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Survey and Tutorial on Hybrid Human-Artificial Intelligence

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Abstract: The growing computing power, easy acquisition of large-scale data, and constantly improved algorithms have led to a new wave of artificial intelligence (AI) applications, which change the ways we live, manufacture, and do business. Along with this development, a rising concern is the relationship between AI and human intelligence, namely, whether AI systems may one day overtake, manipulate, or replace humans. In this paper, we introduce a novel concept named hybrid human-artificial intelligence (H-AI), which fuses human abilities and AI capabilities into a unified entity. It presents a challenging yet promising research direction that prompts secure and trusted AI innovations while keeping humans in the loop for effective control. We scientifically define the concept of H-AI and propose an evolution road map for the development of AI toward H-AI. We then examine the key underpinning techniques of H-AI, such as user profile modeling, cognitive computing, and human-in-the-loop machine learning. Afterward, we discuss H-AI's potential applications in the area of smart homes, intelligent medicine, smart transportation, and smart manufacturing. Finally, we conduct a critical analysis of current challenges and open gaps in H-AI, upon which we elaborate on future research issues and directions.

Key words: hybrid human-artificial intelligence (H-AI); Internet of Things (IoT); artificial intelligence (AI)

1 Introduction

With the significant advances of the Internet of Things (IoT) and computer science, artificial intelligence (AI) has made considerable progress. Since AI was first coined in 1956, when the progress was described as "astonishing"[1], AI techniques have shown great possibilities in handling traceable problems. As a scientific discipline aiming to make machines act like humans, AI simulates the characteristics and intelligence of human beings with intelligent algorithms. It has penetrated every aspect of our daily life and industrial manufacturing and contributes greatly to providing intelligent services[2].

Many studies focus on the breakthroughs brought by AI techniques. For example, Rashidi and Cook[3] pointed out that AI algorithms could make the living environment much more intelligent with a higher quality of life. Parapugna et al.[4] illustrated the great significance of AI in intelligent transportation systems, such as smart vehicle-highway systems, freeway incident detection, urban rail corridor control, and short-term traffic flow prediction. Yu et al.[5] provided an overview of the recent progress in health care brought by AI techniques, such as automatic diagnosis, clinical practice, and basic biomedical research.

However, with the rapid development and uptake of AI techniques in daily life, some scientists have become concerned about the challenges of AI developments, in particular the future relationship between AI and human intelligence. From the technical aspect, due to the engineering limitations and the opaqueness of

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some algorithms, difficulties in totally understanding and interpreting AI techniques exist. Although intelligent machines perform better in dealing with monotonous and laborious work, they still struggle in performing reasoning, inference, cognition, and flexibly adapting to dynamic environments. From the ethical aspect, the progress of AI has accelerated the concerns that AI may overtake, manipulate, or replace humans someday in the future. It is hard to imagine what would happen if autonomous vehicles were out of control and destroyed humans. From the legal aspect, the increasing advances of AI bring conceptual and practical challenges to national regulations. For example, people may need to decide who should take responsibility for the harm caused by autonomous and intelligent machines[6].

Obviously, both human intelligence and AI have respective advantages. Their relationship does not have to be competitive, mutually exclusive, or one that involves replacing the other. One appropriate way to handle the current predicament is to marry their strengths and overcome their weakness for more enhanced intelligence. In this paper, we present the novel concept of hybrid human-artificial intelligence (H-AI) which points out the future direction of intelligence[7]. It is not only limited to the cooperation and collaboration between human intelligence and AI but also emphasizes intelligent convergence to an indivisible unity. The main contributions of this paper are as follows.

- The H-AI concept is introduced, and a development road map of AI toward H-AI is proposed, which has profound significance for future development.
- Key underpinning techniques are identified and elaborated, including user profile modeling, cognitive computing, and human-in-the-loop (HitL) machine learning, to provide technical guidance for further H-AI development.
- Potential H-AI applications such as smart homes, intelligent medicine, smart transportation, and smart manufacturing are envisioned and illustrated.
- Open issues and challenges faced by H-AI are uncovered, and future research areas and directions are pointed out.

The remainder of the paper is arranged as follows: Section 2 illustrates the novel concept of H-AI and depicts the development road map of AI. Section 3 elaborates on the key underpinning techniques related to H-AI. Section 4 envisions the potential applications of H-AI. Section 5 discusses open issues and challenges of H-AI from which possible future research directions are derived. Section 6 concludes this paper.

2 Hybrid Human-Artificial Intelligence and the Evolution Road Map of AI

2.1 Concept and rationale of H-AI

The unprecedented developments of IoT and big data have put forward high requirements for AI technologies. Some bottlenecks of AI technologies need to be resolved for further development. First, AI needs to overcome the large gap between theoretical research and industrial practice. Most relevant studies remain in the simulation stage rather than large-scale application. Breaking through technical bottlenecks is urgent. Second, there are no reusable and standard technology frameworks, platforms, and services that are mature enough to support a perfect AI ecology. Moreover, the uninterpretability of some AI algorithms brings difficulties in strong technical understanding and breakthroughs. Hence developing a new form of AI is necessary.

In this paper, we propose the concept of H-AI, which is in line with the future development trend. H-AI can be regarded as an advanced intelligence that utilizes otherness and complementarity between human intelligence and AI. To the best of our knowledge, the structural characteristics of human brains, genetic factors, and social and cultural determinants give humans the capability of learning, reasoning, analysis, cognition, and creativity. Compared with human beings, AI has specific advantages of efficiency, normalization, objectivity, and repeatability with precise algorithms. For example, machines are able to deal with repetitive grunt work more accurately and effectively[8]. It will largely reduce labor and time consumption. In our proposed H-AI, human intelligence and AI are integrated and hold equally substantial positions to achieve better cognition.

As shown in Fig. 1, the connotation of H-AI is explained from two aspects. First, it means incorporating human intelligence and AI into an independent unity, in which machines could be perfect parts of humans. This could be seen as the initial stage of H-AI development. At this stage, H-AI combines AI and human intelligence in the physical space to deal with complicated and dynamic problems. H-AI also refers to the existence of a simulated "you" in cyberspace. Cyber avatars have the same intuitions, cognition, ideas, and thinking like you, requiring accurate mapping and synchronization between physical and cyber spaces. Under such circumstances, cyber avatars could help perform certain jobs when humans are tired or busy.

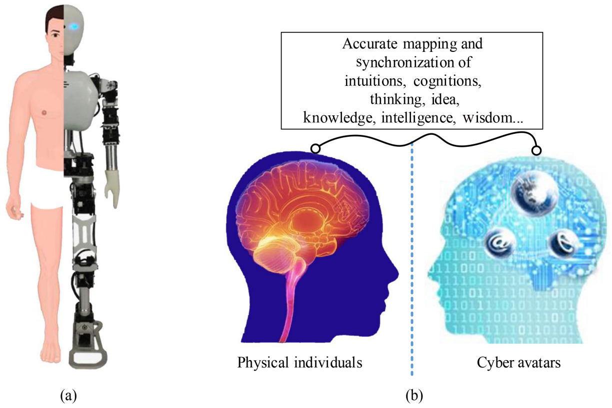

Fig. 1 Interpretation of H-AI. (a) represents the incorporation of human intelligence and AI into an independent unity, in which machines could be perfect parts of humans; (b) refers to the amazing existence of a simulated "you", the cyber avatars that have the same intuitions, cognitions, ideas, and thinking as you in cyberspace.

The concept of cyber avatars in H-AI is somewhat similar to that of the digital twin proposed around 2003[9]. The digital twin refers to a mechanical, passive, and mirror-like reaction and replication of physical systems with no independence, while the concept of H-AI emphasizes more initiative and collaboration between AI and human intelligence. Compared with existing concepts, H-AI refers more to the human-like cognition of machines, the incorporation of human intervention in AI systems, and the integration and synchronization between human intelligence and AI. Table 1 provides a comparison between some relative concepts with AI.

Even if AI technology develops with a huge leap forward, however, realizing the 100% imitation of human intelligence is almost impossible. The unique nature of human brain mechanisms cultivating abilities of cognition, perception, high-level motivation, and self-awareness enables humans to play irreplaceable roles, particularly under the circumstances such as logical analysis and deductive inference together with decision-making. Our proposed concept of H-AI conveys an overall collaboration and synchronization between humans and AI machines or systems, which would be real hybrid intelligence.

2.2 Road map of AI toward H-AI

Since the birth of AI in 1956, research on intelligence has always been in progress. The aim is to make machines much more intelligent, with similar intuitions, perceptions, and cognition as humans. Tracing back the history of AI shows that many studies have focused on new concepts generated from traditional AI. For example, strong AI was first initiated in 1980[10]. This idea suggests that machines may have similar thinking abilities as humans, which was a controversial idea at that time. Afterward, an increasing number of similar ideas were generated and spread. Powers[11] presented the view of human-level computational intelligence, which stimulates discussions around the cognition of human brains and the heuristics, which allow us to struggle through intractable issues. Ahmad and Sumari[12] proposed a version of cognitive AI, which designs AI systems based on cognitive models to emulate human brain mechanisms. It is considered a kind of brain-inspired intelligence with great significance in knowledge extraction and intelligent systems[15].

Table 1 Comparison between H-AI and other relative concepts.

Concept	Main features
Strong AI[10]	It points out that machines could think similarly to humans.
Human-level computational intelligence[11]	It discusses two aspects of human intelligence that AI systems are going to achieve, that is, the cognition of human brains and the heuristics allowing us to struggle through tough issues.
Cognitive AI[12]	It refers to designing AI systems based on cognitive models to emulate human brain mechanisms as intelligently as possible.
Hybrid-augmented intelligence[13]	It emphasizes hybrid-augmented intelligent based on HitL and cognitive computing.
Hybrid intelligence[14]	It defines the combination between human intelligence and AI to achieve joint goals.
Digital twin[9]	It represents a digital replication of physical entities and systems for better simulation and prediction, in which information transmission is unidirectional.
H-AI	It not only focuses on the interaction and collaboration between humans and AI but also proposes an advanced vision of AI, where humans and AI machines could be integrated and fused into one whole individual, as well as the phenomenon of cyber avatars having similar cognition and intuitions as humans, allowing them to work together.

To the best of our knowledge, most advances with reference to AI are closely related to relationships with humans. As pointed out by Hoc[16], the human-machine relationship is developing from human-machine interaction to human-machine cooperation. The human-machine interaction refers to circumstances where users could fully control machines, aiming to make the interaction friendlier and more transparent with various interfaces. Human-machine collaboration emphasizes more collaboration between humans and machines and is an approach to dealing with dynamic situations with more freedom for machines.

Inspired by this idea, we try to elaborate on the development of AI in terms of the relationship between humans and machines or AI. As can be seen in Fig. 2, the development of AI can be divided into three phases. The initial phase refers to the early period of AI research, which is regarded as interactive human-artificial intelligence (I-AI). I-AI emphasizes the information transmission and interaction between humans and AI systems. The interaction goes beyond simple keyboard input or handle manipulation to various interactive modalities, such as touch, speech, gestures, and visions, which is the so-called natural user interface[17]. Notably, this interaction is generally unidirectional.

However, relying only on the interaction between humans and AI is not sufficient. Along with the great advances in AI techniques, machines could have much more complicated abilities to deal with certain jobs. As a result, AI research has entered the intermediate phase named collaborative human-artificial intelligence (C-AI), which emphasizes collaboration and cooperation between humans and AI systems. In 2017, Zheng et al.[13] proposed the concept of hybrid-augmented intelligence, which introduces human intervention in AI systems. Reference [14] also defined a concept of hybrid intelligence (HI) that focuses on the combination between human intelligence and AI. At this stage, humans and AI systems work together based on a collaborative mechanism in which AI is responsible for large-scale mechanical calculations, and humans focus on cognitive analysis, deductive reasoning, and abstract decision-making.

Nevertheless, human intelligence and AI are still independent entities in C-AI and are regarded to be in a transition stage for future AI, which is the emerging H-AI. The idea of H-AI is similar to that of Cyborgs in science fiction, which represents beings that have organic and biomechanical body parts[18]. It is a disruptive and transformative vision that goes well beyond physical limitations. H-AI incorporates human intelligence and AI into an integrated unity by marrying their advantages. It could be an entity, a system, or an ecosystem. In other words, H-AI would achieve the goal of machines being real parts of humans, or the same "you" could exist, i.e., a digital avatar or a shadow in the virtual cyber world.

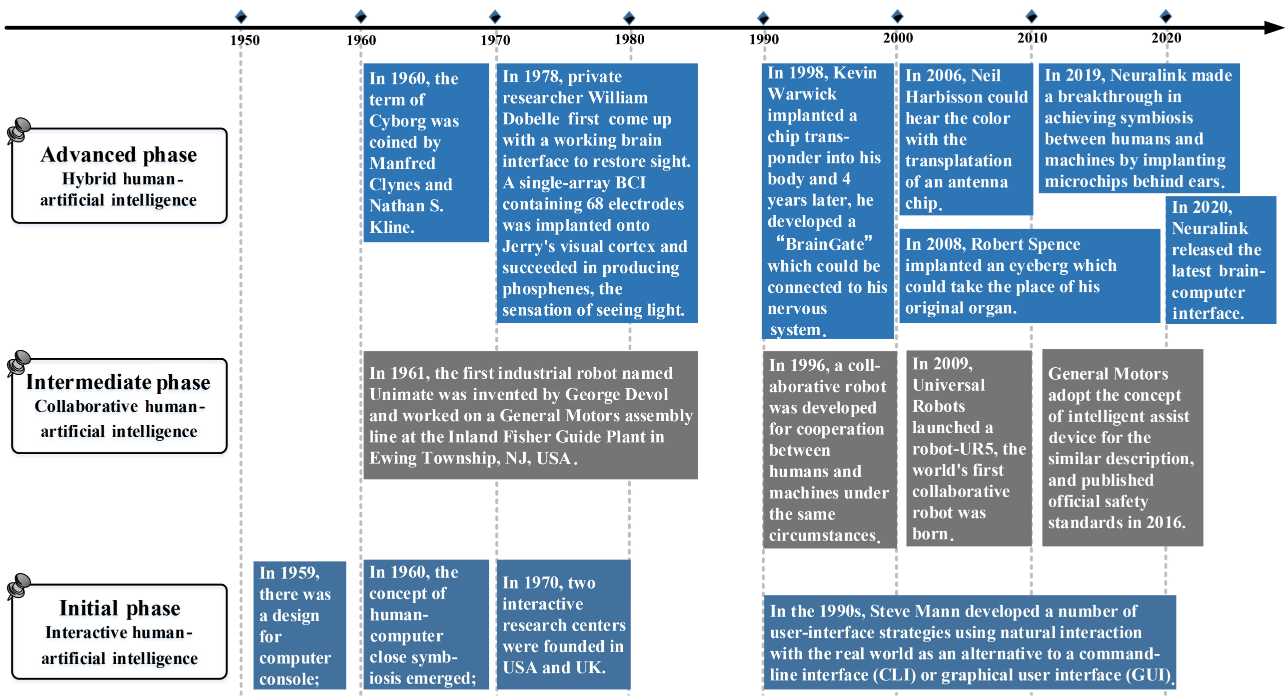

Fig. 2 Evolution road map of AI toward H-AI.

The avatar could feel what you are sensing or thinking about and take your place when you are tired or busy. This concept would be the ultimate direction for future AI development.

Generally speaking, AI is evolving in the direction of providing better services to humans. The evolutionary road map clearly depicts that AI is experiencing dramatic changes toward more advanced intelligence and provides a high-level view of AI development with constructive guidance for further development.

3 Key H-AI Underpinning Techniques

H-AI is still in its infancy; thus, establishing a mature technical system has a long way to go. In this section, we discuss potential techniques of H-AI based on its concept and connotation, including techniques of user profile modeling, cognitive computing, and HitL machine learning.

As can be seen in Fig. 3, techniques related to user profile modeling, such as semantic ontology modeling and tree-code modeling provide the foundation for achieving seamless integration and fusion in H-AI. To achieve a better understanding of humans' intentions, cognitive computing techniques are important for AI machines, which will establish a solid foundation for realizing successful communication and collaboration between humans and machines. HitL machine learning is a significant part of H-AI, because machine learning provides an efficient way to handle complex datasets and knowledge. The intervention of humans could largely avoid any inaccuracy of machine learning. Depending on these intelligent techniques, H-AI could realize the real fusion of human intelligence and AI, and maximize mutual benefits to a large extent.

3.1 User profile modeling

To achieve the complete integration between human intelligence and AI, technologies relating to user profile modeling are the primary approaches. User profiles represent the related information of user characteristics, such as preferences, tastes, habits, interests, and psychological features[19]. Considering higher interpretability and intelligibility, some research adopts semantic ontology modeling to depict user profiles[20]. The ontology can be regarded as the specification of a conceptualization, which provides a spectrum for knowledge expression[21, 22]. In 2015, Ning et al.[23] proposed a tree-code modeling for physical objects on the basis of attributes and behaviors, which inspired user profile modeling to a certain extent. User profiles hold important positions in daily activity recognition and are attracting increasing attention. For example, in 2019, we established a user profile ontology from the perspective of physiological attributes, social relationships, and personal features. The ontology has shown great efficiency in daily activity recognition[24].

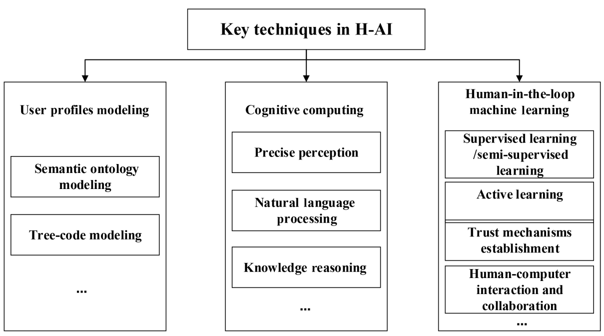

Fig. 3 General spectrum of potential key techniques in H-AI.

In addition to applications in smart homes, user profile modeling has been applied in other areas. For instance, Amato and Straccia[25] pointed out the importance of user profiles in providing appropriate information in digital libraries. Jayakumar and Shobana[26] followed the potential of user profiles in searching web information and established a user profile ontology based on basic information and professional experience. He and Fang[27] explored an ontological method of depicting user profiles based on browsing history and provided personalized information services in e-commerce with long-term and short-term interests. In addition, user profiles play significant roles in social networks, especially in relationship analysis and friend recommendation[28].

Modeling user profiles is one of the most fundamental techniques in achieving H-AI, as it could guarantee seamless individual mapping from physical space to cyberspace and provide technical support for total fusion and integration. In H-AI, user profile modeling is not limited to the descriptions of external features but also includes the complicated replication of human mechanisms such as thoughts, ideas, intuitions, cognition, and creativity.

3.2 Cognitive computing

Cognitive computing (CC) is regarded as a computation ability that allows machines to be much more intelligent by simulating humans' perception, intuition, and cognition[13]. It focuses more on imprecise and uncertain issues related to inference, reasoning, analysis, and decision-making which could contribute greatly toward achieving seamless communication between humans and AI machines. Notably, CC is not an isolated or independent technique but covers and integrates a series of principal techniques. In this section, several major techniques with regard to CC are introduced such as precise perception, natural language processing (NLP), and knowledge reasoning.

3.2.1 Precise perception

Human perception is generally believed to have advantages in perceiving and processing information in a fine-grained and multi-resolution manner. Cognitive systems are pursuing technical enhancements to achieve such precise perception. Generally speaking, some novel ways of perception exist in addition to the traditional ones, such as touch, vision, and hearing.

The first category of precise perception we discuss here is related to the precise location of individuals or objects. With the immense development of 3G, 4G, and 5G communication technology, obtaining objects' accurate positions via mobile network terminals is easier. The geometric position of target objects can be calculated by extracting and analyzing necessary information from signals propagating between mobile stations and transceivers. So far, wireless location techniques mainly include methods based on different network parameters such as cell-ID, signal strength of arrival, and time of arrival[29, 30]. For example, Yao and Yang[31] compared different technologies relating to mobile terminals' location and obtained the mobile terminal location by parsing information from relevant parameters. Guo et al.[32] established a robot perception system that could obtain primary locations via aural sensors and continuously achieve optimization by using charged-coupled device (CCD) cameras.

Sensing techniques based on gestures, actions, and behaviors are other widespread precise perception techniques. One of the most prevalent ways to sense tiny actions is by employing multi-modality sensors. For example, Microsoft Kinect sensors are widely used in gesture perception and recognition. Berri et al.[33] presented a telepresence robot with a Kinect sensor as the main perception device, under which hand gestures and movements could be recognized and tracked easily. Varshini and Vidhyapathi[34] proposed a dynamic gesture recognition system that utilizes a Kinect and detects various finger gestures. Some research focuses on analyzing the Kinect sensor data stream with machine learning to capture gestures and actions more efficiently[35].

In addition, the perception of physiological signals holds an important position in precise perception, which mainly focuses on breath, heartbeat, pulse, blood pressure, and other biometric features. Relevant technologies are usually applied in the area of smart healthcare. Electrocardiogram instruments, blood pressure monitors, and pulse meters are all professional equipment for precise perception. With the significant improvements in medical techniques, monitoring and sensing equipment are becoming more sophisticated, which could support increasingly precise perception.

3.2.2 Natural language processing

NLP aims at language understanding and translation and has high efficiency in processing large amounts of data[36]. It can considered one of the principal techniques to make machines better understand humans. In this section, we discuss some popular methods with reference to NLP.

First, to achieve a complete understanding of natural languages such as articles, sentences, and words, segmentation plays a significant role. The basic segmentation methods are mainly categorized as segmentation based on dictionary, segmentation based on word understanding, and segmentation based on statistics. Taking Chinese as an example, Chen et al.[37] noticed the drawbacks of the single segmentation method and presented a pragmatic approach that integrates different segmentation techniques. This approach highly enhances the performance and accuracy of word segmentation. Zhao et al.[38] proposed a conditional random field segmentation model based on Chinese words, which has been demonstrated in datasets of the State Grid energy literature. It exhibits better performance than existing Chinese word segmentation tools, such as the platform designed by Harbin Institute of Technology and Tsinghua's THU Lexical Analyzer. Zhang et al.[39] depicted a Chinese word segmentation algorithm with the help of tagging methods based on given speech and word frequency. Apart from word segmentation research in Chinese, other languages such as Tibetan, Manipuri, and Manchu are attractive topics in academia[40–42].

Syntactic analysis is also important in NLP, which refers to language analysis with formal grammar rules. It provides syntactic information by analyzing the sentence structures and the relationships between words. When it comes to syntactic analysis, dictionaries and dependency grammars are principal foundations. For example, Park and Kwon[43] established a syntactic analysis system for Korean, which uses many dependency grammar and rules. However, due to the inherent incompleteness, dictionaries or dependent grammars cannot handle all sentences. Therefore, Bessmertny et al.[44] improved the current syntactic analysis by introducing affixes with prepositions to reduce the dependence on dictionaries.

Notably, ambiguity will occur in the process of syntactic analysis, which is why eliminating ambiguity is equally important. To reach a consistent agreement, disambiguation algorithms are widely applied in areas of semantic networks. In Refs. [45, 46], ambiguity is suggested to have four categories, namely, lexical ambiguity, syntactic ambiguity, pragmatic ambiguity, and semantic ambiguity. Most approaches to eliminating ambiguity are based on neural network algorithms. For example, Sharma et al.[47] presented a method that regards ambiguity elimination as a classification problem and demonstrated the elimination with various techniques such as Bayersian network, adaptive boosting, random tree, and random forest (RF) algorithms.

NLP is widely used in machine translation, semantic understanding, and question answering systems, thus becoming an important part of AI systems. However, some technical problems and challenges need to be overcome in the NLP field. For example, language is different and uncertain at different levels of lexicology, syntax and semantics, and the growing dynamics and complexity make it more difficult to deal with. These challenges need to be considered in future technological improvements of the H-AI system.

3.2.3 Knowledge reasoning

Knowledge reasoning refers to extracting, analyzing, reasoning, and obtaining implicit, hidden knowledge from datasets[48]. In this section, we discuss two specific methods of knowledge reasoning based on rules, cases, and fuzzy logic.

Rule-based knowledge reasoning is common, and most knowledge is inferred from the rules generated by the expert system. However, it faces great obstacles in rule management. At the same time, considering the incompleteness of the expert system, rule extraction is not always easy. Therefore, case-based knowledge reasoning is developed, in which the cases could be regarded as templates for similar occasions[49, 50]. Verma et al.[51] presented a conceptual decision-making system with both rule-based and case-based knowledge reasoning mechanisms. This system achieves an efficient and accurate solution by integrating both advantages. Another typical knowledge reasoning approach is based on fuzzy description logic, which represents a series of uncertain and vague knowledge[52]. Chen et al.[53] established an ontology in Web Ontology Language for empirical knowledge expression and provided a structured vision for abstract knowledge.

Knowledge reasoning is an irreplaceable technology for realizing mutual cognition between humans and machines. Explicit information or knowledge accounts for only a small part of the knowledge acquisition system, and mining and processing implicit knowledge are more important. Therefore, further research on knowledge reasoning technology is imperative in H-AI systems.

3.3 Human-in-the-loop machine learning

Nowadays, most machine learning algorithms still depend on human intervention and feedback, and cannot realize automatic learning themselves. HitL machine learning allows humans and machines to interact to resolve complicated tasks. As mentioned by Robert Munro[54], the aim of HitL machine learning is to make humans and algorithms more accurate and efficient to provide more intelligent services. We regard that by continuously optimizing the interactions and collaborations between humans and AI systems, HitL machine learning is one of the basic technologies that can be further expanded and applied in the future H-AI.

Many studies focus on HitL machine learning. For example, Ref. [55] adopted a set of HitL algorithms to explain the failures in AI systems, thus prompting the development of accountable AI. Reference [56] emphasized the importance of introducing HitL to overcome the existing drawbacks of AI systems. Afterward, the authors demonstrated how human intelligence worked and complemented image captioning systems through crowdsourcing, which helps verify and correct systems' output and errors[57]. At this stage, it has demanding requirements for interactions between humans and AI systems although they are still two independent parts. Therefore, more strict demands need to be satisfied in H-AI systems where the collaboration between humans and AI systems is much closer.

To achieve synchronized interaction and collaboration in future H-AI, a significant step is to establish trust between humans and AI machines. The trust mechanisms could obviate conflicts between humans and systems and achieve conflict meditation in collective decision-making[58]. Disuse, abuse, or neglect of trust mechanisms would lead to severe failures and produce a fatal blow to the whole system[59]. According to the principle of human-computer interaction and collaboration, Azevedo et al.[60] proposed a framework based on mutual cooperation between humans and AI systems, in which three aspects are included, namely, explanation, mutual understanding, and mutual trust. In Ref. [61], the authors noticed the low accuracy and high complexity in automating verification, and they proposed a fusion rethinking verification mechanism with human intervention in autonomous systems. Considering the expensive cost when annotating objects, Russakovsky et al.[62] designed an algorithm that adopted the advantages of human intelligence and AI and introduced human feedback to revise the annotation results processed independently by machines.

Moreover, some scientists have begun to study the interaction and collaboration between humans and AI systems by transplanting electric devices or chips into human bodies, that is the so-called brain-computer interface (BCI)[63]. Braingate was first tested by David Vintiner in 1998, and it aims to help patients with loss of limbs, arms or other body parts and could achieve communication and collaboration between sensors and bodies through electrodes[64]. Neil Harbisson was born with a disability and cannot recognize colors except white and black. He conducted a similar experiment by implanting an "eyeborg" into his body, which enables him to "hear" colors through the collaboration between the eyeborg and his brain[65]. In 2019, Neuralink made a breakthrough in achieving a symbiosis between humans and machines by implanting microchips behind the ears, which could help monitor brain signals and treat certain diseases[66]. In 2020, Elon Musk announced a BCI prototype named LINK V0.9 and demonstrated its performance in monitoring and tracking pigs' brain activities[67]. This achievement is a great leap forward toward the future H-AI, particularly in the seamless integration and fusion between humans and AI systems. Undoubtedly, these techniques would play vital roles in H-AI systems are worthy of further study.

4 Applications

H-AI depicts a future blueprint for advanced intelligence, in which humans and AI systems or machines could be integrated into one entity. To deepen and consolidate the understanding of H-AI and provide constructive instructions for both academia and industry, we envision and analyze potential applications of H-AI such as smart homes and daily life, health care and intelligent medicine, smart transportation, and smart manufacturing.

4.1 Smart homes and daily life

Smart home has become a prevalent phenomenon along with the emerging AI developments. It mainly focuses on improving the quality of life of habitants who have disabilities or on helping the elderly live independently[68]. As pointed out by the Agile Ageing Alliance[69], a blueprint for future smart homes is depicted where AI machines or robots could communicate, interact, and collaborate with humans via smart mirrors and head-mounted displays. The vision is that one day, with the total integration and fusion between humans and AI, controlling or manipulating daily devices via intuition and cognition would be much more convenient for humans.

As mentioned in the last section, some scientists have paid attention to intelligent machine parts such as eyeborgs or chips. They could be completely fitted and fused into human bodies and help improve the quality of life by cooperating with humans. To the best of our knowledge, robots have provided support for daily life and smart homes. In 2014, a therapeutic seal robot named PARO successfully achieved a high therapeutic impact on elderly people with mental illnesses[70]. This robot could feel humans' emotions via various sensors and then give appropriate feedback for counseling and encouragement. Synnott et al.[71, 72] adapted the Nintendo Wii based on a similar robot with PARO to help people who are suffering from mild cognitive disorders or loneliness.

Although the real H-AI has not been promoted on a large scale, the interactive and collaborative human-artificial intelligence has been experiencing significant popularization. Gradually, people will notice the great potential of implanting portable chips or devices into human bodies, which could support more advanced and seamless interaction and collaboration. H-AI systems will support daily life in assisted living by providing essential help and guidance and also play important roles in guaranteeing the normal life of the disabled by replacing body parts.

4.2 Health care and intelligent medicine

As for health care and intelligent medicine, H-AI seems to have much more opportunities to help doctors and patients. From the perspective of patients, chips could be designed with similar tissues and functions as humans. Thus, they can be transplanted into human bodies and replace broken organs. In 2008, Ekekwe[73] proposed that neuromorphs and artificial neural microcircuits could play replaceable roles when patients have organ damage. They could help capture biological features by imitating humans' inherent capabilities. The Wyss Institute of Harvard University presented a new concept named organs-on-chip[74], which involved simulating the functions and tissues of lung alveoli on a chip to provide low-cost alternatives for patients. In addition, organs-on-chip could support further sophisticated medical research for fighting disease[75].

For doctors, AI systems are known to be superior at precise prescription based on exact rules and large memories. However, difficulties exist in recognizing all diseases depending on restricted rules. Therefore, human intervention cannot be totally replaced in the areas of health care and intelligent medicine[76]. Some hybrid systems or robots demonstrate the collaboration between humans and AI. For example, IBM Watson is one of the most successful intelligent systems that integrate human knowledge and AI to overcome current obstacles in smart health[77]. The newly released BCI device LINK V0.9 and the surgical robot by Neuralink help relieve depression and addictive behaviors, resolve obsessive-compulsive disorders, and promptly address traumatic brain injuries[67].

In the future, the maturity of H-AI techniques will bring great changes in the development of health care and intelligent medicine. Knowledge memory chips can be implanted into doctors' bodies, with doctors being regarded as hybrid and augmented intelligent systems. With the continuous developments of head-mounted intelligent devices, machines could collaborate with human doctors under special circumstances by understanding their thoughts and ideas.

4.3 Smart transportation

Smart transportation provides innovative services in transport systems and aims to make transport systems much safer. With the emergence of autonomous driving, big companies such as Google and Baidu are focusing their research efforts on autonomous vehicles[78]. However, challenges still exist. For example, handling unexpected situations in a timely and flexible manner is difficult for autonomous vehicles. Large-scale deployment is confronted with difficulties such as technological bottlenecks, legal and moral disputes, and high costs. Therefore, the integration between human intelligence and AI is significant in achieving complete safety.

Evidently, humans have inherent advantages such as robustness, flexibility, and strong adaptability, but they are more likely to be influenced by emotions, fatigue, or bad weather when driving. Considering the respective advantages and disadvantages, studies are beginning to focus on collaborative driving in real applications. For instance, Jungum et al.[79] paid attention to data and information fusion by Bluetooth, which aims to comprehensively understand the surrounding conditions when driving. Li et al.[80] presented a semi-physical simulation system for collaborative driving, which enables drivers and machines to manipulate the vehicles to maintain overall safety.

We expect that H-AI could make transportation much more intelligent through the seamless fusion between human intelligence and AI. Drivers could sense better via various electric devices to make better decisions, and machines could derive synchronized intuitions and cognition dominated by human drivers, thus being able to replace human drivers under bad circumstances.

4.4 Smart manufacturing

In addition to the applications mentioned above, H-AI would play a significant role in smart manufacturing. Smart manufacturing is an intelligent and collaborative landscape that is integrated and equipped with various techniques such as AI, and blockchain[81]. It provides a view for humans and AI to interact and work with each other in smart factories to achieve mutual goals. Along with the promotion of Industry 4.0, more research is focusing on the potential applications for H-AI in smart manufacturing.

The emergence of collaborative robots is a great leap, enabling robots and humans to work together in a defined collaborative workspace. Companies such as BMW, Mercedes, GM, and Skoda employ collaborative robots for manufacturing. Ford introduced for the first time collaborative robots working alongside employees, and they help handle jobs such as quarter glass and engine inspection[82]. In the Tesla's factories, "Iceman" and "Wolverine" are two robots that help move vehicles from one line to another to release the heavy burden on workers and improve production efficiency. In the above cases, robots and humans are still two independent parts that communicate and cooperate with each other. Their relationship is attracting increasing attention to ensure that the best balance is achieved[83].

With the further promotion of H-AI, we believe the collaboration between robots and humans will become much more flexible, in which humans could guide and manipulate robots via cognition and awareness. More importantly, the machine parts would have their own thoughts and be able to communicate with humans bidirectionally. Therefore, the efficiency of smart manufacturing would greatly improve.

5 Challenges and Open Issues

H-AI is considered the future development direction of AI. It combines human intelligence and AI perfectly, thus creating an inseparable unity. However, with the coming popularization of this groundbreaking concept, challenges and open issues will attract serious attention. In this section, we will analyze the potential challenges and related privacy and security issues from the technical, ethical and legal aspects.

First, technical challenges in H-AI development are worthy of further study. The existing technical bottlenecks hinder the seamless communication, interaction, collaboration, and synchronization between humans and AI machines. The accuracy and precision during the fusion and integration process need to be improved. Technical innovations of AI and AI adversarial algorithms should always be underway to ensure safe intelligence. For instance, when the AI system is out of control, an appropriate destruction mechanism will play an important role.

Second, the moral issues stemming from H-AI need to be emphasized. The aim of H-AI is to ensure that machines have a similar cognition to humans. The same "you" may exist in cyberspace, which could take your position under special circumstances. However, the concept challenges humans' status to some extent and has caused some panic and concerns. Hence, an urgent task is to solve the moral problems with reference to the balance between human intelligence and AI. Relevant restrictions should be enhanced. We would like to assume that the premise of H-AI should always be that human beings are in a dominant position and cannot be challenged by robots or machines.

Another troubling problem for H-AI is from the perspective of laws and regulations. A controversial issue that persists is related to who should be responsible for harm caused by robots or machines in H-AI systems. To provide a more harmonious environment, nations and countries should enhance legislation work and clarify the responsibilities in further H-AI.

Last but not least, the privacy and security issues of H-AI need to be explored and studied constantly. Considering the connotation of H-AI, information mapping and synchronization would occur between physical and cyber spaces, which may disclose the privacy of users. Especially in recent years, as the public is more aware of the relevant problems, privacy and security issues need to be taken into consideration.

As an unprecedented new research area, H-AI is bound to affect existing technical, moral, and legal systems. Human beings should constantly explore the coexistence and coevolution mechanisms of human intelligence and AI.

6 Conclusion and Future Work

H-AI is regarded as one of the promising directions in the quest for the next game-changing AI development, attracting increasing attention along with the rapid development of relevant underlying technologies. Nevertheless, H-AI is at a very early stage, with many fundamentals to be defined, clarified, and agreed upon. For example, technical bottlenecks related to seamless integration between human intelligence and AI need to be overcome. In this paper, we provide a clear definition of H-AI which refers to the total integration between human intelligence and AI into an indivisible unity, and depict a development road map of AI from I-AI, C-AI, to future H-AI. The underpinning key techniques and potential applications are also surveyed and concluded. Possible challenges and open issues of H-AI are analyzed from the technical, moral, and legal perspectives, upon which potential directions for future work are pointed out.

We believe this paper provides a solid foundation for researchers and practitioners interested in H-AI studies. The in-depth discussion and identification of the open issues, challenges, and opportunities will provide further guidance for further academic research, technological innovation, and application development.

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