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Research Progress of Human-Machine Fusion Intelligent Decision-Making

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Abstract. With the rapid development of artificial intelligence, human-machine fusion intelligence has emerged, which constitutes a key intermediate form from weak artificial intelligence to strong artificial intelligence. The research in this field not only covers the innovation of basic theory and technology of artificial intelligence, but also needs to systematically examine the complex interaction among human, machine and environment. In highly dynamic decision-making scenarios such as military command, medical diagnosis and automatic driving, it is of profound theoretical significance and urgent practical value to explore the application of human-machine fusion intelligence. Such scenarios require the seamless integration of human intuition and situational reasoning ability with the computational accuracy and scalability of the machine, and this kind of collaboration is precisely what the current artificial intelligence system cannot achieve independently. This paper clarifies the core concepts and implementation paradigms of human-machine fusion intelligence, systematically reviews the research status in this field, and conducts in-depth discussions and prospects on the challenges faced by human-machine fusion decision-making and future research directions.

Keywords: artificial intelligence, human-machine fusion intelligence, human-machine cooperation, intelligent decision-making

1. Introduction

Human intelligence is rooted in the biological nervous system. It is a multi-dimensional cognitive ability accumulated through long evolution and continuous learning. Its core features include: first, autonomous learning and metacognitive reflection, which can extract rules from experience and improve their own behavior; second, logical reasoning and abstract thinking, good at dealing with open problems and high-level conceptual operations; thirdly, emotional intelligence and social cognition can deeply understand complex emotional states and cultural contexts. Fourth, creativity and imagination can break through the existing knowledge framework and produce original ideas and works. In contrast, artificial intelligence refers to the theory, method, technology and application system that simulates, extends and even expands human intelligence through computing systems [1-3]. Its fundamental goal is to enable machines to have human-like capabilities such as perception, reasoning, learning, decision-making, and natural interaction. Although artificial intelligence has shown a performance beyond human beings in specific cognitive tasks, it still has fundamental

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limitations in the internal drive of autonomous learning, the causality of logical reasoning, the context of emotional understanding and the uncertainty of creativity. These differences provide complementary space and research entry point for human-machine integrated intelligence.

The exponential growth of data volume, the significant improvement of computing power and the continuous breakthrough of computing theory have jointly driven the vigorous development of artificial intelligence technology, which in turn has given birth to emerging formats such as intelligent manufacturing, smart city, intelligent medical and intelligent military [4, 5]. However, while artificial intelligence brings unprecedented opportunities to various industries, it also exposes a series of fundamental challenges : high dependence on large-scale labeled data, inexplicability of learning and decision-making mechanisms, insufficient model robustness, and frequent factual illusions [6, 7]. These limitations are particularly prominent in security-critical complex decision-making scenarios, and relying solely on data-driven statistical associations has been difficult to meet reliable, controllable and interpretable intelligence needs. Therefore, it is urgent to systematically integrate human cognitive decision-making ability or humanoid cognitive model into artificial intelligence systems, and develop a new intelligent paradigm-human-machine fusion intelligence that integrates biological intelligence and machine intelligence. Human-machine fusion intelligence emphasizes the synergy between human intelligence and machine intelligence. Its core is to integrate the value judgment, empirical intuition and causal reasoning embodied by human beings in the decision-making process into the algorithm framework, and form an optimized decision-making mechanism with deep coordination between human intuition and machine probabilistic reasoning [8]. The evolution of human-machine integrated intelligence shows that the deep integration of human intelligence and machine intelligence is not only the core line of artificial intelligence development, but also one of the key trends to break through the current technical bottleneck.

In response to the above challenges, this paper systematically reviews the framework of human-machine fusion intelligence and its research status in typical application scenarios. Firstly, the general framework of human-machine fusion intelligent decision-making system is summarized and extracted, which provides a unified conceptual basis for understanding and designing collaboration modes in different situations. On this basis, this paper systematically introduces the representative applications of human-machine fusion intelligent decision-making in military command, medical diagnosis, automatic driving and other fields, and deeply analyzes its technical path and effect. Finally, we focus on the core bottlenecks such as interpretability, robustness, and trust calibration exposed in the current research, look forward to the research directions that may make breakthroughs in the future, and summarize the full-text work.

2. Human-machine fusion intelligent decision-making system framework

Although artificial intelligence technology has made significant progress, it is still difficult for the system to achieve reliable autonomy without human supervision under the constraints of deep factors such as imperfect trust mechanism and ethical norms to be established, especially in security-critical application scenarios [9]. This reality strongly calls for a new decision-making architecture that can deeply integrate human cognitive advantages with machine computing capabilities. To this end, this section summarizes the general framework of the human-machine integrated intelligent decision-making system, which consists of two core levels: situational awareness and collaborative decision-making. The situational awareness layer focuses on the acquisition and understanding of multi-source environmental information, integrates time series modeling, causal reasoning and interactive visualization technology, and conducts in-depth insight and interpretable representation of the current situation to provide a robust basis for subsequent decision-making. According to the

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nature of decision-making tasks and human-computer interaction, the collaborative decision-making layer flexibly adopts three modes : 'human-led decision-making', 'machine-led decision-making' and 'human-machine collaborative decision-making', which are applicable to different decision-making situations such as value sensitivity, real-time response and dynamic uncertainty, so as to achieve a balance between efficiency and risk.

2.1. Situation Awareness layer

The concept of Situation Awareness (SA) was first proposed by Endsley [10], an American psychologist. It was originally designed to describe how pilots perception of aircraft status and surrounding environment affects their decision-making behavior. This fundamental work establishes a three-level model of SA composed of situation awareness, situation understanding and situation prediction, and organically connects the cognitive levels through specific task situations. Subsequently, the JDL data fusion model further expands the functional model of situational awareness from the military field to a wide range of civilian scenarios, refines it into a five-level structure including fine processing and human-computer interaction, and explicitly introduces human-machine interfaces to enhance efficient collaboration between humans and intelligent systems. This evolution from individual cognition to human-machine collaborative perception provides a key theoretical cornerstone for the design of situational awareness layer in human-machine fusion intelligence. The following will systematically elaborate the core theories and technical methods involved in the situational awareness layer from the three dimensions of perception, fusion and analysis.

In the current multi-modal perception system, various modalities such as visual, auditory and biological signals have been widely used in the perception tasks of different scenes, which together constitute the basic form of multi-source information input. Among them, visual perception relies on imaging equipment to capture multi-band visual information and generate high-quality images, which plays a central role in environmental understanding. For example, Gao et al. [11] proposed a Single Shot Multibox Detector (SSD) gesture recognition method that combines spatial and channel attention mechanisms for the high uncertainty of gesture recognition under complex background and dynamic lighting conditions in the space station. This method maps the identified gesture position from the RGB image to the depth map, and further projects it into the remote robot operation space, realizing the precise coordination of human intention and robot action in dynamic interference.

Auditory perception realizes the deep recognition of emotional tendency and semantic content by extracting acoustic features such as rhythm and spectrum in speech signals, and carries important signal channel functions in multimodal human-computer interaction. For example, Abdolrahmani et al. [12] developed an auxiliary navigation system that integrates voice output and vibration feedback for airport indoor navigation scenarios, providing multi-channel path guidance for visually impaired people. In recent years, large language models (LLMs) represented by pre-trained language models such as Bidirectional Encoder Representations from Transformers and GPT series have shown close to or even surpass human performance in cross-task reasoning and natural language generation. However, these advances have not fundamentally eliminated the inherent challenges faced by auditory perception in actual deployment: the lack of robustness of far-field speech recognition in non-stationary noise environments, and the contextual recognition of emotional intonation is still highly dependent on limited labeled data and scene priors.

Biological signal perception captures the physiological signals and motion parameters of the human body through interactive devices such as brain-computer interfaces and exoskeletons, providing a key channel for human-machine fusion systems to directly perceive human intentions

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and real-time states. For example, the ' super Nyquist [13] developed by Carnegie Mellon University supports high-density neural signal acquisition, but it is susceptible to noise interference and the recognition accuracy is limited. At the same time, the economy, manufacturing convenience and later maintainability of the equipment constitute important constraints for large-scale applications. These constraints not only increase the access cost of the system, but also weaken the comfort and user compliance of long-term wear.

2.2. Collaborative decision-making layer

According to the inherent nature of decision-making tasks and the interaction between humans and machines in the decision-making loop, human-machine fusion intelligent decision-making can be divided into three typical modes : when the task is faced with high uncertainty and the environment is highly open and dynamically changing, human situational intuition and value judgment are still irreplaceable, and human-led decision-making should be adopted. When the task is in a low uncertainty and highly structured situation, the calculation accuracy and response speed of the machine have outstanding advantages, and the machine-oriented decision-making can be adopted. When the two sides of human and machine form complementary capabilities at the level of perception, reasoning and execution, it is necessary to adopt human-machine collaborative decision-making, and realize the integration of advantages through two-way information exchange and cognitive alignment.

Human-led decision-making constitutes a decision-making paradigm that deeply embeds human beings in the decision-making loop, fully releases their cognitive advantages, and ultimately provides high-value feedback and corrective signals for machines. For example, the Human-Cyber-Physical System (HCPS) framework proposed by Zhou et al. [14] is composed of human, intelligent information system and physical system. In this framework, the physical system acts as a task executor, and the information system undertakes the migration function of partial perception, analysis and decision-making ability to reduce human cognitive load and improve operational efficiency. Human beings always maintain the ultimate decision-making power and implementation control, and are in an irreplaceable dominant position. The core value of this kind of method is to pre-inject human causal reasoning and value trade-off into the decision-making model, so as to ensure the interpretability and ethical controllability of the decision-making chain in a highly uncertain task situation.

In the machine-dominated decision paradigm, the goal of the system is to reproduce and continuously optimize human decision-making strategies, so as to approach the high level of human intelligence. The core difference from human-led decision-making is that the role of human beings has shifted from real-time supervision and intervention to offline participation in model design and training. The fundamental challenge is how to make the cognitive reasoning and behavior patterns of the system deeply fit the real decision-making mechanism of human beings. For example, Li et al. [15] proposed a pedestrian-vehicle interaction method that combines Inverse Reinforcement Learning (IRL) and game modeling. Based on the generative adversarial imitation learning framework, the multi-agent game relationship between vehicles and pedestrians is explicitly modeled in the unsignalized intersection scenario. This method effectively improves the modeling accuracy of pedestrian intention inference and dynamic interaction behavior. This method provides an important technical path for the machine-led decision-making system to achieve trusted autonomous interaction without relying on real-time human intervention.

The human-machine collaborative decision-making paradigm takes the deep alignment of human and machine in value judgment and cognitive mechanism as the core, and emphasizes that the

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system can dynamically and adaptively optimize the collaborative strategy according to the environment. Through two-way cognitive coupling and continuous interaction, credible, interpretable and robust decision-making can be produced. For example, the concept of ' adjustable autonomy ' proposed by Zieba et al. [16], enables the system to dynamically adjust the human-machine collaboration strategy in real time according to changes in the external environment, the agent 's own load, and the overall collaboration efficiency, so as to build a human-machine integration intelligent framework with high situational adaptability. This paradigm not only seamlessly embeds human ethical judgments and value preferences into the decision-making loop, but also provides a structured mechanism for machines to actively seek human intervention in uncertain situations, which lays a methodological foundation for the reliable deployment of human-machine integration systems in safety-critical scenarios.

3. Application progress of human-machine collaborative decision-making

Human-machine collaborative enhanced intelligent control system has shown deep application potential in many safety-critical, high-dynamic and human-machine strong coupling fields. This paper focuses on representative scenarios such as medical, industrial and military, and systematically analyzes the key application paradigms of human-machine collaborative enhanced intelligence under real task constraints.

3.1. Intelligent military

In the military field, man-machine fusion intelligent decision-making has deeply penetrated into key directions such as task search and rescue, equipment intelligence, actual combat simulation training, and man-machine cooperative formation, showing a distinct trend from static function allocation to dynamic cognitive co-evolution. Taking UAV control as an example, the system generally adopts the 'dual-mode control' architecture: the optimal controller maintains high autonomous flight in the conventional cruise phase; once a high-value target is detected or a voice command is received, the control mode is seamlessly switched to operator guidance, fully integrating human situational intuition and decision flexibility. At the same time, the advanced haptic sharing control technology enables the operator to sense the intensity and direction of the wind field suffered by the drone in real time with the help of the force feedback handle. AI provides dynamic risk avoidance prompts synchronously, and builds a two-way transparent perception channel between human and machine at the physical interaction level. In high-risk decision-making links such as fire control, AI is responsible for locking targets and submitting authorization requests according to the rules of engagement, and the final decision-making power is absolutely retained in the hands of human operators. The weapon system must wait for its active confirmation before it can be unlocked. This design ensures the accountability and ethical security of key choices from the architectural level.

In addition, Bouras et al. [17] proposed an intelligent search and rescue system based on long-distance wireless communication technology (LoRa). They constructed a dynamic path prediction model by analyzing the gait characteristics and behavior patterns of missing persons, and introduced a multi-modal interaction architecture to organically integrate tactile feedback, physiological parameter monitoring and spatial location visualization of wearable devices to form a closed-loop collaborative search and rescue mechanism of "perception-decision-feedback." For autonomous surface ships, Huang et al. [18] designed a human-machine collaborative control framework that supports operator safety intervention and on-demand takeover, which effectively guarantees navigation safety in complex sea conditions. These cutting-edge practices jointly reveal the core

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values and challenges of building a human-machine integration system with adaptive collaboration, intention transparency and credible intervention capabilities in a highly dynamic and uncertain military mission environment.

3.2. Intelligent medical

In the medical field, human-machine integrated intelligent decision-making is gradually developing into a key enabling technology to improve the safety of diagnosis and treatment and the quality of patient care. It has been widely used in core scenarios such as surgical assistance, rehabilitation treatment and clinical decision support system (CDSS). This paradigm integrates the situational judgment of clinical experts with the accurate calculation of machines, and promotes the evolution of medical decision-making from a single experience dependence to a human-machine co-intelligence model driven by data and knowledge. The micromanipulator developed by Li et al. [19] deeply integrates human operation intention and machine precise control in microsurgical suture, effectively suppresses physiological hand tremor, and significantly improves the stiffness and accuracy of fine operation. Cai et al. [20] proposed Individualized Interval-valued Decision Rules, which can adaptively allocate the optimal dosage and dosing interval by considering the patient 's dynamic state, drug efficacy and potential side effects. These work together reveal that in a highly dynamic and safety-critical medical context, building an intelligent decision-making system with interpretability, personalized adaptation, and seamless collaboration capabilities is not only a core challenge, but also the only way to a trusted human-machine integrated medical system.

3.3. Intelligent driving

In the field of intelligent driving, human-machine fusion intelligent decision-making mainly focuses on driver assistance systems, covering core tasks such as driver status monitoring, path planning and steering control. Through the analysis of large-scale real driving data, Wang et al. [21] deeply capture and analyze the driver 's decision-making behavior in diverse scenarios, so that the automatic driving system can adapt to complex road conditions and dynamic traffic environment more accurately. Hu et al. [22] constructed a safe driving decision-making method based on cascade imitative learning network, using sensor data to extract key operational features in dangerous scenes such as collision and rollover, so as to realize early prediction and active avoidance of risks. In general, the human-machine fusion decision-making technology for intelligent driving is rapidly evolving, and has expanded from a single driving assistance to human-machine co-driving and highly autonomous collaboration. In line with this trend, Chinese and foreign technology companies such as Tesla, Baidu, Huawei and Xiaomi are actively promoting the development and large-scale implementation of related technologies. In the future, how to realize the seamless transition from human-machine cooperative driving to trusted autonomous driving under the premise of ensuring absolute safety will become the core issue that needs to be broken through in this field.

4. Conclusion

In the present work, we review the research progress of human-machine integrated intelligent decision-making, summarizes the two-layer framework with the closed-loop of ' perception-understanding-decision ' as the core, extracts three typical paradigms of human-led, machine-led and human-machine collaboration, and analyzes their applications in safety-critical fields such as military, medical and driving. At present, cognitive alignment, interactive robustness and dynamic

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decision switching are still the core challenges. Future research should focus on deep alignment of human-machine value, adaptive coordination mechanism, robust multi-modal perception and interpretable trustworthiness evaluation, promote human-machine integration from assistance to deep cognitive communion, and finally build an enhanced intelligent system with trustworthiness and situational flexibility.

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