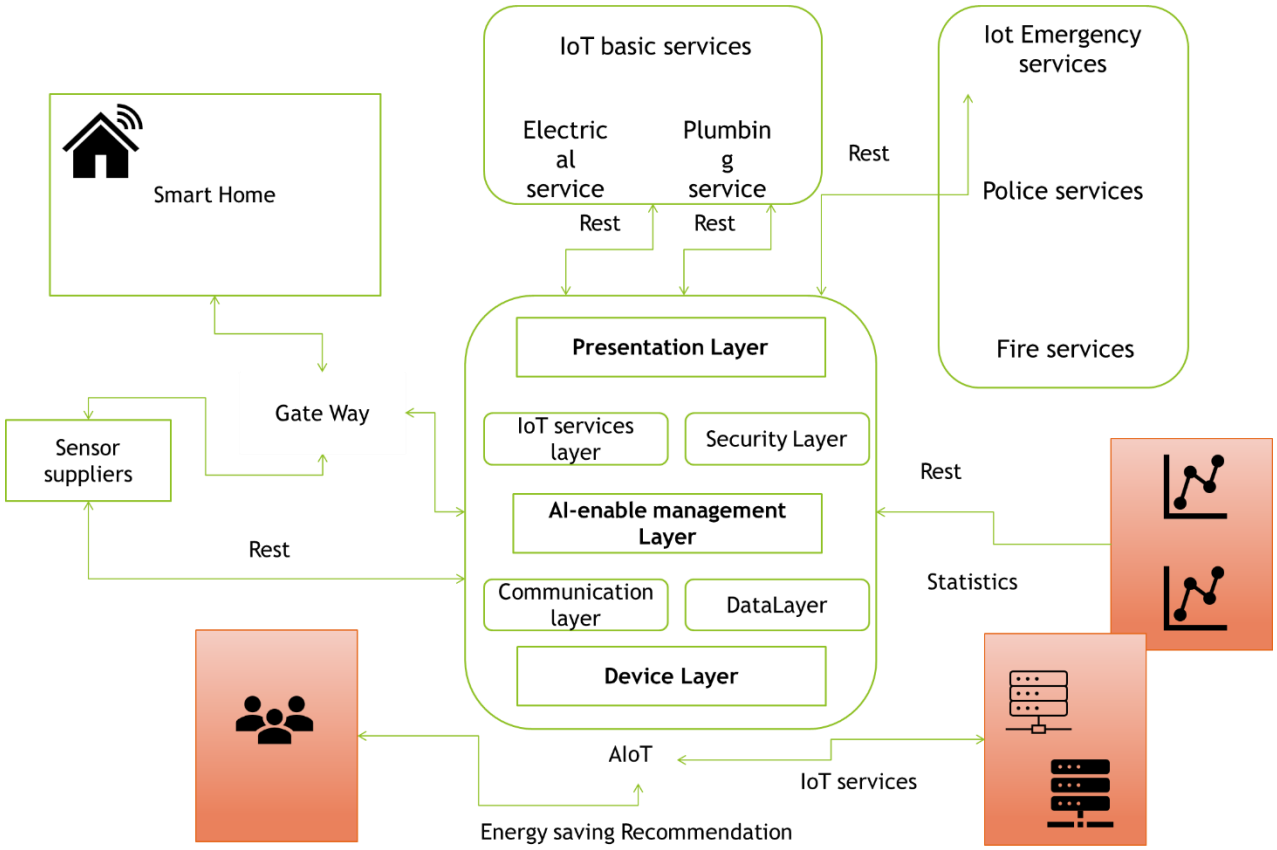

Figure 1: conceptual framework of AI-managed smart home.

2. Background Information

The concept of using AI in smart homes has been around for several years, but it has gained significant attention and adoption in recent years due to advances in AI technology and the growing demand for connected homes. The concept of smart homes originated in the 1980s, but the technology was expensive and complicated to use, limiting its adoption. In the 21st century, with the growth of the internet and the development of wireless connectivity, the idea of a connected home became more feasible. As technology continued to advance, the integration of AI into smart homes became more common. AI technology provides the ability to automate and optimize various functions in a smart home, from energy management to security to personalization (See Figure 1).

Today, many companies offer AI-powered devices and systems for smart homes, including Amazon, Google, and Apple. These devices can be controlled via voice commands, smartphone apps, or web-based interfaces, allowing homeowners to easily manage their homes from anywhere. As technology continues to advance, we can expect to see even more innovative applications of AI in smart homes, making them more efficient, convenient, and safe for homeowners.

AI is being used in a wide range of applications in smart homes, including energy management, security and safety, personalized experiences, and predictive analytics. AI-powered virtual assistants like Amazon Alexa and Google Assistant can be used to control various devices in a smart home, such as lights, thermostats, and security systems. These assistants can understand natural language and respond to voice commands, making them easy to use for all family members. For energy management, AI can be used to optimize energy usage in a smart home. For example, an AI-powered thermostat can learn a user's preferences and automatically adjust the temperature based on their past behavior, reducing energy consumption and saving money on energy bills. For security and safety: AI can be used to monitor the home and detect potential safety and security threats. For example, AI-powered cameras can detect motion

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and alert the homeowner if someone is on their property. AI can also be used to detect smoke and fire, alerting the homeowner and emergency services. For personalization, AI-powered devices can learn a user's preferences and adapt to their needs over time. For example, an AI assistant can learn a user's daily routine and suggest optimal times to turn on lights, adjust the temperature, or remind them of important tasks. more, AI can be used to analyze data collected from sensors and other devices in a smart home to predict user behavior and adjust the environment accordingly. For example, an AI-powered lighting system can adjust the color and intensity of lights based on the time of day and the user's behavior patterns.

2.1 Challenges of using AI in Smart Homes

The use of AI in smart homes presents a number of challenges that need to be addressed to ensure that these systems are safe, reliable, and effective. These challenges include concerns about privacy and security, complexity, cost, data quality, and bias. Addressing these challenges will require careful design, implementation, and ongoing monitoring of AI-powered smart home systems. However, if these challenges can be successfully addressed, the potential benefits of AI in smart homes are significant, including increased efficiency, convenience, and safety for homeowners. While AI has many potential benefits for smart homes, there are also some challenges that need to be addressed.

- Privacy and security: As smart homes become increasingly popular, concerns about privacy and security are growing. Smart home devices collect a large amount of personal data, such as user preferences, behavior patterns, and even sensitive personal information. This data is used to power AI systems, which can make the home more efficient and convenient, but also raise concerns about privacy and security. Hackers or other malicious actors could potentially access this data and use it for nefarious purposes. Additionally, the proliferation of smart home devices increases the attack surface for cyberattacks, as each device represents a potential point of entry into the home network. To ensure that smart homes are safe and secure, it is important to address these privacy and security challenges through robust data protection measures and secure device design.
- Complexity: The increasing complexity of smart home systems is a growing concern for homeowners. As more and more devices are added to the home network, the setup and configuration of these systems can become increasingly complex and time-consuming. AI-powered smart home systems add an additional layer of complexity, as they often require technical expertise to set up and configure properly. This can be a barrier to adoption for many homeowners, who may not feel comfortable with the technical aspects of setting up and using these systems. To address this challenge, it is important for smart home manufacturers to design systems that are easy to set up and use, with clear instructions and intuitive interfaces. Additionally, providing support and education to homeowners can help them overcome any technical challenges they may encounter when using these systems.
- Cost: Another challenge associated with using AI in smart homes is cost. This includes upfront costs, in which AI-powered smart home devices and systems can be more expensive than traditional smart home devices, which could limit their adoption among homeowners. It also includes maintenance costs, in which smart home devices require maintenance and upgrades over time, and AI-powered devices may require more frequent updates or replacements due to the fast pace of technological advancements. More, some AI-powered smart home devices may consume more energy than traditional devices, leading to higher energy bills for homeowners. To address these cost challenges, it is important for smart home manufacturers to balance the benefits of AI with the cost of implementation. This may involve designing systems that are energy-efficient, using cost-effective components, and providing flexible payment options for homeowners. Additionally, educating homeowners about the long-term benefits of AI-powered smart homes can help to overcome any cost concerns they may have.
- Data quality: Another challenge associated with using AI in smart homes is data quality. For instance, AI-powered smart home systems rely on accurate data to make informed decisions. Inaccurate data can lead to incorrect or ineffective responses from the system. Besides, AI systems require a continuous flow of data to operate effectively. Poor connectivity or data interruptions can impact the system's performance. AI systems may struggle to interpret data that is complex or unstructured, such as natural language data or video feeds. To address these data quality challenges, it is important for smart home manufacturers to use high-quality data sources and implement robust data quality control measures. Additionally, AI systems should be

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designed to handle missing or incomplete data and provide transparent feedback on their decision-making process.

- Bias: Another challenge associated with using AI in smart homes is bias. For training data bias, AI systems rely on data to learn and make decisions. If the training data is biased, the system may perpetuate that bias in its decision-making process. From the perspective of algorithmic bias, some AI algorithms are inherently biased, either due to the data they are trained on or the way they are designed. This can lead to discriminatory outcomes that unfairly disadvantage certain groups of people. From a user standpoint, users may inadvertently introduce bias into the system by selecting certain settings or preferences that reflect their own biases. To address these bias challenges, it is important for smart home manufacturers to use diverse and representative training data and implement robust testing procedures to identify and mitigate algorithmic bias. Additionally, AI systems should be designed to be transparent and provide clear explanations of their decision-making process to help identify and address any biases introduced by user input.

2.2 Opportunities of Using AI in Smart Homes

The integration of AI in smart homes presents numerous opportunities that can improve homeowners' quality of life. AI-powered smart home systems can provide increased convenience by automating routine tasks and providing personalized experiences. They can also enhance energy efficiency by optimizing energy usage and improving security with advanced features such as facial recognition and anomaly detection. Furthermore, AI can monitor and analyze health data from wearable devices and other sensors to provide personalized health recommendations and alerts. Finally, AI-powered smart home systems can also improve accessibility for people with disabilities or mobility challenges by automating tasks and providing voice-activated controls. These opportunities demonstrate the potential for AI to transform the way we interact with our homes, making them more comfortable, secure, and personalized.

The use of AI in smart homes presents many opportunities for homeowners. Here are some of the key opportunities:

- Increased convenience: AI-powered smart home systems can automate routine tasks and provide personalized experiences for homeowners, making life more convenient and enjoyable.
- Improved energy efficiency: AI systems can optimize energy usage in the home by adjusting temperature, lighting, and other systems based on user behavior and preferences.
- Enhanced security: One significant opportunity presented by AI in smart homes is the ability to enhance security. Smart home systems can be equipped with AI-powered security features such as facial recognition, anomaly detection, and predictive analytics, which can provide advanced security capabilities and help keep homeowners and their properties safe. Facial recognition technology can be used to identify individuals who enter a home, providing an additional layer of security beyond traditional locks and keys. By analyzing facial features and comparing them to a database of authorized users, AI systems can quickly identify and flag unauthorized access attempts. Anomaly detection is another powerful security feature enabled by AI. By analyzing patterns of activity in the home, AI systems can detect abnormal behavior and alert homeowners to potential security threats. For example, if the front door is opened at an unusual time, the system can send an alert to the homeowner's smartphone or other devices. Predictive analytics can also be used to improve home security. By analyzing data on previous security breaches and other incidents, AI systems can predict when and where future breaches are likely to occur. This allows homeowners to take proactive measures to prevent security incidents before they happen.
- Personalized health monitoring: Another significant opportunity presented by AI in smart homes is the ability to improve the health and well-being of homeowners. Smart home systems can be equipped with AI-powered health monitoring features that can track vital signs, monitor medication intake, and provide personalized health recommendations and alerts. AI-powered sensors can monitor a range of health indicators, including heart rate, blood pressure, and sleep patterns. This data can be analyzed by AI systems to provide valuable insights into the user's health and well-being, allowing for personalized health recommendations and alerts. AI-powered smart home systems can also monitor medication intake and provide reminders when it's time to take medication. This is especially important for individuals with chronic conditions who need to take medication regularly. Smart home systems can also be equipped with voice-activated controls and other features that make it easier for individuals with mobility challenges or disabilities to manage their health. For

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example, an AI-powered smart home system could be used to adjust the lighting or temperature in a room without requiring the user to get up and physically adjust the controls.

- Increased accessibility: AI-powered smart home systems can improve accessibility for people with disabilities or mobility challenges by automating tasks and providing voice-activated controls.

These opportunities demonstrate the potential for AI to transform the way we interact with our homes, making them more comfortable, secure, and personalized. Additionally, AI can help homeowners save money by reducing energy consumption and improving the overall efficiency of their homes. Finally, AI-powered smart home systems can provide valuable insights into user behavior, which can be used to develop new products and services that better meet the needs of homeowners. Overall, the opportunities presented by AI in smart homes are significant and have the potential to revolutionize the way we live.

3. Related work

The literature on AI for smart homes has been growing rapidly in recent years, reflecting the increasing interest in using AI to improve the functionality and efficiency of smart home systems. Several key themes have emerged in this literature, including the use of AI for energy management, security, health monitoring, and home automation. In [1], the authors provided an overview of the various concepts, configurations, and technologies used in home energy management systems (HEMS) for the smart grid by reducing energy consumption, peak demand, and associated costs. They also highlighted the importance of communication protocols and standards in HEMS, such as the OpenADR protocol, to ensure interoperability and efficient communication between different devices and systems. they delved into the various technologies used in HEMS, such as AI, and IoT, and discussed how these technologies can be leveraged to optimize energy consumption, demand response, and grid stability. In [2], the authors studied the security challenges and countermeasures for consumer IoT devices in smart homes. They discussed the concept of the smart home and the increasing prevalence of consumer IoT devices and debated the security risks associated with these devices, such as unauthorized access, data leakage, and device compromise, and the potential consequences of these risks. They provided a comprehensive architecture for securing consumer IoT devices in the smart home environment. The architecture consists of several layers, including device security, network security, cloud security, and user security, each with its own set of challenges and countermeasures. In [3], the authors surveyed the use of WiFi sensing technology in the context of smart homes by explaining how WiFi sensing is a promising technology for smart homes, which leverages the existing infrastructure of WiFi networks to detect and track human presence and activities. They provided a detailed overview of the various WiFi sensing techniques used in smart homes, such as received signal strength (RSS) analysis, channel state information (CSI) analysis, and Doppler radar in conjunction with their limitations and challenges of each technique, such as the impact of environmental factors on WiFi signals and the need for advanced signal processing algorithms. In [4], the authors reviewed the security challenges and countermeasures for IoT-enabled home automation systems. they introduced a comprehensive taxonomy of the attacks and threats that IoT-enabled home automation systems face, including device compromise, denial-of-service attacks, privacy breaches, and physical attacks. They also paper provided a detailed description of each attack, its impact, and the techniques used to carry it out. then, they discussed various countermeasures for securing IoT-enabled home automation systems, such as secure communication protocols, access control mechanisms, intrusion detection systems, and data encryption techniques. The paper also highlights the importance of user education and awareness in ensuring the security of these systems. In [5], the authors investigate the factors that influence patients' adoption of the wireless sensor network (WSN)-based smart home healthcare systems by developing an integrated model of facilitators and barriers to patients, which consisted of four categories of factors: individual, social, technological, and environmental. The individual factors include patients' perceived usefulness and ease of use of the system, their attitude towards technology, and their health status and needs. The social factors included the influence of family, friends, and healthcare providers on patients' adoption decisions. The technological factors included the system's compatibility, reliability, and security. The environmental factors included the availability of support and resources, the regulatory and legal framework, and the cultural and societal norms. In [6], the authors studied the understanding of the negative perceptions of elderly users towards smart home technology in Asia. They presented an end-user negative perception model of smart home technology adoption, based on a qualitative study of elderly users in Asia. The model consisted of four categories of negative perceptions: technological, usability, financial, and psychological. The technological perceptions embraced concerns about the complexity and reliability of the technology, as well as the lack of control over the system. The usability perceptions comprised concerns about the difficulty of using the technology, as well as the lack of support and training. The financial perceptions comprised concerns about the cost of installation and

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maintenance, as well as the perceived lack of value for money. The psychological perceptions comprised concerns about the loss of privacy and independence, as well as the fear of technology. The paper provided a detailed description of each category and its impact on elderly users' adoption decisions, and also highlighted the need for a user-centered approach to the design and implementation of smart home technology, which takes into account the individual needs and preferences of elderly users. In [7], the authors explored the relationship between smart home technology and the quality of life for elderly individuals by examining competing models of smart home technology and their potential impact on the quality of life for elderly users. They studied the use of smart home technology to monitor and manage the health and well-being of elderly individuals. This model emphasized the use of sensors and monitoring devices to detect changes in the individual's health status and alert healthcare providers or caregivers if necessary. Their model emphasized the use of automation and remote-control features to simplify tasks and reduce the need for the physical effort by using adaptive and personalized technology to enable individuals to maintain their independence and engage in meaningful activities.

In [8], the authors explored the adoption of AI and big data technologies in smart building systems by surveying the current state of research in this field and identifying key challenges and opportunities for future development. They provided a detailed survey of the current state of research in this field, including various aspects of ML and big data technologies in smart buildings, such as data collection and management, data analytics, and control and optimization. They identified the key challenges and opportunities for future development in this field, such as the need for more accurate and reliable data collection methods, the development of more effective algorithms and models, and the need for greater interoperability and standardization.

In [9], the authors explored the potential of IoT and smart home technology to improve healthcare for elderly individuals by providing end-user perspectives on the use of these technologies and identifying key factors that can impact their adoption and use. That work presented the findings from a survey of elderly individuals and their caregivers, which explored their perceptions and attitudes towards the use of IoT and smart home technology for healthcare. The survey identified several factors that can impact the adoption and use of these technologies, such as ease of use, cost, privacy concerns, and the need for personalization and customization. In [10], the authors studied the various prediction algorithms that can be used in smart home systems by presenting a detailed survey of the current state of research in this field, including a comprehensive review of relevant literature and case studies. This work covered various aspects of prediction algorithms in smart homes, such as data collection and management, algorithm selection and evaluation, and control and optimization. It also identified key challenges and opportunities for future development in this field, such as the need for more accurate and reliable data collection methods, the development of more effective algorithms and models, and the need for greater interoperability and standardization. In [11], the authors explored the use of mobile apps and ML in smart energy grids, with a particular focus on consumer engagement in different aspects of smart home developments such as user engagement, energy consumption modeling, demand response, and renewable energy integration.

4. Future research directions

As AI continues to evolve and mature, it is poised to revolutionize many aspects of our daily lives, including the way we interact with our homes. AI-driven smart homes have the potential to improve energy efficiency, enhance occupant comfort and safety, and enable better healthcare for elderly and disabled individuals. However, as with any emerging technology, there are many areas where further research and development are needed to fully realize the potential of AI in smart homes. In this context, this section explores some of the key areas of future work for AI in smart homes, including improved sensing and data analysis, personalization, and adaptive learning, integration with other emerging technologies, and ethical and responsible AI.

- Improved sensing and data analysis: AI algorithms can be further developed to better analyze and interpret data from various sensors and devices in smart homes, such as cameras, motion sensors, and smart appliances. This can help to improve the accuracy of predictive models and decision-making processes.

- Personalization and adaptive learning: AI algorithms can be designed to learn from user behavior and preferences to provide more personalized and adaptive experiences in smart homes. This can help to improve user satisfaction and engagement, as well as enhance energy efficiency and other performance metrics.

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- Integration with other emerging technologies: AI can be integrated with other emerging technologies, such as the IoT, blockchain, and big data analytics, to further enhance the capabilities and benefits of smart homes. For example, blockchain can be used to securely manage and share data in smart homes, while big data analytics can be used to identify patterns and insights that can help to optimize energy usage and other aspects of home automation.

- Digital twin: it is a virtual replica of a physical object or system, and it can be a powerful tool for designing and managing smart homes. In the context of smart homes, a digital twin can provide a real-time simulation of the home's physical and operational characteristics, such as energy usage, temperature, and lighting levels. By using this simulation, homeowners and designers can identify potential issues and optimize the performance of the home's systems. For example, a digital twin can be used to simulate the effects of different lighting configurations or temperature settings, and homeowners can use this information to adjust their smart home systems accordingly. Similarly, a digital twin can be used to identify potential energy savings by simulating the impact of different energy management strategies, such as adjusting HVAC settings or using energy-efficient appliances. In addition to design and optimization, a digital twin can also be used for predictive maintenance and troubleshooting. By continuously monitoring the home's systems and comparing their performance to the digital twin simulation, homeowners and technicians can identify potential issues before they occur and take proactive measures to prevent them.
- Ethical and responsible AI: As AI-driven smart homes become more ubiquitous, it is important to ensure that they are developed and used in an ethical and responsible manner. Responsible AI for smart homes involves designing and implementing AI systems that prioritize user privacy, security, and transparency. One key aspect of responsible AI for smart homes is data privacy. Smart home devices collect a significant amount of personal data, such as user behavior and preferences, and it is important to ensure that this data is collected and stored securely and used only for its intended purposes. This can be achieved through the use of encryption and other security measures, as well as by providing users with clear and transparent information about how their data is being used. Another aspect of responsible AI for smart homes is transparency. AI systems in smart homes should be designed in a way that is transparent and explainable so that users can understand how they work and make informed decisions about their use. This can involve providing users with clear information about the algorithms and models used by the AI systems, as well as the data sources and assumptions that underlie them. Finally, responsible AI for smart homes also involves ensuring that the benefits of AI are distributed equitably and that they do not perpetuate existing biases and inequalities. This can involve designing AI systems that are inclusive and accessible to all users, regardless of their age, gender, race, or socioeconomic status., it will be important to develop ethical and responsible AI frameworks that prioritize user privacy, security, and transparency. This can help to build trust and confidence in AI-driven smart home technologies and ensure their long-term viability and sustainability.

5. Conclusion

In conclusion, we survey the literature for applying AI approaches in smart homes by highlighting the potential benefits of using AI technologies in the design and implementation of smart homes. The survey provides a comprehensive overview of the current state of research in AI technologies in the design and implementation of smart homes, covering various aspects such as sensing, data analysis, decision-making, and human-machine interaction. We also highlight key challenges and barriers that must be addressed to fully realize these benefits, such as privacy and security concerns, the need for interoperability and standardization, and the importance of user-centered design and human-machine interaction. We also identify key opportunities for future research and development, such as the integration of AI with other emerging technologies like the IoT, blockchain, and big data analytics, as well as the need for more robust and scalable AI algorithms and models.

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