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CYBER-PHYSICAL SYSTEMS IN THE SMART HOME: A REVIEW

SISTEMAS CIBERFÍSICOS EN EL HOGAR INTELIGENTE: UNA REVISIÓN

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Abstract:
Cyber-physical systems are composed of collaborative computational entities that are closely integrated with the physical environment, with smart home systems representing one of their most prominent applications. Through intelligent sensors and actuators, smart home systems aim to provide personalized services that enhance interaction between the digital and physical domains. However, existing conceptualizations of cyber-physical systems and smart home systems are often superficial and lack sufficient technical depth. To address this gap, this study analyzes journal articles and conference papers indexed in Web of Science and Scopus, guided by five research questions, while excluding works with low relevance or limited data integrity. The results reveal sustained growth in scientific production between 2014 and 2024, increasing from 405 publications in 2014 to 1,587 in 2023, which represents an approximate growth of 292%. The predominant enabling technologies identified include the Internet of Things, Artificial Intelligence, Machine Learning, and digital twins, which collectively account for more than 70% of the proposed systems. Current developments are primarily oriented toward health, safety, and energy efficiency, while significant challenges persist in data security, privacy, and system explainability.

Resumen:
Los sistemas ciberfísicos están conformados por entidades computacionales colaborativas estrechamente integradas con el entorno físico, siendo los sistemas de hogar inteligente una de sus aplicaciones más representativas. A través de sensores y actuadores inteligentes, los sistemas de hogar inteligente buscan ofrecer servicios personalizados que fortalezcan la interacción entre los dominios digital y físico. Sin embargo, las conceptualizaciones existentes sobre los sistemas ciberfísicos y los sistemas de hogar inteligente suelen ser superficiales y carecen de profundidad técnica. Para abordar esta brecha, el presente estudio analiza artículos de revistas y trabajos de conferencias indexados en Web of Science y Scopus, guiado por cinco preguntas de investigación, excluyendo aquellos con baja relevancia o limitada integridad de los datos. Los resultados evidencian un crecimiento sostenido de la producción científica entre 2014 y 2024, pasando de 405 publicaciones en 2014 a 1 587 en 2023, lo que representa un incremento aproximado del 292 %. Las tecnologías predominantes identificadas incluyen el internet de las cosas, la inteligencia artificial, el aprendizaje automático y los gemelos digitales, que en conjunto representan más del 70 % de los sistemas propuestos. Los desarrollos actuales se orientan principalmente hacia la salud, la seguridad y la eficiencia energética, persistiendo desafíos relevantes en seguridad, privacidad y explicabilidad de los sistemas.

I. INTRODUCTION

Technology has significantly transformed our homes over the last decade. The integration of cyber-physical systems within the smart home framework has emerged as one of the most prominent trends, given its potential to significantly change the way we interact with our domestic environment [1]. This technology system can collect information from its surroundings and adapt its actions based on that information. The development of smart products and services has contributed to the growing interconnection of devices and the exchange of information, such that the development of smart home technology has spread rapidly around the world, as it focuses on human well-being thanks to these systems [2].

The term “smart home” is not limited to people's residences. It has a broader technological meaning [3], encompassing smart homes, smart cities, smart factories, and smart societies, all regulated by computing technologies [4].

Researchers have increasingly become interested in the subject of smart home technology due to its advantages and the potential for a large global market technology [5]. Hence, the amalgamation of disciplines such as computer science, electronics, and engineering has expedited the advancement of cyber-physical systems in the context of smart homes. This notion entails the integration of physical objects with computing platforms, facilitating intelligent, two-way communication and interaction between them [6].

In this way, Fig. 1 describes the trend of review items in the field of the smart home that have been produced in the last decade and are listed in Scopus. Between 2014 and 2021, a steady increase in the number of review articles published on this topic is evident, from 11 in 2014 to 80 in 2021. We can attribute this increase to the growing interest in integrating smart technologies in homes to enhance comfort, efficiency, and safety. However, there is also a slight decrease in the number of revised articles between 2022 and 2023, which could indicate a stabilization or a change in the direction of research in this field. By March 2024, 22 articles had already been published, representing 29.73% compared to 2023.

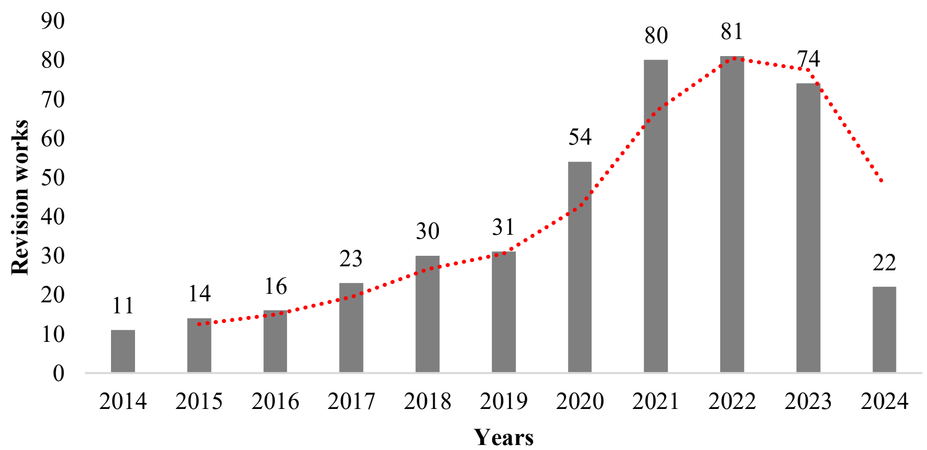

Figure 1. Revision work in the smart home domain

A second search for papers in the smart home domain, focusing specifically on scientific articles published between 2014 and 2024, shows a steady increase in the number of publications (Fig. 2). This increase is remarkable, starting with 405 articles in 2014 and reaching a peak of 1587 in 2023. This scenario reaffirms what was mentioned in the first paragraphs and ratifies the growing interest and dedication of the scientific community to research in this area of knowledge.

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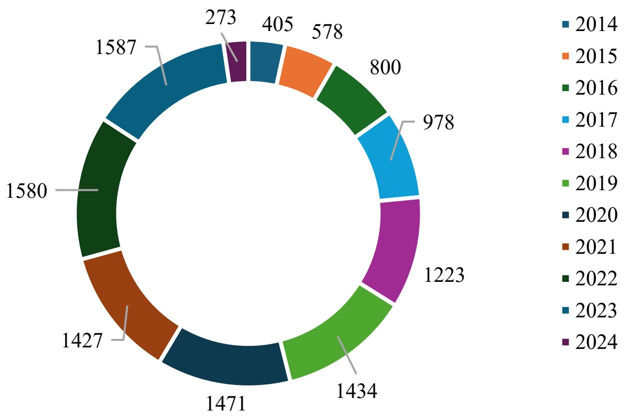

Figure 2. Scientific articles produced in the smart home field

It's essential to take into account that by including actuators, sensors and control systems in smart homes, there are many opportunities to enhance comfort, safety, security, healthcare, convenience and energy efficiency [7]. They also improve the quality of life through the remote and automatic control of household appliances [8]. Smart Home Systems (SHS), for example, provide a platform for remote supervision, utilizing telecommunications and Internet access to allow users to monitor and control their home remotely, focusing on elderly care [8]. For this reason, users can be able to control their home appliances while outside the house, as well as do some tasks at home before returning, using the SHS [9]. Additionally, using intelligent sensors, you can turn on/off lights, set the temperature and humidity levels of your home so as to maintain an optimum environment based on your preferences. One of the additional advantages of smart homes includes security systems, which include intrusion detection systems, allowing for higher security levels [10].

This rapid technological advancement has drastically changed the way we conceive and inhabit our homes. However, despite the progress made in this field, significant challenges remain that require careful attention. The primary concern revolves around the necessity to tackle the difficulties encountered by Cyber-Physical Systems (CPS) in the smart home sector. Although these systems promise to improve efficiency, security, and comfort in our homes, questions still arise about the technology they employ, what systems have been developed, and whether they are reliable for users. Several review articles [11] [9] [12] [13] [14] provide brief descriptions of advances in the field of SHS. However, these papers failed to provide a categorical analysis exposing the most current technologies and which systems could be reliably used by users. scientific review aims to investigate the necessity of acquiring a comprehensive comprehension of cyber-physical systems within the framework of smart houses. This paper addresses the gap in earlier reviews and establishes the following research questions:

- Question 1: What are cyber-physical systems?
- Question 2: How are smart homes defined?
- Question 3: What are the technologies used by cyber-physical systems in smart homes?
- Question 4: What systems have been proposed for smart homes?
- Question 5: What are the benefits and challenges of cyber-physical systems in smart homes?

The central goal of this work is to provide a comprehensive analysis of cyber-physical systems in an environment of smart homes. To achieve this purpose, Section 1 provides an introduction and motivation for studying.

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We have divided Section 2 into two segments: the collection, inclusion, and exclusion of articles, and the data collection that focuses on the research questions. Section 3 provides an analysis and review of the selected research articles, as well as answers to each research question. Section 4 discusses in a timely manner some approaches to cyber-physical systems, smart homes, technologies, current systems, gaps, and benefits. Finally, Section 5 presents the conclusions of the review.

II. METHODS

Fig. 3 provides a comprehensive overview of the investigation technique employed in this study. The research is structured into three distinct phases: data retrieval, analysis of reviews, and discussion of findings and results. Each stage considers selected excerpts that could be considered a reference model for related researchers in the future.

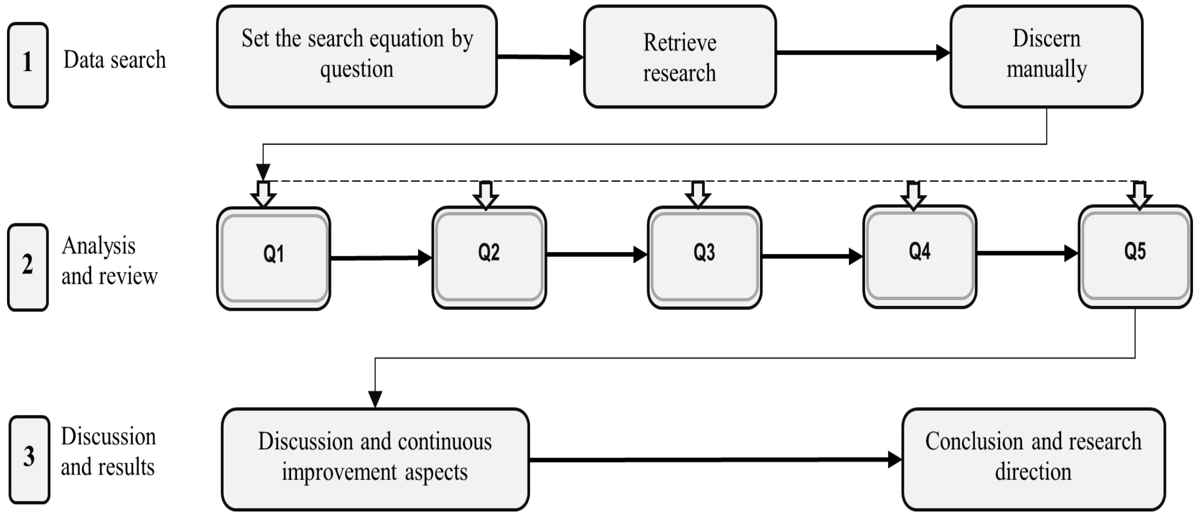

Figure 3. Methodology for the review

2.1 Article collection, inclusion and exclusion

The collection of articles began by defining the most prestigious databases of scientific quality. Scopus and Web of Science (WoS) were selected among several databases due to their completeness and accuracy in searching articles [15]. These systems offer comprehensive coverage of the worldwide research literature, with the WoS Core Collection comprising about 75 million records of publications [16]. In this investigation, relevant publications were acquired by Scopus and WoS Core Collection using their sophisticated search features.

The next step was to determine the search equations to ensure the success of a literature review. In this study, two groups of keywords were designed, considering the research questions. The first set focuses on terms related to "cyber-physical systems", while the second set addresses aspects specific to the "smart home". Both sets of keywords were extended to cover all possible combinations. Table 1 shows the search equations. Equation (1) explains the query string for searching articles in Scopus and equation (2) for searching in WoS. Thus, answering the research questions: what are cyber-physical systems? What technologies do cyber-physical systems use in smart homes? and What are their advantages and challenges? While searching equations (3) for WoS and (4) for Scopus answer the questions. How is smart home defined and what systems have been proposed for smart homes?

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Table 1. Search equations

N	Query's
1	(TITLE-ABS-KEY("cyber-physical systems") OR TITLE-ABS-KEY("CPS")) AND (TITLE-ABS-KEY("smart home*") OR TITLE-ABS-KEY("intelligent home*") OR TITLE-ABS-KEY("home automation") OR TITLE-ABS-KEY("house automation")) AND (TITLE-ABS-KEY("technologies") OR TITLE-ABS-KEY("benefits") OR TITLE-ABS-KEY("challenges"))
2	(ts = ("cyber-physical systems" OR cps) AND ("smart home*" OR "intelligent home*" OR "home automation" OR "house automation") AND ("technologies" OR "benefits" OR "challenges"))
3	(ts = ("smart home*" OR "smart house*" OR "intelligent home*" OR "intelligent house*" OR "remote home*" OR "remote house*" OR "home automation" OR "house automation" OR "automated house*" OR "smart living" OR "home automation system" OR "intelligent building" OR "domotics" OR "connected home" OR "ambient intelligence" OR "smart environment" OR "Internet of Things (IoT) home" OR "ambient assisted living") AND ("natural" OR "voice" OR "speech" OR "spoken" OR "verbal" OR "gesture" OR "touch" OR "emotion" OR "expression" OR "gaze" OR "eye*" OR "fixation" OR "position" OR "locat*" OR "vision" OR "hearing" OR "auditory" OR "taste" OR "olfactory" OR "smell" OR "haptic" OR "touch sensation" OR "sensory perception" OR "multimodal interaction"))
4	(TITLE-ABS-KEY("smart home*" OR "smart house*" OR "intelligent home*" OR "intelligent house*" OR "remote home*" OR "remote house*" OR "home automation" OR "house automation" OR "automated house*" OR "smart living" OR "home automation system" OR "intelligent building" OR "domotics" OR "connected home" OR "ambient intelligence" OR "smart environment" OR "Internet of Things (IoT) home" OR "ambient assisted living") AND TITLE-ABS-KEY("natural" OR "voice" OR "speech" OR "spoken" OR "verbal" OR "gesture" OR "touch" OR "emotion" OR "expression" OR "gaze" OR "eye*" OR "fixation" OR "position" OR "locat*" OR "vision" OR "hearing" OR "auditory" OR "taste" OR "olfactory" OR "smell" OR "haptic" OR "touch sensation" OR "sensory perception" OR "multimodal interaction"))

In addition to the foregoing, the PRISMA approach was employed due to its methodical and rigorous nature, making it suitable for conducting systematic reviews and meta-analyses of multidisciplinary investigations. Fig. 4 illustrates the stages that contribute to the research. The approach begins by measuring the amount of research based on the available bibliographic databases, which then leads to the search for up-to-date and high-quality scientific articles. This cycle also considers factors such as selection, eligibility, and inclusion of publications that are relevant to the study topic.

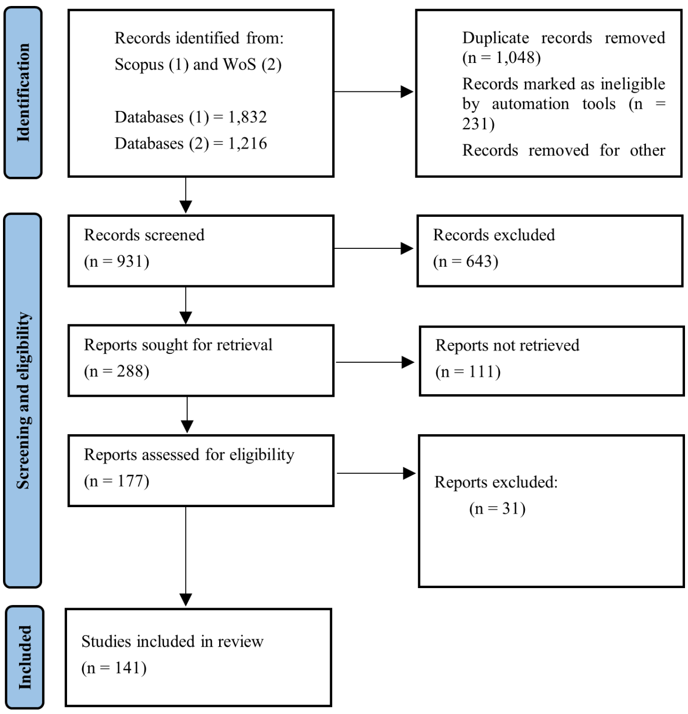

Figure 4. Procedure for the review

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To ensure that high-quality information was obtained, the “ts” operator was used together with double quotation marks in the search code. This ensured that the keywords were exactly present in the title, abstract, author keywords, or plus keywords of the articles. The search was restricted to English. Only reviews, papers, presentations, and conference proceedings were included in this investigation because of excluding editorials and book reviews from consideration. During the search process, irrelevant topics were removed as well. The time frame for the collection of articles was defined as between 2005 and 2024 (up until March 11), so that all relevant publications could be retrieved.

2.2 Data Collection

In the data collection process, the focus was on answering research questions. For the first research question, “What are cyber-physical systems?”. The focus of this question is to obtain additional information on the current definitions and characteristics of cyber-physical systems. The second research question, “How do you define smart homes?” is of great interest due to the increasing implementation of smart technologies in residential environments. The precise definition of smart homes will help to understand professionals from different disciplines, such as engineers, interior designers, architects, and software developers, but it will also inform consumers about the related products and services in smart homes. In addition, a clear definition can guide the future development of policies and regulations in this field. For the third research question, “Technologies using cyber-physical systems in smart homes?” the purpose is to identify those trends so that designers, developers, and manufacturers of smart home-related products have the means to integrate more automated solutions in areas such as wellness or health, climate, security, energy control, and comfort.

The fourth research question is, “What systems have been proposed for smart homes?” involves recognizing technological solutions such as smart energy management systems, home automation devices for home automation (such as smart lighting systems, smart thermostats, and smart locks), advanced security systems with smart cameras and sensors, virtual assistants for remote home control and monitoring (such as Amazon Alexa, Google Assistant, or Apple HomeKit) [17], and health and wellness systems based on sensors and wearable devices (such as physical activity monitors and telemedicine devices). The fifth research question is, “Benefits and challenges of cyber-physical systems in smart homes?” aims to make visible as much as possible the benefits and the risks or shortcomings faced by users and society in general.

III. RESULTS

The purpose of this section is to address all the research questions raised and, in addition, to offer a reflection that promotes understanding and interest among the scientific community dedicated to this discipline.

3.1 Question 1: What are cyber-physical systems?

Cyber-physical systems are an exciting fusion of the physical world and the digital world, bringing together computational power, communication and control in physical devices in the "real" world that have never been seen before; creating a whole new generation of technological innovation and capabilities for interacting and responding to their environment [18]. They can be found in all areas such as Industrial Automation, Autonomous Vehicle, Smart Home, and Smart City development. All of these technologies will bring improved efficiency, accuracy, and convenience. However, in recent years, an increase in research dedicated to this area of knowledge has been observed, revolutionizing the way infrastructures are designed and managed with the aim of improving their capabilities through a synergistic combination of sensing, computing, and control mechanisms [19].

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Among the identified limitations, the lack of CPS readability in current developments [20] and a conceptual framework that nurtures each development phase and process stand out.

In order to strengthen the above-mentioned, a conceptual model of CPS could be sketched according to Fig. 5. This illustration shows communication interaction that starts by collecting information, determining actions that have been performed, the state in which the system is, determining the decision according to the available data, and establishing an axis of interaction with humans. This conceptual model could not only contribute to having a clearer idea of how this type of system communicates but also allow for more graphic and current vision of the CPS.

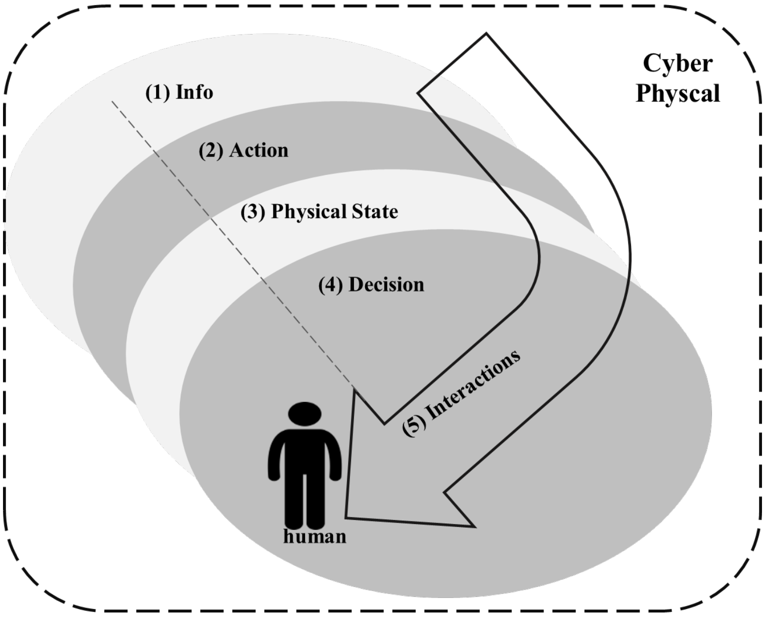

Figure 5. CPS conceptual model

Therefore, Fig. 6 illustrates what the basic structure of a cyber-physical system could be. The physical layer contains tangible components such as sensors, actuators, machines, and vehicles, which interact with the physical environment, generating data and performing actions. The sensor layer collects information from the environment, such as temperature, pressure, or location, and transmits it to the processing layer for analysis. The actuator layer executes physical actions in response to decisions made by the system. The processing layer uses algorithms and artificial intelligence systems to perform data analysis, decision-making, and system control. The communication layer facilitates data transmission between components using wired or wireless protocols. Similarly, the user interface layer provides tools for users to interact with the system, such as graphical interfaces or mobile applications, allowing monitoring, adjustments, and access to relevant information. Each of these layers collaborates to create a CPS.

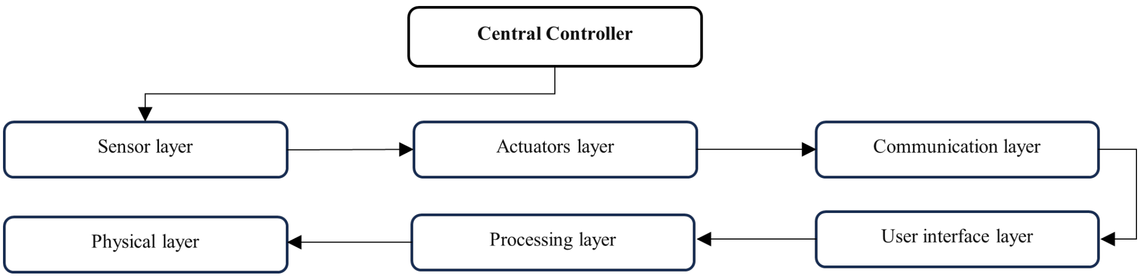

Figure 6. Basic structure of CPS

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In this sense, authors such as [21] indicate that CPS are systems based on the integration of computer algorithms and physical components (controllers, sensors, and actuators) [22]. Although CPS are innovative systems that combine computer, control, and communication technologies to connect the virtual and physical realms, it is feasible to create hardware solutions that serve as interfaces for workstations [18] [23]. According to the information provided, CPSs are systems that are created to (1) improve the abilities of humans to interact with machines through interfaces, using techniques of human-computer interaction that are designed to adjust to the cognitive and physical requirements of operators, and (2) improve the physical, sensory, and cognitive abilities of humans by utilizing different technologies. Furthermore, it is specified that CPSs refer to the entities that serve as both the components of computers and physical processors [24]. The physical level encompasses sensors of CPS nodes that gather data, including information about the environment (such as temperature, humidity, and illumination), operating status information (such as velocity, vibration, and motion), and operating information to process (such as position, dimensions, and quality) [25].

Considering the information provided, Fig. 7 illustrates the core technologies involved in cyber-physical systems. These technologies include sensors and actuators, which are responsible for gathering data from the physical world and carrying out actions based on system signals. The Internet of Things is defined as a network of Internet-enabled physical objects. This allows for the exchange of information among all the different components of CPS. Cloud computing enables us to use scalable computer power to store and process the vast amounts of sensor data generated by CPS. Cloud computing also enables us to run CPS analysis and control algorithms. Wired and wireless communication networks allow for data exchange between the different CPS components. AI and machine learning are used in CPS to analyze data in real time, make decisions based on that analysis, and optimize performance of CPS. Cybersecurity protects sensitive data in CPS with techniques like encryption, authentication, and intrusion detection. We consider these technologies to be working together to create an efficient interface between the digital world and the physical world in cyber-physical systems.

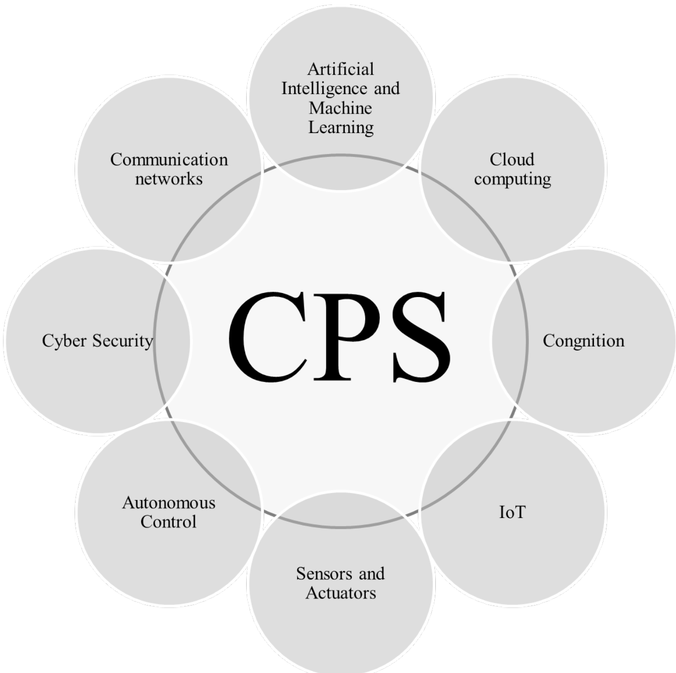

Figure 7. Basic technologies of CPS

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Additional information shows that a CPS is made up of a combination of a physical component and a cybernetic twin. A cybernetic twin is defined as an imitation of an object (such as a computer program) of a physical entity. Developing a CPS will require developing a new platform of software as well as compliance with strict guidelines regarding mobility, safety, privacy, security, and the management of large amounts of data [26] [27]. For Cardin et al. [20] CPSs are sets of collaborative computational entities that maintain a close connection with the surrounding physical environment and its ongoing processes. These systems enable the simultaneous utilization of handling services and data that are accessible on the Internet. The research undertaken by [28] confirms that CPS are participatory computer systems that are intricately connected to the physical environment and its continuous operations. These systems offer both data access and data processing services that can be accessed on the Internet at the same time.

Also, [29] determines that this class of systems is defined by a tight integration of physical [30] and software processes for task management and user-centred decision-making through a mechatronic system (the physical world) coupled with software entities and digital information that allude to the industry 4.0 paradigm [31] [32]. One of the little-known facts lies in the fact that SCPs have allowed the transition from Industry 3.0 to Industry 4.0 [33]. If we talk about software, we refer to model-based design. While in the past, physical and software component models were developed separately, the trend towards cyber-physical system design has resulted in models with discrete and continuous dynamics, so-called hybrid systems [1].

The spectrum of CPSs leans towards technologies including robotics, the Internet of Things [3], and machine learning [34]. Nevertheless, it is important to note that a Cyber-Physical System primarily gathers and manages data about physical phenomena using networks of interconnected devices to accomplish its objective. On the other hand, the Internet of Things (IoT) encompasses all connected devices and a specific network of interconnected objects [35]. All this [6] determines CPS as an intelligent system in which physical and computational systems are integrated to control and detect the changing state of real-world variables. As for [36], CPSs are collaborative embedded computing devices capable of sensing and controlling physical elements and often responding to humans. Throughout several studies developed over time, we have considered it important to create a timeline (Fig. 8) that symbolizes the evolution of CPS from 2014 to 2024. Each stage in this timeline highlights a significant advancement in the field of CPS, spanning from collaborative computational entities, software, controllers, sensors, and actuators to the integration of algorithms and interaction elements with the physical world. Undoubtedly, these advances and perspectives are destined to improve or complement diverse functions in society.

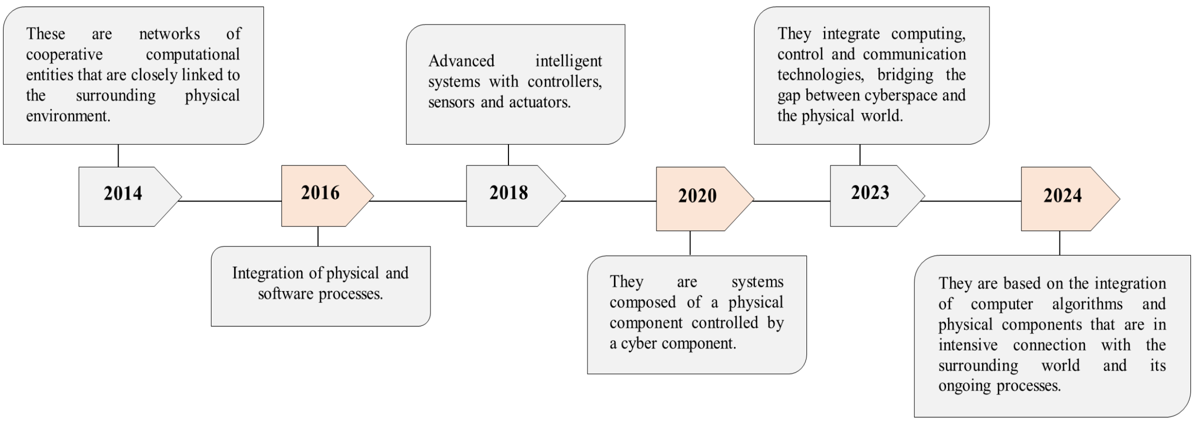

Figure 8. Definitions in recent years of CPS

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The CPS has a wide variety of benefits, starting with the reduction of costs and development time along with the improvement of the designed products. This involves product virtualization. Virtualization allows for monitoring, controlling, and influencing the physical world in an adaptive and intelligent way with lower costs in the different development phases [37]. One of the reasons it is appealing is because it involves the collaboration of various fields [38], including mechanical engineering, electrical engineering, and computer science [39]. A CPS can interact with computer systems such as microprocessors and digital communication connections, as well as many physical systems including mechanical, chemical, structural, and biological ecosystems [40].

The integration of all these systems allows the development and inclusion of elements in health and biomedical surveillance, robotic systems, and intelligent edge devices for smart homes, among many other functions, and in opportunities that could be used to correct natural disasters, human errors, malicious actions, etc [30]. Ahmadi et al. [33] confirm that CPSs have a broad engineering scope that enables their use in various applications such as emergency response, air transportation, infrastructure, medical and health care, intelligent transport, robotics for services, and special smart manufacturing.

On the other hand, CPSs not only represent benefits, but they also face challenges that have to be addressed as part of the best continuum; among them we refer to security, data integrity, empathy, and understanding of their actions [41]. In this sense, we consider that the stability of SCP requires means that ensure reliable communication, safety, security, sensors, and electronics [6]. Each of the insights discussed above not only provides us with a clear picture of the evolution of cyber-physical systems but also allows us to discern and establish a functional structure on which these systems are predominantly focused (Fig. 9).

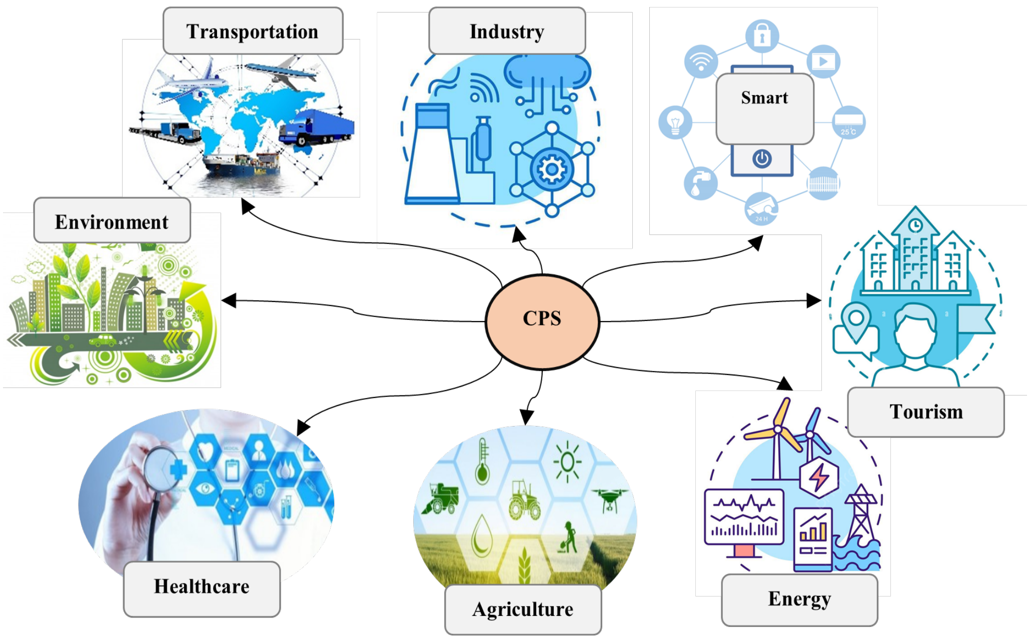

Figure 9. Industry vision through cyber-physical systems

On this path, various industries such as transportation, energy, healthcare, smart home, and many other sectors have excelled in adopting and adapting to innovations derived from CPS. For example, in the transportation sector, autonomous vehicles and intelligent traffic management have revolutionized urban mobility and logistics. In energy, the implementation of smart grids has improved energy efficiency and facilitated the integration of renewable energy sources. In

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healthcare, telemedicine and connected medical devices have enabled more personalized and accessible medical care. In the context of smart homes, cyber physical systems that work together for the purpose of making both our lives easier and more comfortable and provide us with an opportunity to save energy and resources on a long-term basis. This is clear when you consider examples such as use of both thermal and motion sensors, which can be integrated into smart control systems. In this way, a smart home can automatically adjust heating/cooling (air-conditioning) and lighting based upon occupancy in each room, thereby reducing overall energy usage. Each of these examples illustrates how SCP is fundamentally transforming various aspects of society by offering more efficient, safer, and sustainable solutions to contemporary challenges.

3.2 Question 2: How are smart homes defined?

A considerable number of studies have explored the discipline of smart homes through the development of systems, applications, and methodologies, among other contributions that would benefit the community; however, as society moves into the future, the concept of smart homes has evolved beyond simple automation to become an integral part of achieving inclusive and sustainable industrialization [4]. In that sense, we have thought it convenient to reflect in this subsection the most recent and relevant definitions of the Smart Home (HS), since there are partially overlapping or similar definitions to the smart home [42].

Strangers et al. [43] indicates that the smart home concept first appeared in the 1930s as "homes of tomorrow". One of the first smart home devices was the 100-pound "kitchen computer" [44]. Today [9] points out that smart homes are systems that automate household tasks. While [14] specifies that they are homes with technologically advanced systems that allow the automation of household tasks through simpler and more secure communication. According to Alam et al. [12], an intelligent home is a sophisticated environment that can adapt to the actions of its inhabitants. Furthermore, HS, as defined by [45], is considered a viable tool for automating or aiding users in various ways, such as by environmental intelligence, online home control, or systems for home automation. In [46], it is described as a sophisticated residential structure with incorporated equipment, highlighting contemporary technology, convenience, and domestic efficiency. Smart homes are defined in [46] as advanced residential structures that incorporate hardware for modern technology, comfort and efficiency. A "smart" home includes an overall view of the whole environment by combining all of the different devices and sensors in the home. Thus, this will allow a better fit for future usage and predictions based upon current status of the system and historical data of the occupants [13]. As shown in Fig. 10, each smart home has the same basic parts which include: end-user devices, sensors, appliances and actuators.

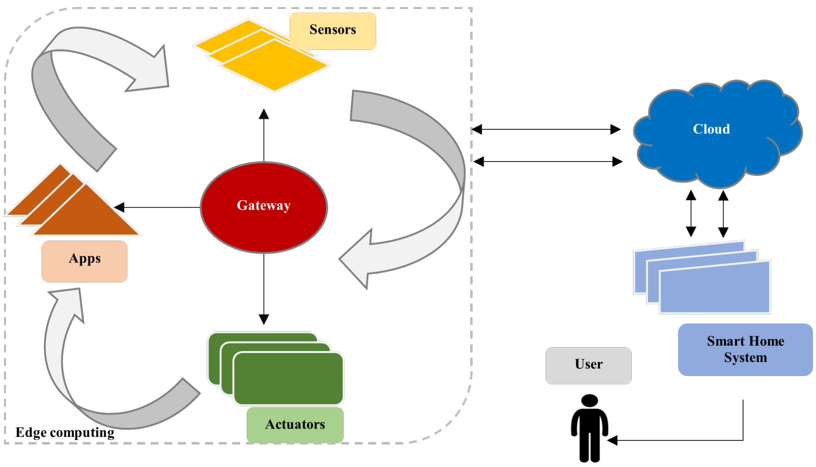

Figure 10. Architecture of a smart home

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The devices in the system communicate with each other by way of a peripheral gateway which serves to connect the home networks internally with the public internet externally. This peripheral gateway acts as an intermediary for communication between the devices at both ends and detectors/systems as a whole and the public internet. The entire system is engineered to provide the most efficient service possible for the user's needs and wants.

According to [14], the main objective of HS is to offer superior comfort, enhance security, simplify energy management, minimize environmental pollutants, and achieve energy efficiency. According to [12], the term "smart home" refers to a modern use of ubiquitous technology that involves incorporating intelligence into the administration and functioning of homes for purposes such as comfort, healthcare, security, and energy saving [47]. These descriptions verify that the main objective of a smart house is to enhance the comfort of the occupants and simplify their everyday lives [48] [49] [50] [51] [52]. In this path, the functionality of the HS lies in establishing communication between appliances and users to enhance the automation, monitoring, and remote-control capabilities of the appliances [53] [54]. Smart houses incorporate a variety of technologies that can sense specific conditions and adjust the features of the household accordingly. In addition, they utilize remote monitoring over the Internet to enhance the intelligence, safety [55], and automation [56] objects. For instance, certain sensors are employed to monitor many factors including humidity, temperature, motion, safety (to activate an alarm or alert) [57], healthcare, LPG leaking, etc [58] [59] [60] [61] [62] [17].

According to the insights, smart homes offer comfort, health care, and protection to their residents. These comfort and health care services can be managed both locally and remotely. In addition to providing security measures that limit unauthorized access, Fig. 11 shows how some of the services most exposed by recent work are categorized.

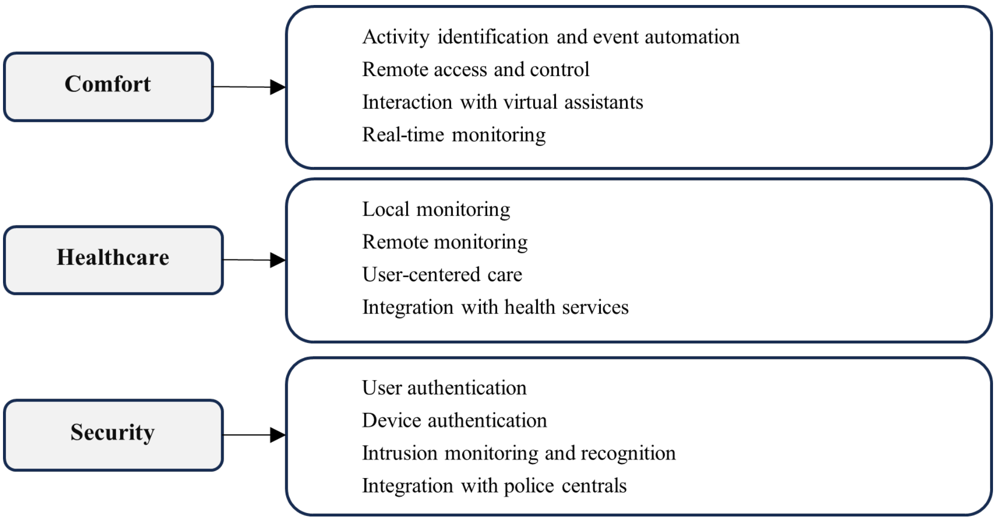

Figure 11. Categorization of some of the services expected in smart homes

Complementing the aforementioned, comfort is one of the main benefits of smart homes, facilitating daily life by increasing user productivity. This is achieved by identifying related human activities and automating events in local environments, remote management of the home from distant locations, interaction with virtual assistants, and permanent monitoring. Opportunities for such qualities optimize energy use because the home is smart enough to reduce energy consumption by controlling unattended appliances. In the same way, healthcare is responsible for providing healthcare services to patients, the elderly, and healthy people. This service can generate local health reports and, above all, integrate remote healthcare providers for emergency assistance. In the same

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direction, security is another relevant factor in smart homes, which are vulnerable to user and device authentication. However, new interaction mechanisms and the integration of external services could contribute to reducing this gap and improving the perception of residents.

Another of the simple concepts of HS can be (1) automation and interactive technologies [63], (2) various devices are connected through the Internet and can communicate with each other to exchange information [64], and (3) personalized environments where residents participate in daily activities in their own way [65]. However, authors such as [66] point out that smart homes constitute an overlay network along with service providers such as cloud storage and smartphones. In this regard, [67] acknowledges that the term “smart home” denotes a residential setting equipped with sophisticated technology that allows for the supervision and management of its inhabitants, promoting self-sufficiency through the use of sensors and actuators to regulate the environment or by predicting well-being through the analysis of behavioral patterns. Jensen et al. [68] explain in their definition of a smart home a residence with a pervasive, intelligent, and interconnected system. The system is capable of identifying and satisfying the needs of comfort [11], convenience, entertainment, and safety of its occupants. Also notes that the evolution of smart homes has improved the notion of user identification, which has both protected users' private information and enabled vendors to deliver personalized services to them [69].

If we talk about sensors or actuators, these components are part of a technical structure, which can be constituted by several interconnected elements that work together to provide an efficient and adaptable residential environment to the needs of its inhabitants. In this way, Fig. 12 characterizes an alternative technical structure in the domain of smart homes, where sensors are considered the basis of this structure, collecting data from the environment such as temperature, humidity, movement, and air quality. This data can be processed by an automation platform, which allows programming rules and scenarios to automatically control the connected devices. On the other hand, the communication network facilitates the connection between all components, either through wired or wireless connections. Intelligent devices, such as lights, thermostats, locks, and security cameras, are controlled and monitored through this network. To interact with the system, an intuitive user interface is provided, which can be a mobile application, a web interface, or voice commands. In this way, data collected by sensors and devices is stored and analyzed to extract useful information about user behavior and improve the efficiency of the system over time.

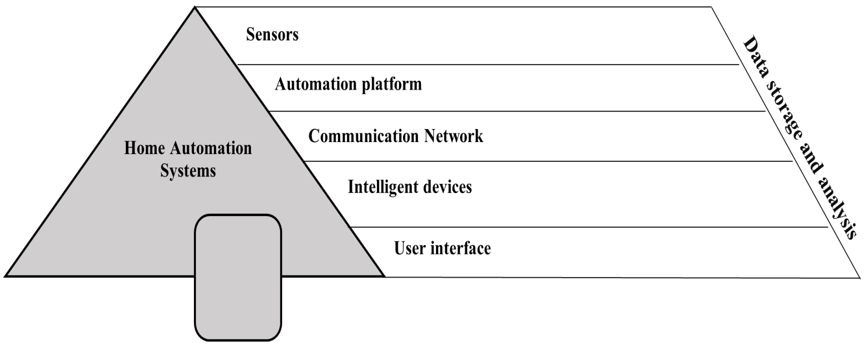

Figure 12. Technical structure of a smart home

On the other hand, smart homes are recognized as an important link in the IoT field, as they can benefit users or stakeholders [70] [71], in addition to improving people’s quality of life [44]. Among these improvements, we talk about living a more comfortable, economical (managing their energy consumption) [56] [72], healthy (assessing the health conditions of human activities through physical movement signatures) [73], environmentally friendly (reducing carbon emissions and using

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renewable energy sources) [74], and secure via assistive services (i.e., automated services that are cognizant of the context) provided by ubiquitous computing applications [2].

We consider that applications with a ubiquitous approach in the smart home domain provide a cross-cutting look from the way of interacting to the right time to receive some kind of information. That is why some trends are inclined to recognize actions by voice or, in the best case, through interconnected devices in the cloud. In this way, Fig. 13 illustrates the interaction of a resident, a possible communication mechanism through various devices permanently accessible to the user, achieving the fulfillment of actions that optimize resources in terms of time and money.

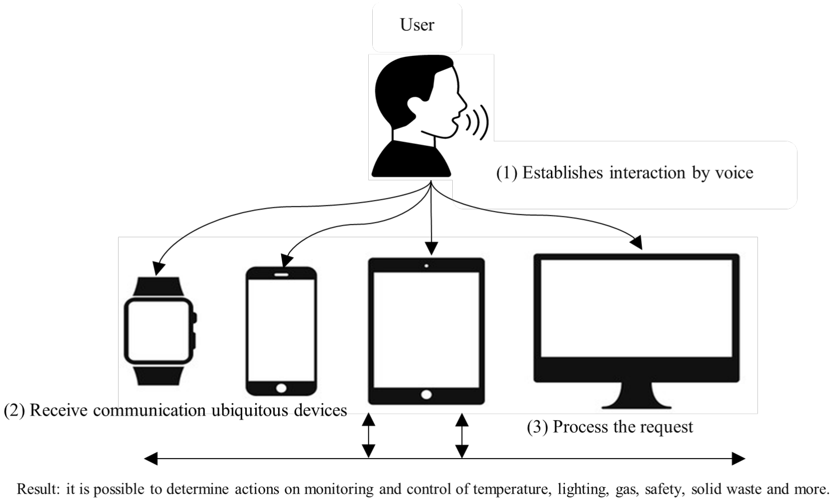

Figure 13. Interaction of a smart home based on voice recognition

A home system consists of a network of hardware and software components that observe the living space by gathering data on the homeowner's behavior and understanding their actions. By doing this, the system is able to identify and notify about potentially dangerous situations and carry out measures on behalf of the resident to their contentment [49]. Among the different challenges to data loss due to interference is efficient energy management. Smart home technology is expected to become widespread in the future and adapt to a green transition to reduce and change energy consumption [75] [76]. In this way, people can control the home environment efficiently and conveniently [5]. Finally, the acceptability of smart homes depends on user’s perceptions of their benefits and their concerns related to monitoring (IoT sensors) and sharing or variability of their data [7] [77].

3.3 Question 3: What are the technologies used by cyber-physical systems in smart homes?

In this section, we will address the key technologies that make possible the automation and intelligent control of smart homes through cyber-physical systems. To this end, Table 2 responds to this question.

Table 2. Technologies used by cyber-physical systems in HS

Studies	IoT	AI	ML	Digital Twin
[78] [79][80]	+			+
[81][82][83]	+	+	+	
[84][85]	+	+	+	+
[86] [87]	+	+		
[88] [89] [90][91] [92] [93][94][41] [95] [96]	+			

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Table 2 summarizes the technologies used by cyber-physical systems in the smart home domain, among the most common of which are IoT, AI, ML, and digital twins. Most researchers are inclined to believe that IoT is the most predominant technology for the development of this type of system. On the other hand, technologies such as AI and ML complement the execution of the tasks that are part of this type of system for the benefit of users. However, recent studies have mentioned the participation of digital twins. The latter technology could represent a disruptive change in the development of cyber-physical systems in the field of smart homes due to its ability to create accurate virtual replicas of physical devices and real-world processes. In this regard, it is remarked that digital twins allow simulations, analysis, and optimizations to be performed before implementing changes in the physical environment, which reduces the costs and risks associated with live testing. In this way, we believe that their integration into the smart home landscape promises to improve operational efficiency, personalization of user experiences, and adaptability to changing situations.

The technological advancements made by these technologies (IoT, AI, ML, Digital Twins) are developing Home Systems significantly. However, one cannot overlook the fact that this technology has the potential to revolutionize the Home Experience. Unlike previous smart home technologies that were designed to automate the day-to-day household chores, the new advances are not only capable of automating household tasks, but they will provide an even greater level of understanding for the individual needs and desires of those inhabiting the home. This increased understanding can be achieved through combining the data from smart sensors and advanced algorithms to allow smart home systems to proactively adjust to improve comfort, safety, and other functions based on the well-being and satisfaction of the user(s). For example, by analyzing behavioral patterns, these systems can anticipate user needs and automatically adjust the home environment to meet them. In this sense, CPS and HS not only offer advanced technological solutions but also promote more intuitive and human-centered interaction (Fig. 14) in the home environment of the future.

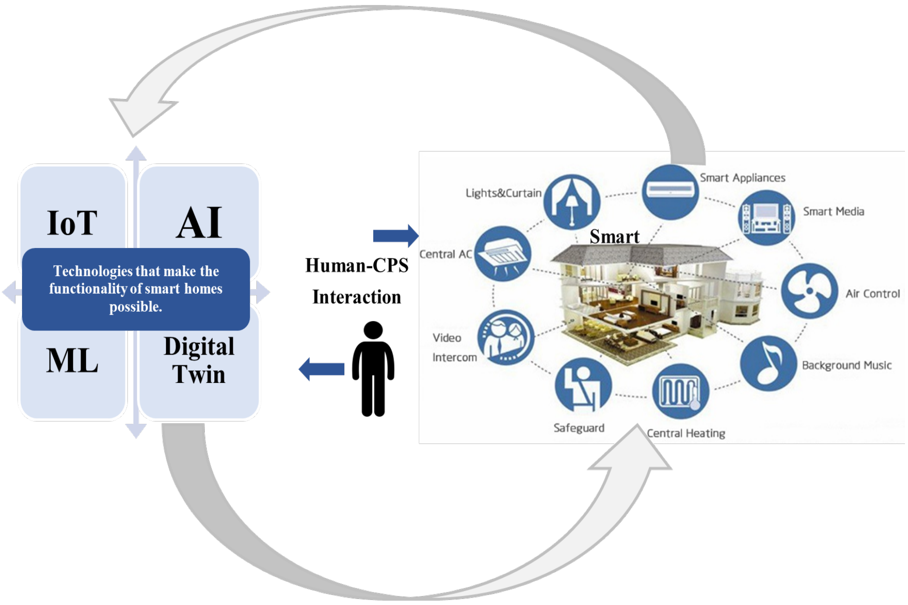

Figure 14. Current technologies focused on CPS in the field of HS

Finally, we believe that the development of this type of system could be complemented by integration mechanisms with augmented reality to improve the user experience in the configuration and control of domestic devices, allowing a more intuitive and visual interaction with the digital and physical environment. In this context, Fig. 15 exemplifies the role of augmented reality in the smart

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home domain. In this specific example, the use of a smart refrigerator that is monitored by the residents through augmented reality is shown. This technology allows the user to check the status of the food inventory in the refrigerator, which facilitates decision making on the need to replenish supplies or identify available food at the time of inspection.

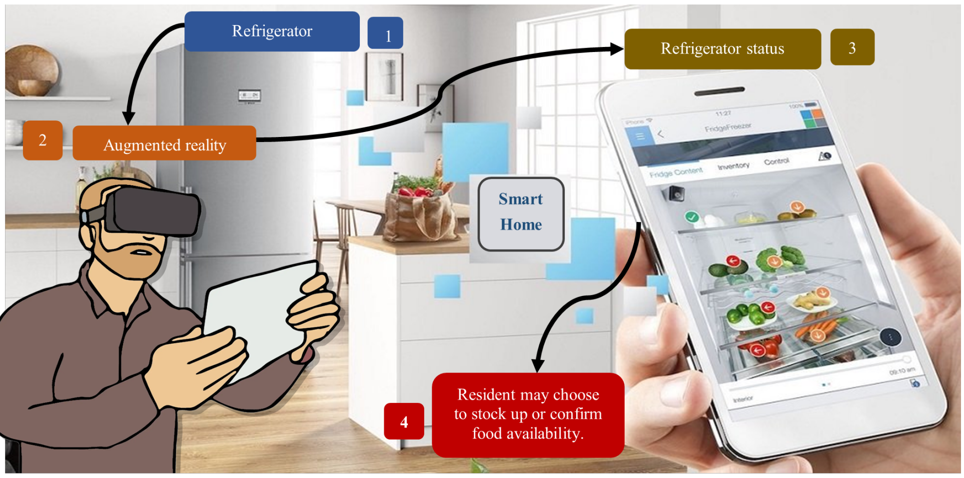

Figure 15. An example of the use of augmented reality in the smart home

On the other hand, blockchain technology could also contribute to ensuring the security and privacy of data in the cyber-physical systems of smart homes, providing a decentralized and transparent infrastructure for information management [97]. However, these precisions should be addressed in future studies in a way that drives and motivates the participation of ubiquitous and dynamic technologies with the sole purpose of providing greater flexibility and scalability in the management of connected home devices and services.

3.4 Question 4: What systems have been proposed for smart homes?

In the search carried out, a variety of systems aimed at the concept of smart homes were identified. From the review of 2000 scientific articles, 66 were rescued, and 14 categories of this type of system were determined (Table 3). Each category addresses different aspects of domestic life. A summary of these systems is presented below, highlighting their importance and application in the context of smart homes:

Table 3. Systems in the smart home domain between 2007 and 2024

Category	Description	Studies
Water	Regulating supply, detecting leaks, and promoting sustainable practices are increasingly common, optimizing the use of this vital resource.	[98][99]
Animals	Monitor the health, feeding, and behavior of pets, intelligently integrating them into family dynamics.	[100]
Heating	Prioritize energy efficiency and resident comfort by adjusting the room temperature precisely and according to the needs of each space.	[101][102][103]
Home Appliance Control	Its purpose is to establish more efficient energy consumption and greater convenience for users, who can monitor and control their devices from anywhere.	[104]
Voice Emotions	Adapt the home environment according to the emotional state of the residents, improving their emotional well-being.	[105]
Energy	Optimizing energy consumption, energy management systems integrate renewable sources, smart storage, and efficient technologies to reduce costs and promote sustainability in the home.	[106][107][108][109][110] [111][112][113]

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Table 3 (continued)

Category	Description	Studies
Metaverse	It offers immersive and personalized experiences through metaverse systems, redefining the way they interact with the home environment.	[114]
Movements	Its purpose is to establish more effective security management and provide comfort to the inhabitants by adapting the environment to their needs.	[115]
Multifunctional	They combine diverse functionalities to offer comprehensive solutions for multiple aspects of home life, from security to entertainment.	[116][117][118][119][120][64][121][122][123][124][125][126][127][128][129]
Multifunctional Low	They offer similar functionalities to multifunctional systems, but with a focus on accessibility and economy of resources, providing intelligent solutions at a reduced cost.	[130][131][132][133][134]
Solid Waste	Its objective is to contribute to environmental sustainability, from separation and recycling to waste reduction, by promoting responsible practices among residents.	[135]
Irrigation	They optimize the use of water and ensure proper maintenance of vegetation, thus improving the domestic environment and promoting connection with nature.	[136][137]
Health	Prioritization of residents' well-being and health. These systems offer solutions to monitor, diagnose, and manage chronic diseases, as well as promote healthy living habits.	[138][8][139][140][141][142][143][144][145][146][147][148][149][150][151][152]
Security	Safeguarding the residents' integrity. These systems integrate technologies for surveillance, intrusion detection, and early warning of risk situations, guaranteeing the protection and peace of mind of residents.	[153][10][154][155][156][157][158]

Together, these systems represent a distinctive advance in improving the quality of life in the home, promoting efficiency, comfort, and the well-being of its inhabitants through the intelligent integration of innovative technologies. We consider that the effective implementation of these systems will transform and generate a new life experience for the user by providing a safer, more sustainable, and adaptable home to their needs.

To complement Table 3, we have statistically quantified the categories in which more smart home-centric systems are under development in Fig. 16. The smart home systems that focus on the health component (24.24%) are the ones that have been proposed and implemented the most. Similarly, multifunctional systems had 22.73%, security had 13.64%, and energy management had 12.12%. These types of systems have been the most predominant, while, in this analysis, recent research has shown that metaverses, something new and disturbing for residents, are being considered. Another important consideration is that smart home systems are beginning to be developed that involve household pets, such as cats. This spectrum, integrating pets as part of the family, is an inclusive advance that has been little anticipated but is undoubtedly a complementary alternative to the comfort of users in the domestic environment.

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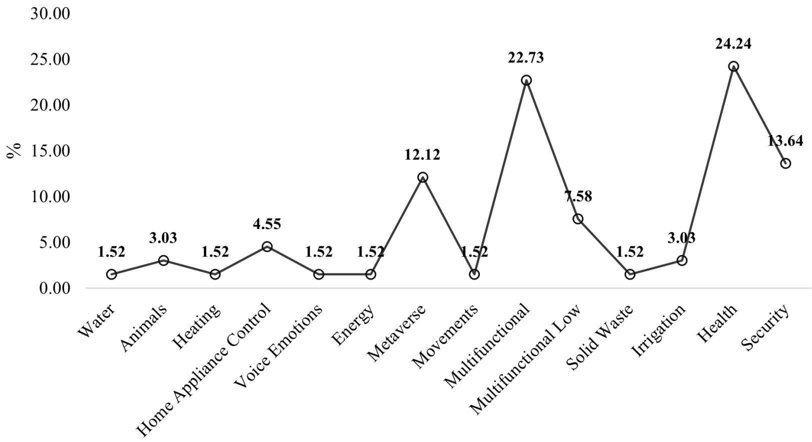

Figure 16. Type of systems in the smart home domain between 2007 and 2024.

3.5 Question 5: What are the benefits and challenges of cyber-physical systems in smart homes?

Cyber-physical systems in smart homes represent a significant evolution in the integration of technologies to improve the quality of life of residents [159]. They offer a wide range of benefits, from automating everyday tasks to personalizing experiences and advanced health monitoring [160]. This system has the capability to provide healthy convenience to residents by integrating modern technology in a way that is efficient at improving areas that include lighting, HVAC, energy, and security. This will allow the residents to have an added sense of security and peace of mind, as well as protect them from unwanted threats.

In this way, the advantages mentioned in Fig. 17 are amplified and extended as it is shown that these systems also allow the automation of many different functions that increase the comfort and reduce the time spent by users. These devices also help to optimize the energy consumption of homes, therefore the users have lower bills for utilities and the best possible use of the available resources. Smart locks and surveillance cameras can enhance the security of a house by allowing remote viewing and real-time notification of unusual activity. They can also provide an experience that is customized to the needs of each resident, so that they may be able to take advantage of their unique preferences, habits and requirements. Home owners can access and manage different features of their homes using either their mobile device or computer, including temperature, lighting and appliances, which will create even greater convenience and effectiveness in managing their homes.

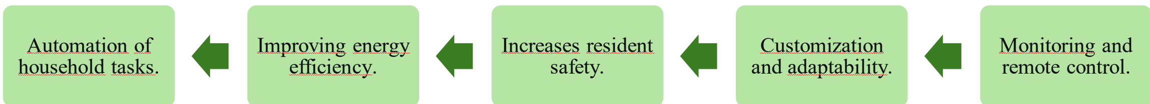

Figure 17. Benefits of cyber-physical systems in the smart home

However, the implementation of these systems also presents challenges, such as privacy, security [161], data variability [162], reliance on AI [163], as well as interoperability between devices and manufacturers. On the other hand, the collection of personal data assets makes smart homes a target for cyberattacks [164]. Similarly, [138] indicates that there is poor manageability, rigidity, difficulty in achieving security, and high ownership costs. Another obstacle is the deployment of CPS applications that often do not know how to process and manage large amounts of data generated for

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decision-making [165]. It is also known that several CPS devices from major vendors have suffered vulnerabilities in their operating systems, leading to unauthorized information disclosure [166].

Fig. 18 summarizes the most common challenges affecting cyber-physical systems in smart homes, as described in the previous section. For example, due to the connectivity of devices in smart homes, concerns may arise regarding the privacy and security of individuals' personal data, depending on whether adequate security precautions have been taken to protect such data. Another potential problem is the complexity of integrating multiple devices from different manufacturers that use different communication protocols, making it difficult for them to work together (interoperability) to avoid compatibility and usage issues. The cost of installing these systems often involves a high initial cost, followed by long-term maintenance and updates for all devices and software. Last but not least, the operation of many devices may depend on an active and continuous Internet connection, which could be problematic for those living in areas where coverage is limited and/or subject to service interruptions. Adopting new technologies in the home can take time and effort for users to become familiar with the features and functions of the systems, which can lead to resistance to change or initial frustration.

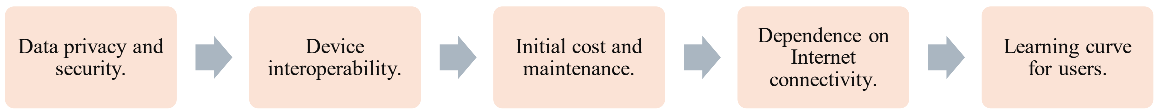

Figure 18. Challenges of cyber-physical systems in smart home

In order to mitigate cyber dangers, it is necessary to develop new planning processes, tactics, and strategies to govern both internal and external devices, notwithstanding the numerous advantages offered by cyber-physical technology [167] [168] [169]. Finally, we consider that to fully exploit the benefits of cyber-physical systems in the smart home domain, it is necessary to consider the social aspect [170] and that the design and development of the systems should focus on including the "human" in the whole process [171] [172].

IV. DISCUSSION

Our review of cyber-physical systems for smart homes offers us an extremely interesting and exciting vision of this convergence of technologies to improve the quality of life of the inhabitants of this environment. In response to the initial question posed to us about the definition of CPS, we have found that the list of definitions is varied and highlights the richness and complexity of this field. In their purest definition, CPS are a fusion of computing and physical components, such as sensors and actuators, to interact richly and responsively with the physical world. This fusion of technologies contributes to the automation and control of smart homes, but it also transforms the way we relate to everyday life. There are many definitions of CPS, depending on the perspective and how they are used. From a more technical perspective, CPS could be defined as all the technology needed to combine computer systems and physical processes to improve interaction between these peers or increase their efficiency. In the case of the smart home, CPS is key to understanding the automation, control, and intelligent use of a multitude of devices and systems, from lighting and temperature or climate control to security and health monitoring, where CPS offers residents undeniable benefits in terms of comfort and efficiency in the home. In addressing the technologies involved in CPS, we have shown the decisive role played by IoT, AI, machine learning, and digital twins.

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While IoT remains the predominant technology, we observed a growing interest in digital twins as an innovative tool to simulate, analyze, and optimize the operation of home devices and processes before their physical implementation. To strengthen the perspectives, Fig. 19 illustrates some emerging technological solutions for smart homes where the integration of cyber-physical elements is possible. The IoT is expected to remain the main driver for the interconnected ecosystem, facilitating the integration of intelligent devices, networked communications, and services.

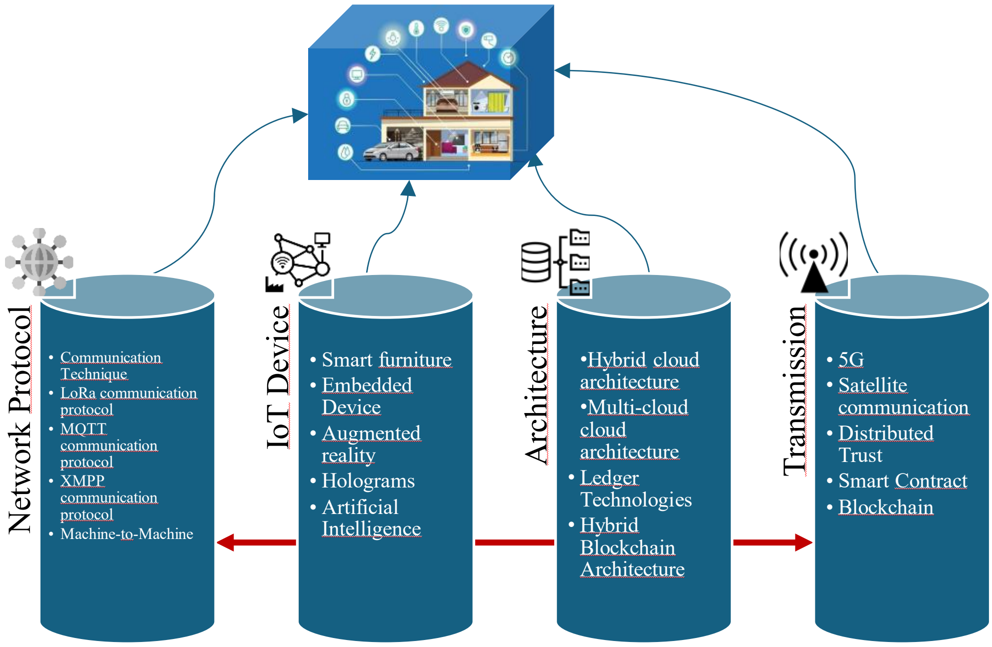

Figure 19. Emerging technologies for smart homes

Today's IoT devices are rarely able to make efficient use of the data from users' activities in a real-world environment because of their lack of sensors and actuators. The amount of time it takes for an individual to interact with a terminal device can be reduced by utilizing AI to provide speech and gesture input which ultimately increases the efficiency of the terminal device. In addition, the ability to have rapid access to relevant data about an individual's activity through 5G technology will allow people to continue to enjoy the highest possible level of independence when remotely monitored. As a result of ongoing advancements in 5G technology, IoT and AI, there will likely be new areas of growth in this area as well in the future.

On the other hand, the diversity of systems developed for smart home (home health systems, etc.) can range from multifunctional to security systems. These systems will improve the quality of life within the home through increased efficiency, comfort and well-being for the residents. A growing number of these systems include household pets in their design. Therefore, it represents an inclusive approach to designing a whole home environment that meets all the needs of the family. There are many challenges to overcome with implementation of these systems. They include privacy, security, interoperability, and reliability on artificial intelligence as they relate to safe and widespread usage of Cyber-Physical Systems in the Smart Home. Reflection on our research on CPS in the Smart Home has provided us a starting point for thinking about the transformation potential of technology while simultaneously addressing the ethical and practical challenges that have arisen to create a more connected and digital future.

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V. CONCLUSIONS

Based on the analysis of cyber-physical systems in relation to smart homes, we can conclude that CPS are defined by the way they are able to interconnect computing, communication, and control in the context of a real environment, driving various sectors and achieving efficiency, spontaneity, and comfort. On the other hand, the concept of the smart home has included a series of existing technological systems that allow them to both plan and execute tasks, as well as increase security, manage energy, and improve the comfort of occupants. However, the arrival of other technologies such as IoT or AI (artificial intelligence), machine learning, and digital twins allows for a greater role in the automation of smart home control, providing clear benefits in terms of efficiency, comfort, and security. To take advantage of these advances, it is necessary to address various associated issues related to privacy, security, interoperability, and dependence on AI.

Another identified weakness is the lack of explainability in most smart home systems, leading to user distrust and disengagement. In the future, the research direction will likely expand to address new advances and challenges in the field of cyber-physical systems in smart homes. This could include research on even more advanced emerging technologies, such as quantum computing applied to home CPS, the integration of wearable devices, augmented reality in the home environment, and generative AI. As a second instance, in the design and development of standards and regulatory frameworks to ensure safe and ethical implementation of cyber-physical systems in the smart home, as well as in the assessment of their long-term impact on the quality of life of individuals and society.

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The authors contributed equally to the manuscript review process.

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Informed consent statement:

Not applicable.

Data availability statement:

The data used in this paper can be requested from the corresponding.

Conflicts of interest:

The authors declare that they have no conflicts of interest to report regarding the present study.

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