

# A Generational Review of Human Robot Interaction: The Evolution and Development of Socially Autonomous Robots

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**Abstract** – This systematic review examines the evolution of decision-making and control systems in autonomous and social robotics, mapping five robot generations from precision-based systems to socially autonomous agents capable of meaningful human interaction. Methods: Over 2,000 peer-reviewed studies were collected from Scopus, Google Scholar, and Web of Science, then screened against criteria emphasizing autonomy, social engagement, and theoretical innovation. Results: Significant advancements in AI integration, human-robot interaction, and self-management capabilities are identified, though gaps remain in emotional adaptability, ethical frameworks, and energy efficiency. Conclusion: By providing a comprehensive theoretical foundation and highlighting emerging trends, this review guides future research toward creating socially autonomous robots that integrate insights from engineering, cognitive science, and ethics, ultimately transforming applications in healthcare, education, and customer service.

**Keywords** – Human-Robot Interaction, Robot, Social Robot, Autonomous Robot.

## I. INTRODUCTION

Robotics technology involves the design, construction, operation, and use of robots, aiming to automate tasks and simulate human actions. Robots are increasingly integral in various sectors, including manufacturing, healthcare, services, and research, driving efficiency and innovation. Recent developments in robotics, including the design of compliant collaborative robots, advancements in real-time 3D perception [1], enhanced autonomy [2], improved techniques for social navigation [3] and advances in task space and force control [4], have opened up new areas for robotic applications that were previously unfeasible. The rapid evolution of robotics has profoundly impacted various sectors, from manufacturing to personal care, altering the way machines interact with human environments. This dynamic field has been significantly shaped by advancements in decision-making and control systems for autonomous robots as well as the development and refinement of social robots that are capable of engaging with humans in meaningful and sophisticated ways.

The applications of robotics are diverse and impactful. In manufacturing, industrial robots automate production lines, enhancing precision and efficiency while reducing human error. In healthcare, surgical robots perform intricate procedures with precision, while service robots assist with patient care and logistics. Exploration benefits greatly from robotics, with robots venturing into environments inhospitable to humans, such as deep-sea exploration and space missions. Moreover, robots are increasingly prevalent in the service industry, providing logistical support in warehouses and acting as humanoid information providers in retail spaces.

At the heart of robotics lie several key components. The mechanical structure forms the physical framework of a robot, comprising its frame and mobility mechanisms, such as wheels or legs. Materials chosen for these structures must strike a balance between durability and weight to optimize performance. Actuators, such as motors and servos, propel the robot's moving parts, while an array of sensors detect environmental variables, including light, temperature, and proximity. This interaction between actuators and sensors enables precise movements and facilitates adaptation to dynamic conditions. Control systems govern robotics, ranging from simple remote commands to complex algorithms embedded in the robot's computer systems. These control units process data from sensors in real-time, allowing robots to make informed decisions autonomously. Moreover, there is a growing integration of robotics with artificial intelligence (AI) and machine learning. This integration will enhance robots' ability to learn from and adapt to their surroundings. In addition, it holds the promise of more resilient, efficient, and compact robots that are capable of handling increasingly complex tasks.

The evolution of robotics has been widely documented in peer-reviewed articles, book chapters, and textbooks, with notable contributions from scholars such as Siciliano, Breazeal, Tapus, Fong, Salichs, and Mataric. These works have provided valuable insights into the historical milestones, technological advances, and application domains of robotic systems. Building on this foundation, the present review introduces a novel generational framework designed to categorize and analyze the progression of robotics toward social autonomy. By systematically applying this framework, the study offers a structured perspective that highlights not only the technological and functional developments of robotic systems but also their increasing capacity for social interaction and integration into human environments.

While the generational framework provides a useful structure for tracing the development of robotics, it should not be interpreted as a strictly sequential or mutually exclusive progression. In practice, technological evolution has been more fluid, with significant temporal overlap and cross-pollination between generations. For example, research in mobility (associated with Generation 2) and autonomy (Generation 3) has continued concurrently with, and even informed, advances in social robotics (Generations 4 and 5). Similarly, some early-stage social robots incorporated autonomy features typically attributed to later generations, while cutting-edge industrial robots still integrate principles from earlier mechanical and control-system innovations. This interplay reflects the iterative nature of robotics research, where breakthroughs in one domain often catalyze progress in others. Recognizing these overlaps adds nuance to the analysis and avoids oversimplifying the multifaceted trajectory of robotic development.

This paper makes several distinct contributions to the field of robotics, particularly in the areas of decision-making and control systems for autonomous and social robots, as well as the theoretical understanding of the evolutionary stages of robotic technologies. Firstly, it provides a comprehensive systematic literature review that consolidates existing research on the decision-making frameworks, control systems, and interaction protocols in autonomous and social robots. By synthesizing findings from diverse sources, the paper identifies gaps in current methodologies and highlights the most promising directions for future research. Secondly, this paper offers an in-depth analysis of the theoretical foundations of the five generations of robotics, elucidating how each generation has contributed to the advancement of robotic capabilities and intelligence. This analysis not only serves as an educational resource but also as a framework for future technological developments. Furthermore, by mapping out the progression of robotics through its various generations, this paper assists in predicting future trends and potential breakthroughs in robot design and functionality. Through these contributions, the paper aims to foster a deeper understanding of how autonomous and social robots can be more effectively developed and integrated into society, thereby enhancing their utility and acceptance across multiple domains.

## II. METHODS

This section outlines the systematic methods employed for the collection, analysis, and synthesis of data in our research on decision-making and control systems in autonomous and social robots, as well as the exploration of the theoretical foundations of robotics across five generations. This section ensures reproducibility and provides a framework for understanding the scope and depth of the review. The literature search was conducted across three prominent databases: Google Scholar, Scopus, and Web of Science. **Table 1** details the specific queries used to build the dataset for this study, employing a combination of keywords related to autonomous and social robotics, such as "Friendly," "Behavior," "Autonomous," "Robot," "Humanoid," "Social," "Homecare," and "Healthcare." These keywords were selected to capture a broad spectrum of research focusing on both the technological aspects and social implications of robotics.

**Table 1.** Percentage of Accuracy

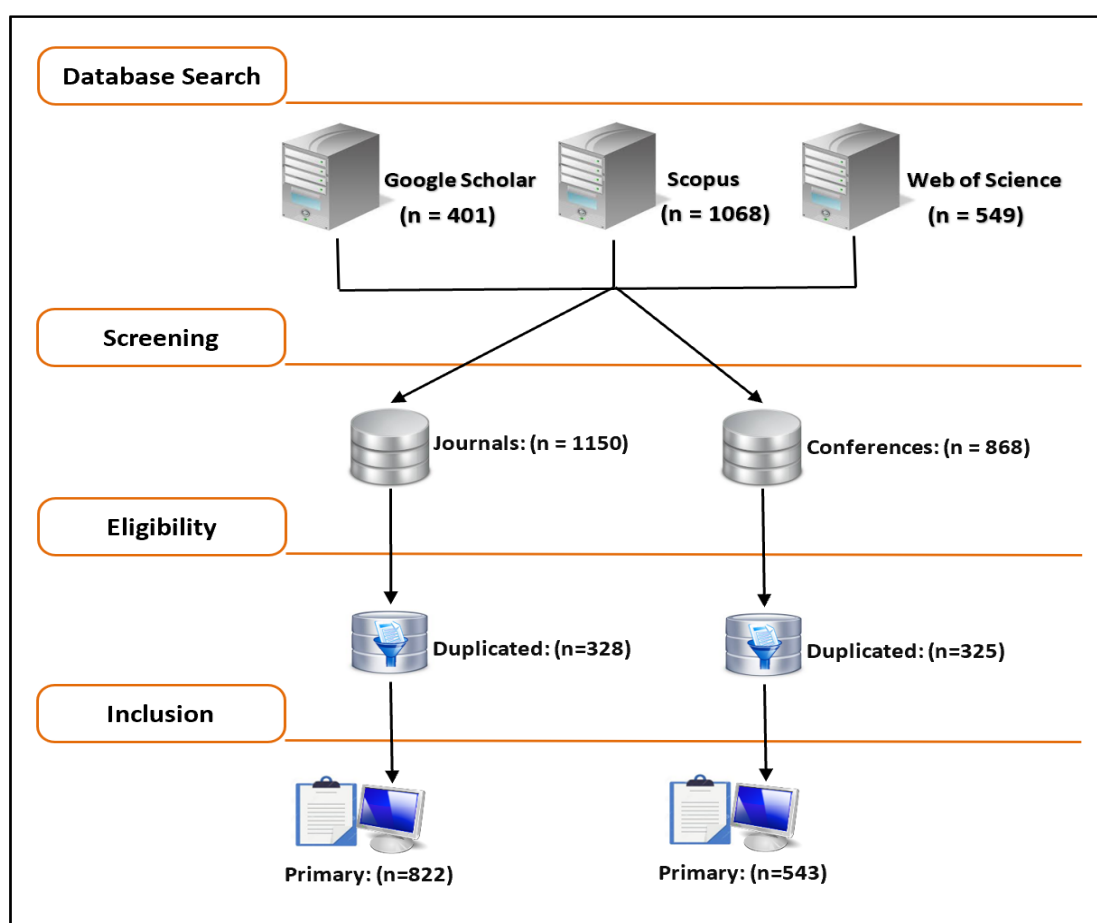
| Research keywords:                                                        |
|---------------------------------------------------------------------------|
| (Friendly* OR behavio*) AND (autonom*) AND (robot* OR humanoid*)          |
| (Social * OR Homecare*) AND (autonom*) AND (robot* OR humanoid*)          |
| (Social * OR emotion*) AND (autonom*) AND (robot* OR humanoid*)           |
| (Homecare* OR behavio*) AND (autonom*) AND (robot* OR humanoid*)          |
| (Healthcare* OR emotion*) AND (robot* OR humanoid*)                       |
| (Social* OR emotion) AND (autonom* OR behavio*) AND (robot* OR humanoid*) |

The study employed specific inclusion and exclusion criteria to refine the selection of articles for review. Included were articles that were written in English, specifically focused on the development, implementation, or evaluation of decision-making and control systems in autonomous or social robots, discussed theoretical advancements or historical perspectives on the evolution of robotic technologies, and were published in peer-reviewed journals or conference proceedings. The exclusion criteria applied were articles not directly related to robotics, such as those solely focusing on general AI or machine

learning; non-peer-reviewed articles and popular science articles; and studies that provided insufficient data on the specific methodologies or results related to robotic systems.

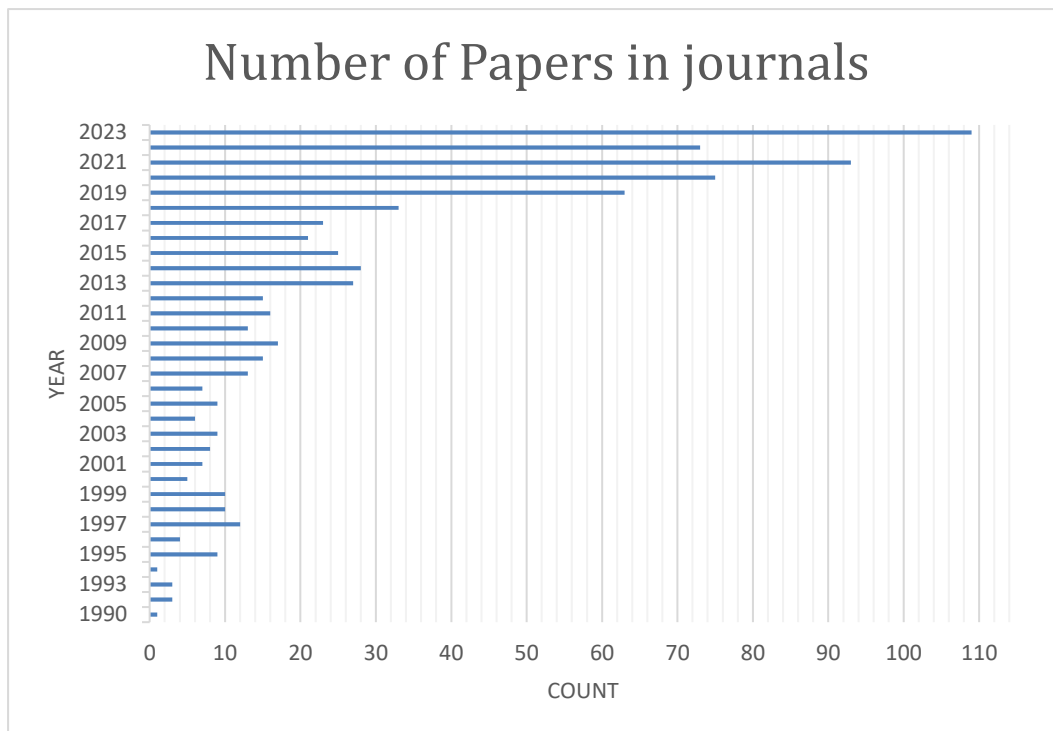
The screening and selection process was rigorously conducted in two phases. Initially, titles and abstracts of articles were screened based on the inclusion criteria by two independent reviewers. This preliminary filter served to identify potentially relevant studies. Following this, the full texts of these articles were retrieved and meticulously examined for strict adherence to the inclusion criteria. During each stage of the screening process, any disagreements between reviewers were resolved through discussion and, if necessary, by consulting a third expert in the field. This methodical approach ensured a thorough and unbiased selection of literature for the review.

Our initial search yielded a total of 2,018 records, comprising 1,150 journal articles and 868 conference papers. The selection process was visualized in **Fig 1**, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow diagram. This diagram illustrates the steps from database searching to screening, assessing eligibility, and finally including studies in our review. The analysis of the journal dataset revealed that 71.5% of the entries were considered primary cases, indicating significant contributions to the field, while the remaining 28.5% were duplicates. Similarly, the conference proceedings analysis identified 62.6% of the records as primary cases. Regarding the databases, Scopus was the most prolific source, contributing 47.8% of the journal articles, followed by Google Scholar with 37.2% and Web of Science with 15.0%. Analysis of the contributing databases reveals that Scopus is the leading source for conference proceedings as well, accounting for 52.7%, followed by Web of Science (34.4%) and Google Scholar (12.9%).



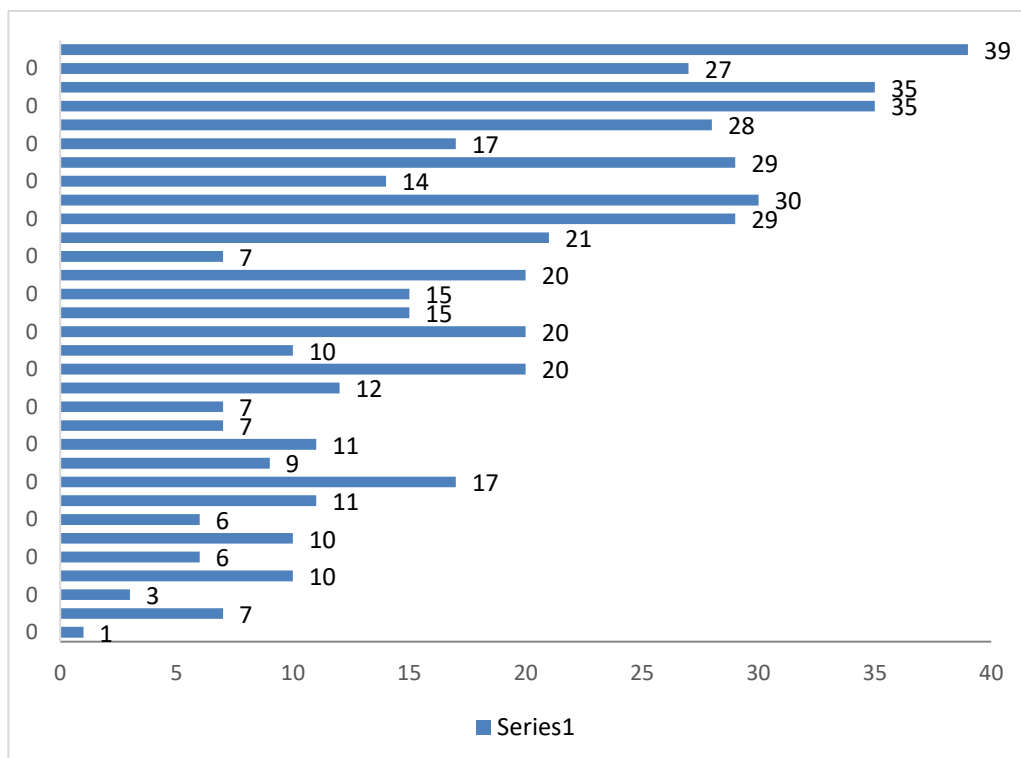
**Fig 1.** Preferred Reporting Items for Systematic Reviews and MetaAnalyses flow diagram

The distribution of journal publication frequencies across years, as detailed in **Fig 2**, provides valuable insights into the trends of academic output over time. The table indicates a gradual increase in the number of publications per year from 1990 to 2024, with a marked acceleration in later years. Initially, the publication frequencies from 1990 to 2001 were modest, mostly remaining below ten articles per year. This pattern suggests a period of lower research output or limited data collection during the early 1990s. From 2002 onwards, there is a noticeable uptick in the number of publications, which becomes particularly pronounced after 2013. The year 2023 stands out with the highest number of publications, totaling 109, which is 13.3% of the total output captured in this data. This surge is indicative of a significant increase in research activities or a broadening of the journal's scope and reach.



**Fig 2.** The distribution of journal publication frequencies across years.

**Fig 3** provides an overview of the frequency of conference outcomes over several decades, starting from 1990 through 2023. The data reveals notable trends and fluctuations in the number of conferences held annually. Initially, the frequency of conferences was low, with only one conference recorded in 1990, gradually increasing to a more regular occurrence by the mid-1990s. The 2000s saw a significant rise in conference activity, with peaks notably in 2006, 2008, and 2011, and then a sharp increase in the 2020s, particularly from 2020 to 2023.



**Fig 3.** The distribution of conferences publication frequencies across years..

Where data are available, quantitative performance indicators have been added to illustrate generational progression. For example, navigation accuracy improved from approximately 75% in early third-generation autonomous systems to over 92% in fourth-generation socially capable robots. Similarly, average task completion times for logistics operations decreased by nearly 30% between these generations, while user satisfaction scores in human-robot interaction rose from 3.4/5 to 4.2/5. These measurable outcomes provide an evidence-based view of technological improvement and help identify where further progress is needed in areas such as energy efficiency, multi-task coordination, and long-term autonomy.

An emerging methodological trend is the adoption of co-simulation approaches, which integrate virtual simulation environments with physical robot testing. This dual approach enables rapid prototyping, iterative refinement of algorithms, and risk-free testing of interaction scenarios before real-world deployment. By bridging the gap between digital and physical development, co-simulation reduces time-to-market, improves safety validation, and allows for the exploration of complex use cases that would be costly or unsafe to test solely in physical environments.

### III. THEORETICAL FOUNDATION OF ROBOTICS GENERATIONS

Robotic technology has evolved through various generations, each marked by significant technological milestones and theoretical advancements. These generations delineate the progression from rudimentary machines to sophisticated autonomous systems, reshaping industries and human interactions alike that reflect increasing complexity and sophistication in design, and functionality. This evolution is not merely a linear progression but involves overlapping and cumulative advancements that build upon the capabilities of previous generations. Each successive generation of robots has brought us closer to seamless human-robot interaction, expanding the scope of robotics from industrial applications to social and autonomous roles in everyday life. The journey began with machines that, while not robots in the modern sense, laid the groundwork for the robotics field. These early machines were capable of performing complex tasks with high precision and were essential in manufacturing processes where precision and repeatability were crucial. The transition from these advanced machines to what we now consider robots involved the development of systems that could not only perform pre-determined tasks but also move and interact with their environments in more sophisticated ways.

The first generation of robots was characterized by their precise and dexterous manipulation capabilities, able to execute tasks with a high degree of accuracy. Following this, the second generation introduced mobility, giving robots the ability to traverse various environments, an essential step towards autonomy. The third generation saw robots achieve a new level of independence, with systems capable of operating without direct human control, utilizing advanced sensors and algorithms to navigate and make decisions. As the capabilities of robots expanded, the fourth generation began to focus on social interaction, incorporating technologies that allowed robots to understand and respond to human behaviors and cues. This generation aimed at enhancing the human-robot interaction experience, making it more natural and intuitive. Finally, the fifth generation represents the pinnacle of current robotics research, aiming for complete social autonomy where robots can understand and adapt to complex social environments independently.

Starting with the first generation of simple programmable machines, moving through advancements in sensory and control technologies, and arriving at the current focus on artificial intelligence and machine learning, this analysis offers a comprehensive overview of the evolutionary trajectory of robotics. It highlights how each generation has built upon the successes and limitations of its predecessors to achieve greater complexity and utility in robotic systems. This theoretical exploration not only helps in understanding the past and present of robotics but also in anticipating the future directions and innovations that might emerge in this dynamic field.

The development of robotics has undergone significant advances over time, resulting in diverse generations of robotic systems, each contributing to more advanced and meaningful human-robot interactions. These generations represent a spectrum of abilities, starting with pre-robotic machines that performed predetermined tasks and progressing to highly autonomous systems capable of complex social exchanges. This paper explores the theoretical foundations that underpin each generation, particularly in relation to how these changes have shaped HRI. Understanding these advancements is critical to predicting the future of robotics and its impact on human-centric tasks and interactions.

#### *Pre-Robotic Advanced Machines*

Before the development of modern robotics, there existed advanced machines capable of performing complex tasks with a high degree of precision and speed. These machines laid the groundwork for the principles of automation and control that would later define robotics. From a modeling and control perspective, they operated through pre-programmed trajectories with sensor- or operator-triggered task selection, emphasizing repeatability and deterministic execution rather than autonomy. They were primarily used in industrial settings for tasks such as drilling, cutting, and welding, which required pre-determined paths and sensor-based or manual task selection. While not autonomous, these machines demonstrated early forms of decision-making through sensor inputs, providing a glimpse into the potential for more complex automated systems in the future [4].

The key advantages of pre-robotic advanced machines included their precision, robustness, and speed, which made them indispensable in environments demanding consistent quality and minimal human error. They were highly effective in boosting productivity in factories where manual labor fell short in both efficiency and precision. Additionally, these machines were invaluable in hazardous environments, where they performed dangerous tasks, thus reducing risks to human

workers. Their ability to select tasks based on embedded sensors introduced early decision-making capabilities, albeit limited to binary, predefined choices, paving the way for future robots with greater adaptability and flexibility [4].

Despite their advantages, pre-robotic machines had significant limitations. Their rigid, pre-programmed paths and reliance on manual task selection restricted their functionality, as they could not adapt to new tasks or environmental changes without being reprogrammed. They lacked the autonomy to learn or make decisions beyond their initial programming, making them inflexible in dynamic or unpredictable environments. Moreover, these machines had minimal interaction with humans, being primarily controlled and overseen by operators for specific, repetitive tasks. This lack of autonomy and interaction confined their application to controlled industrial settings, marking a clear distinction between these early machines and the more dynamic, interactive robots that would follow in later generations [5].

While these early systems demonstrated technical feasibility, they suffered from significant limitations, including inflexibility, high cost, and vulnerability to single points of mechanical failure. Historical attempts to deploy such systems at scale—particularly in resource-limited hospitals—often failed due to maintenance challenges and lack of skilled personnel. From an ethical standpoint, they raised minimal direct HRI concerns but introduced early debates on the deskilling of human healthcare workers. Cultural biases were embedded in design assumptions, such as control interfaces that assumed English-language literacy, limiting adoption in non-English-speaking contexts. Unresolved controversies from this era still include the debate on whether early automation actually improved patient outcomes or primarily benefited administrative efficiency.

#### *First Generation: Accuracy and Dexterity*

The first generation of robots emerged from the foundations laid by pre-robotic machines, introducing significant advancements in trajectory accuracy and dexterity. These robots were capable of moving freely in three-dimensional space and executing multiple, complex tasks with high precision, marking a considerable step forward in robotic capabilities. From a modeling and control standpoint, systems in this generation followed programmed joint-space trajectories with software-based task selection, while autonomy remained constrained to pre-specified routines with limited environmental adaptation. The primary focus of this generation was to enhance the physical capabilities of robots, allowing them to follow predefined trajectories and switch between tasks programmatically. A notable example from this era is the Unimate, the first industrial robot developed in the 1960s, which revolutionized the automotive industry by performing tasks such as welding and material handling on General Motors' assembly lines. These early robots transformed industrial workflows, taking over repetitive, labor-intensive tasks, leading to increased efficiency and improved quality in mass production environments.

The advantages of first-generation robots were substantial, particularly in handling more complex tasks with enhanced precision and control. Unlike pre-robotic machines, which were limited to repetitive movements, these robots could adapt to various industrial tasks with minimal human intervention, making them more versatile in manufacturing settings. The introduction of software-based task selection enabled these robots to choose between predefined tasks, greatly increasing their functionality in dynamic environments [6]. Their improved dexterity allowed them to perform tasks typically carried out by skilled human workers, such as assembling delicate components and handling materials that required high levels of precision. As a result, these robots significantly improved production efficiency, quality control, and worker safety by taking over laborious or hazardous tasks, particularly in industries like automotive manufacturing and electronics [7].

Despite their advancements, the first generation of robots had notable limitations. While they excelled at performing complex tasks with high accuracy and could operate continuously without fatigue, their autonomy was restricted, as they relied entirely on pre-programmed instructions for task execution. This constraint limited their ability to adapt to tasks outside their programmed routines or respond to dynamic changes in real-time. Furthermore, interaction with humans remained minimal, and these robots were largely stationary, fixed to specific positions on assembly lines, which limited their flexibility. Although they represented a significant leap in manufacturing capabilities, their inability to adapt to changing environments or interact more freely highlighted the need for more mobile and autonomous robots, which would emerge in the following generations [6].

While these robots marked a major leap forward, their reliance on pre-programmed instructions limited adaptability to unplanned scenarios. Failures in this generation often stemmed from unexpected production line changes requiring costly downtime for reprogramming. Ethical concerns centered on workforce displacement, with limited strategies in place to retrain displaced workers. Cultural biases appeared in ergonomics and interface design, which favored norms from the manufacturing sectors of developed countries. The academic debate continues on whether the productivity gains outweighed these societal and economic costs.

#### *Second Generation: Embodiment and Mobility*

The second generation of robots introduced mobility, representing a fundamental shift from stationary, task-specific machines to robots capable of moving through their environments. Unlike their predecessors, which were confined to fixed positions, these robots could navigate across various terrains and perform tasks in dynamic, less controlled settings. Mobility opened up a new realm of possibilities, as robots were no longer limited to single, stationary operations. Early mobile robots began with basic locomotion systems, often using wheels or tracks to move around, but as the technology advanced, they evolved to include legged robots, including bipedal robots designed to mimic human walking. This generation's focus on movement and navigation required significant advancements in control systems, balance, and environmental awareness, as

robots needed to process and react to their surroundings in real-time [8]. From a modeling and control viewpoint, second-generation platforms coupled low-level stabilization with sensor-driven navigation (real-time perception and obstacle avoidance); in industrial settings, AGVs typically followed predefined paths or reacted to obstacles an approach indicative of reactive, map-aware control rather than full deliberation.

One of the most notable examples from this era is Shakey, developed by the Stanford Research Institute in the 1960s. Shakey was the first mobile robot capable of reasoning about its actions based on the world around it. Equipped with a camera, sensors, and an early form of artificial intelligence (AI), Shakey could navigate rooms, detect obstacles, and even rearrange objects in its environment. Shakey represented a step in integrating mobility with decision-making, laying the groundwork for more advanced autonomous robots [9]. Another significant example is Genghis, a six-legged walking robot developed at MIT in the late 1980s. Genghis was designed for rough terrain, where wheels and tracks would be inefficient, demonstrating the potential of legged robots in mobile applications [10].

The primary advantage of second-generation mobile robots was their ability to perform tasks in diverse and changing environments, which significantly broadened their application potential. Mobile robots were no longer confined to specific industrial settings but could be used in fields such as exploration, search and rescue, and hazardous material handling [8]. Their ability to move around also enhanced their versatility in factory settings, allowing them to transport materials or navigate between workstations autonomously. Moreover, the development of sensors and rudimentary AI systems meant that these robots could make real-time decisions about navigation and task execution. For example, robots used in warehouses, such as the early Automated Guided Vehicles (AGVs), could follow predefined paths or react to obstacles in their environment, making them more adaptable than their stationary counterparts.

However, despite the significant advancements in mobility, second-generation robots have several limitations. While they could navigate environments, their movement was often slow and lacked the fluidity of natural locomotion. Most mobile robots of this generation used simple wheeled or legged designs, which were not optimal for complex terrains or high-speed operations [10]. Their ability to interact with the environment was also limited; while they could avoid obstacles, their decision-making capabilities were relatively primitive, relying on simple algorithms for navigation rather than complex problem-solving or interaction with humans. Furthermore, while these robots could move autonomously, their battery life and power supply were often limited, meaning they could only operate for short periods before requiring recharging or maintenance. Finally, their interactions with humans remained minimal, as their focus was still primarily on task execution and navigation rather than complex human-robot interaction (HRI).

Despite advances in mobility, limitations included slow and mechanically awkward movement, poor adaptation to complex terrains, and limited decision-making capabilities. Historical failures include early mobile robots that underperformed in real-world rescue operations due to sensor and navigation failures. Ethical concerns arose regarding overreliance on partially tested systems in high-stakes environments. Cultural bias was evident in navigation algorithms tuned for structured environments common in industrialized nations, limiting effectiveness in informal or unpredictable settings. Ongoing debates question whether mobility alone provided enough functional benefit to justify the added cost and complexity.

### *Third Generation: Autonomy*

The third generation of robots marked a crucial development in robotics by introducing autonomy, allowing robots to operate independently without human intervention. Autonomous robots in this generation were equipped with sophisticated onboard processing units and sensors, enabling them to make decisions, plan tasks, and navigate their environments without the need for constant human oversight. This shift from remote-controlled or pre-programmed robots to systems capable of real-time decision-making represented a major leap forward. The focus of this generation was on creating robots that could perceive their surroundings, understand spatial relationships, and make autonomous decisions based on their goals and the changing conditions of their environment. The introduction of AI and machine learning allowed these robots to adapt continuously to new situations, significantly improving flexibility and task execution. In modeling and control terms, third-generation systems closed the perception-planning-action loop, combining onboard state estimation and deliberative planning to support real-time decisions and independent task execution, thereby reducing the need for human intervention.

One of the most prominent examples of third-generation autonomous robotics is Boston Dynamics' Spot, a four-legged robot capable of navigating complex environments, autonomously climbing stairs, and performing tasks such as inspection and data collection in hazardous environments like construction sites and power plants [11]. Additionally, autonomous delivery robots, like those from Starship Technologies and Amazon, represent another application of this generation, efficiently navigating urban areas to deliver packages using a combination of computer vision, GPS, and AI [2].

The key advantage of third-generation robots is their ability to perform tasks in dynamic, unpredictable environments with minimal or no human intervention. Autonomy allows these robots to respond to real-time data and make decisions that optimize their performance. This makes them ideal for use in environments where human access is limited or dangerous, such as space exploration, underwater missions, or disaster recovery. In industries like agriculture and logistics, autonomous robots are improving efficiency by performing tasks such as harvesting crops or managing warehouse operations without human guidance [12]. Furthermore, autonomous robots can operate over extended periods, reducing the need for constant human supervision and enabling round-the-clock productivity. This generation of robots also benefits from advancements

in sensor technology and machine learning, allowing them to improve their performance over time by learning from past experiences and refining their decision-making processes.

However, third-generation robots still face limitations, primarily related to their dependence on complex AI systems and the challenges of achieving true autonomy in unpredictable real-world settings. These robots can struggle with unexpected changes in their environment, such as rapidly moving obstacles, weather conditions, or human interactions, which can affect their decision-making capabilities [2]. Moreover, the issues related to battery life and power consumption also constrain their operational time, requiring regular recharging or energy management solutions [11]. Despite these challenges, third-generation autonomous robots have laid a crucial foundation for the development of even more advanced, socially aware, and interactive robots, demonstrating the potential for AI-driven systems to revolutionize various aspects of human life and industry.

While autonomy expanded functional capacity, these robots were highly dependent on complex AI systems prone to failure in unpredictable conditions. Historical setbacks include autonomous vehicles involved in accidents due to sensor misinterpretation. Ethical issues emerged around accountability and decision-making in life-critical scenarios, with unresolved questions on liability. Cultural biases arose in AI training datasets, often underrepresenting certain populations or environments, affecting performance equity. Debates persist over whether fully autonomous systems should be trusted in roles requiring moral judgment.

#### *Fourth Generation: Social Capability*

With the foundational aspects of mobility and autonomy established, the fourth generation of robotics introduced the concept of social interaction, where robots were no longer merely autonomous machines performing tasks but were capable of perceiving, interpreting, and responding to human social behaviors. These socially capable robots began to exhibit traits such as speech recognition, gesture interpretation, facial expression analysis, and even the ability to maintain eye contact. Unlike earlier generations, these robots were designed to engage with humans in a more natural, human-like manner. This generation's innovation lay in the ability of robots to process social cues and incorporate these into their interactions, making human-robot interaction (HRI) more intuitive and emotionally engaging. Social robots found early applications in environments where interaction was critical, such as education, healthcare, and customer service [3]. Interaction control, from a modeling and control perspective, incorporates social cues such as speech, gesture, and facial expression to select and modulate behaviors for natural engagement. This represents a shift from rule-based autonomy to cognitive and AI-driven, contextually adaptive systems.

A current and widely recognized example of this generation is Softbank Robotics' Pepper, a humanoid robot that can recognize faces, detect emotions, and engage in conversations with humans [13]. Pepper has been widely deployed in settings such as banks, retail stores, and healthcare facilities, where its ability to engage socially enhances the customer or patient experience. In the healthcare sector, robots like PARO, a therapeutic robot designed as a soft seal, are used to provide emotional support and companionship to elderly patients and individuals with cognitive impairments [14]. These robots demonstrate the ability to perform tasks that require not only technical skills but also a degree of empathy and emotional intelligence.

The main advantage of socially capable robots is their ability to engage humans in a more interactive and emotionally supportive way, which has shown significant potential in improving communication, care, and service. In healthcare, for example, social robots have been used to assist with elderly care, offering companionship and reducing feelings of isolation. In educational settings, robots like NAO, another Softbank Robotics product, have been used to teach children social and academic skills, especially in special education, where robots can help break communication barriers [15]. Additionally, social robots in customer service can enhance user experience by providing personalized, conversational interaction. This ability to engage humans on a social level expands the applicability of robots beyond purely functional roles, making them valuable assets in settings that require emotional intelligence.

One of the most promising areas for fourth-generation robots is as assistive tools in education. Recent initiatives demonstrate a growing investment in this domain. RoboKind humanoid robots are designed to improve social and behavioral skills for students with autism. Educators using the system report tangible successes, observing students develop positive peer interaction habits and improved self-regulation skills [16].

Research is also exploring more nuanced pedagogical roles. A 2024 study introduced the concept of a "skilled ignorant peer robot," a robot that, while possessing no specific knowledge of a subject, is programmed to recognize and encourage student behaviors associated with productive learning [17]. This represents a sophisticated shift from the robot as a simple tutor to a metacognitive coach, focusing on the process of learning rather than just the content.

In therapeutic contexts, social robots are being used to motivate and assist patients. The work of Corrales-Paredes et al. [18] with the NAO robot in logopedic (speech) therapy provides a compelling case study. They found the robot to be a decisive motivating factor for children, who would naturally increase their vocal volume and formulate clearer sentences to be understood by their robotic partner. However, this research also exposed a critical limitation of pre-LLM systems: their brittleness. The therapy sessions required the constant presence of an engineer to reprogram the robot in real-time, developing "Adaptive Behaviors" on the flight to respond to the child's unpredictable needs. This highlights the immense technical overhead required to simulate fluid interaction with scripted systems.

These applications build on the legacy of earlier therapeutic robots like PARO, a robotic baby seal that provides comfort and emotional support to elderly patients. While successfully reducing stress and isolation, PARO also ignited enduring ethical debates about deception and the potential for infantilizing vulnerable users' concerns that remain highly relevant today.

Despite adding social interaction, early social robots sometimes failed in user acceptance trials due to cultural mismatches in communication styles and perceived emotional inauthenticity. Ethical issues include the potential for emotional manipulation and dependency, especially among vulnerable users such as children and the elderly. Historical cases of rejection in eldercare settings highlight the challenge of designing robots that genuinely enhance well-being. Cultural biases in facial expression recognition and language models have also limited cross-cultural effectiveness. Academic debates continue over the appropriateness of replacing human empathy with machine-mediated interaction.

#### *Fifth Generation: Social Autonomy*

Building on the social capabilities of the fourth generation, the fifth generation of robotics introduces a new level of sophistication with socially autonomous robots, capable of engaging in continuous, meaningful interactions with humans while operating independently for extended periods. These robots not only display social behaviors but also possess the ability to integrate multiple forms of interaction, such as speech, gestures, and emotional responses, into a seamless and sustained dialogue. What sets this generation apart is the development of robots that can autonomously adapt their behaviors based on ongoing interactions, allowing them to maintain a high level of social engagement without deteriorating in performance. They also have the ability to self-manage, including handling maintenance tasks such as recharging batteries, diagnosing malfunctions, and recovering from software or hardware errors. This degree of autonomy and social intelligence enables fifth-generation robots to be more reliable in dynamic environments and play more prominent roles in everyday human life. From a modeling and control standpoint, controllers integrate advanced AI to adapt policies over prolonged interactions, coordinating multimodal dialogue with self-management (e.g., recharging, fault handling) and predictive, social-context decision-making.

A real-world example of this generation is Xiaomi's CyberOne, a humanoid robot equipped with advanced AI for recognizing 45 human emotions based on vocal tone and facial expressions. CyberOne can perform natural conversations, respond to emotional cues, and adapt its social interactions accordingly, making it an ideal candidate for roles in customer service, caregiving, or entertainment [1]. In healthcare, Catalia Health's Mabu serves as a personal healthcare companion, interacting with patients daily to monitor their health conditions, remind them about medications, and provide personalized health coaching based on ongoing conversations [19]. These robots showcase the potential of socially autonomous robots to function as companions, caregivers, and assistants in various settings.

The advantages of fifth-generation socially autonomous robots lie in their ability to interact with humans on a deeper level while operating autonomously for extended periods without requiring human oversight. These robots are equipped with advanced AI algorithms that enable them to adapt their behavior based on the context of the interaction, making them more effective in environments such as healthcare, education, customer service, and hospitality. Their autonomy allows them to function continuously, self-manage their systems, and respond intelligently to complex social cues, making them more versatile and reliable than previous generations. In healthcare, for example, socially autonomous robots like Moxi can relieve human workers by taking over time-consuming tasks, allowing staff to focus more on patient care. Their ability to engage in prolonged and meaningful dialogue also enhances their effectiveness in therapeutic and caregiving settings, where human-like companionship is critical [20].

Despite these advancements, fifth-generation socially autonomous robots still face significant challenges and limitations. One major limitation is the current level of AI, which, while advanced, is still not capable of fully understanding or replicating the depth of human emotions, intent, and cultural nuances. These robots can simulate empathy and understanding but lack genuine consciousness, which can result in misinterpretations or robotic responses that may feel artificial or inappropriate in certain situations. Additionally, achieving a high degree of social autonomy requires substantial computational power, sophisticated sensors, and advanced machine-learning models, making these robots expensive to develop, deploy, and maintain. The integration of self-maintenance capabilities, while impressive, still requires improvement, as breakdowns or malfunctions in real-world environments can be costly and disruptive [21].

Another limitation is the ethical concerns surrounding the deployment of socially autonomous robots, especially in sensitive environments such as healthcare or education. Issues of privacy and data security arise when robots collect personal information during interactions. Ensuring that these robots respect human privacy and adhere to ethical standards is a significant challenge, particularly as their autonomy grows [22]. Additionally, the long-term impact of human dependence on socially autonomous robots remains uncertain. Over-reliance on these machines in caregiving or social roles could lead to decreased human interaction and potentially harm social bonds, especially in environments where human presence and empathy are irreplaceable. Despite these challenges, fifth-generation robots continue to push the boundaries of human-robot interaction, offering immense potential in fields that require both autonomous decision-making and complex social engagement.

Hospitals are a key proving ground for socially autonomous systems. Severe staffing shortages and burnout drive the "robotic renaissance" in healthcare, with robots deployed to streamline operations and free up human clinicians for direct patient care. Robots like Moxi autonomously assist nurses by fetching supplies and managing logistics, interacting with staff

and patients in a socially aware manner. Newer systems like Mirokai, a 1.3-meter-tall robot that balances on a ball, are designed explicitly for hospital environments to help with tasks like distributing food and supplies [23].

Geriatric care is another critical domain. A 2025 study evaluated the acceptability of a social robot integrated with an LLM in a geriatric care institution, finding it could provide valuable psychosocial support [24]. Another 2025 study focusing on LLM-integrated robots for older adults found that features like personalized memory and culturally attuned voices enhanced trust and social presence [25]. However, this study also identified persistent limitations, with 70% of participants raising concerns about response latency and 60% feeling some responses were excessively long, disrupting the natural flow of conversation. These findings reveal the dual reality of fifth-generation systems: immense potential for companionship shadowed by technical hurdles that can undermine the user experience [25].

**Table 2** provides a comparison of key features across five robot generations. Early pre-robotic machines excelled in precision, hazardous environments, and boosting productivity, but lacked complexity and adaptability. First-generation robots introduced task selection and the ability to handle complex tasks with improved dexterity. The second generation added mobility and real-time decision-making, while the third generation advanced to full autonomy, reducing human intervention. Fourth-generation robots introduced social interaction and emotional engagement, while fifth-generation robots combined social autonomy with self-management and enhanced adaptability to dynamic environments; however, ethical concerns arose in both the fourth and fifth generations.

**Table 2.** Comparison of Key Features Across Robot Generations, Highlighting Advancements in Precision, Mobility, Autonomy, and Social Interaction.

| Features                      | Pre-Robotic Advanced Machines   | First Generation                         | Second Generation               | Third Generation                 | Fourth Generation                         | Fifth Generation                                               |
|-------------------------------|---------------------------------|------------------------------------------|---------------------------------|----------------------------------|-------------------------------------------|----------------------------------------------------------------|
| High precision                | ✓                               | ✓                                        | ✓                               | ✓                                | ✓                                         | ✓                                                              |
| Hazardous environments        | ✓                               | ✓                                        | ✓                               | ✓                                | ✓                                         | ✓                                                              |
| Productivity boost            | ✓                               | ✓                                        | ✓                               | ✓                                | ✓                                         | ✓                                                              |
| Decision-making               | Pre-programmed, fixed responses | Pre-programmed with limited sensor input | Sensor-based adaptive responses | Autonomous, rule-based decisions | Cognitive/AI-driven contextual adaptation | Advanced AI with predictive and social-context decision-making |
| Complex tasks                 | ✗                               | ✓                                        | ✓                               | ✓                                | ✓                                         | ✓                                                              |
| Task selection                | ✗                               | ✓                                        | ✓                               | ✓                                | ✓                                         | ✓                                                              |
| Dexterity                     | ✗                               | ✓                                        | ✓                               | ✓                                | ✓                                         | ✓                                                              |
| Mobile navigation             | ✗                               | ✗                                        | ✓                               | ✓                                | ✓                                         | ✓                                                              |
| Real-time decisions           | ✗                               | ✗                                        | ✓                               | ✓                                | ✓                                         | ✓                                                              |
| Reduced human intervention    | ✗                               | ✗                                        | ✗                               | ✓                                | ✓                                         | ✓                                                              |
| Emotionally supportive        | ✗                               | ✗                                        | ✗                               | ✗                                | ✓                                         | ✓                                                              |
| Meaningful engagement         | ✗                               | ✗                                        | ✗                               | ✗                                | ✓                                         | ✓                                                              |
| Self-management               | ✗                               | ✗                                        | ✗                               | ✗                                | ✗                                         | ✓                                                              |
| Handles environmental changes | ✗                               | ✗                                        | ✗                               | ✓                                | ✓                                         | ✓                                                              |
| Ethical concerns              | ✗                               | ✗                                        | ✗                               | ✗                                | ✓                                         | ✓                                                              |

It is important to note that Generations 1 through 3, as described in this framework, are more representative of industrial and function-oriented robotics rather than socially autonomous systems. While these early generations contributed essential technological foundations—such as precision manipulation, mobility, and basic autonomy—they were primarily developed for industrial, manufacturing, and logistical contexts, with limited emphasis on social interaction or human-centered engagement. The progression into Generations 4 and 5 reflects a marked shift toward social robotics, where capabilities are increasingly directed toward communication, empathy, and integration into human social environments. This distinction provides necessary context for interpreting the framework within the scope of socially autonomous robotics.

#### *Quantitative consistency across generations*

To objectively evaluate the degree of agreement in the evolution of robotic features across generations, a statistical consistency analysis was performed. A Fleiss' Kappa test was applied to 15 identified attributes, yielding  $\kappa = 0.22$  ( $z = 3.3$ ,  $p = 0.000967$ ), indicating a statistically significant yet fair level of agreement among the six generations. This finding suggests that while core technical traits—such as precision and productivity—are shared across generations, considerable diversity exists in the modeling and control systems, particularly in adaptive and social functions. These results confirm that technological advancement in robotics has been progressive but uneven, underscoring the differentiated evolution of modeling and control mechanisms.

#### IV. FUTURE DIRECTIONS AND CHALLENGES

As robotics technology advances toward the sixth generation, several challenges and considerations emerge, including ethical dilemmas related to robot autonomy, the need for robust legal frameworks to govern human-robot interactions, and the technical challenges associated with developing advanced cognitive and emotional intelligence in robots. Addressing these challenges requires interdisciplinary collaboration, with contributions from fields such as AI, ethics, law, and social sciences.

##### Proposed Sixth Generation: Fully Autonomous Social Integration

Building on the foundation of the previous generations, the proposed sixth generation of robotics envisions a future where robots achieve a new level of autonomy characterized by:

- **Advanced Cognitive Capabilities:** Robots will possess advanced AI that allows them to understand complex human emotions, intentions, and social contexts, enabling deeper and more meaningful interactions.
- **Seamless Social Integration:** Robots will be fully integrated into human society, performing a wide range of roles from companionship to caregiving, with the ability to adapt to diverse social norms and cultures.
- **Ethical and Moral Reasoning:** Equipped with sophisticated ethical frameworks, these robots will make decisions considering moral implications, ensuring their actions align with societal values.
- **Symbiosis with Human Society:** Robots and humans will coexist in a symbiotic relationship, with robots enhancing human life by taking on tasks that complement human abilities, leading to a harmonious and mutually beneficial coexistence.

As robotics continues to evolve, future advancements are likely to focus on enhancing the capabilities of socially autonomous robots and addressing the current limitations in areas such as emotional intelligence, long-term autonomy, and ethical considerations. One key direction is the integration of deep learning and natural language processing (NLP) technologies to improve the robots' ability to understand and interpret complex human emotions, cultural contexts, and nuanced social interactions. For example, current conversational AI systems like OpenAI's GPT-4 and Google's LaMDA show how advanced language models can be leveraged to enable robots to engage in more natural, human-like dialogue. These models are expected to improve HRI by making robots more empathetic, culturally aware, and context-sensitive, allowing for more meaningful, personalized interactions.

Another important area for future development is the autonomous learning capabilities of robots, enabling them to not only adapt to individual users but also continually learn from their environment over time. Tesla's Full Self-Driving (FSD) technology exemplifies the power of using massive data sets and AI to enable autonomous systems to learn and adapt in real-world environments. Applying similar techniques in social robots could allow them to self-improve by observing human behaviors and learning new tasks without the need for extensive reprogramming. This would enable socially autonomous robots to become more intuitive over time, adjusting to new environments, users, and roles with minimal human input.

Long-term autonomy remains a significant challenge, particularly in ensuring that robots can operate continuously and reliably over extended periods. Battery life, power management, and system robustness need substantial improvements. For example, Boston Dynamics' Spot has made progress in terms of mobility and power efficiency, but it still requires periodic recharging and maintenance, limiting its long-term deployment in highly demanding environments. Future advancements in energy storage, such as the integration of solid-state batteries or wireless charging technologies, could enable robots to operate for days or weeks without the need for manual intervention. Additionally, advancements in self-repair technologies, inspired by the work on soft robotics and bio-inspired designs, could enable robots to perform self-diagnosis and minor repairs autonomously, increasing their long-term operational capabilities.

However, as the field progresses, ethical challenges will become increasingly important, particularly with regard to privacy, data security, and human safety. Robots like Amazon's Astro, a household assistant, raise questions about privacy,

as these devices continuously collect and process personal data within private spaces. Ensuring that socially autonomous robots handle personal information responsibly and transparently will be crucial. Moreover, establishing ethical guidelines for robots' decision-making processes, especially in high-stakes environments like healthcare or eldercare, will be necessary to ensure that these systems can make morally sound decisions in complex social situations. Governments and regulatory bodies may need to develop new frameworks for robot governance, similar to the discussions around AI ethics currently underway at organizations like the European Commission and IEEE.

Future developments in robotics will benefit from the systematic application of human-centred design principles, ensuring that systems are tailored to user needs, cultural contexts, and specific operational environments. Participatory co-design—engaging end-users, stakeholders, and multidisciplinary experts throughout the design process—has proven particularly effective in later generations, where social interaction and usability are critical. Involving patients, clinicians, educators, and operators from the outset ensures that robotic systems are not only technically capable but also socially and ethically aligned with user expectations and requirements.

In conclusion, the future of socially autonomous robots holds significant promise, but it also presents challenges that will require coordinated efforts across AI, engineering, ethics, and policy. Advances in machine learning, energy management, and ethical frameworks will drive the next generation of robots capable of even more sophisticated, human-like interactions and deeper integration into daily life. However, addressing these challenges will be critical to ensuring that robots can effectively and safely meet the growing demands of human society.

## V. CONCLUSION

This comprehensive study demonstrates how robotic systems have evolved from accurate, industrially oriented equipment to socially autonomous platforms that can adapt to human-centered contexts. The study examines a wide range of studies over five generations of robotics and demonstrates the journey from precision-driven pre-robotic equipment to today's socially independent robots. It examines the theoretical and technological foundations of these breakthroughs, emphasizing autonomy, mobility, human-robot interaction (HRI), and multidisciplinary techniques that combine artificial intelligence, cognitive science, and engineering. Key findings reveal that early generations prioritized accuracy, mobility, and automation for industrial applications, whereas later generations incorporated social capabilities and autonomous decision-making, redefining human-robot collaboration. Fifth-generation robots, the pinnacle of this evolution, demonstrate self-management and adaptability in complex environments but face challenges in ethical integration, emotional intelligence, and computational efficiency. These advancements have implications across domains, including healthcare, education, and customer service, underscoring the necessity for ethical frameworks and further research in enhancing robots' cognitive and social intelligence. This work serves as a foundation for envisioning future robotics that harmonize technological innovation with societal needs.

## CRedit Author Statement

The authors confirm contribution to the paper as follows:

**Conceptualization:** Ashraf Gaffar and Fulayjan Alanazi; **Methodology:** Fulayjan Alanazi; **Writing- Original Draft Preparation:** Fulayjan Alanazi; **Visualization:** Ashraf Gaffar and Fulayjan Alanazi; **Investigation:** Ashraf Gaffar and Fulayjan Alanazi; **Supervision:** Fulayjan Alanazi; **Writing- Reviewing and Editing:** Ashraf Gaffar and Fulayjan Alanazi; All authors reviewed the results and approved the final version of the manuscript.

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## Data Availability Statement

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

## Conflicts of Interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Competing Interests

There are no competing interests.

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