Current Status and Development Trends of Research on Autonomous Decision-Making Methods for Unmanned Swarms

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Abstract. Autonomous decision-making has the advantages of strong information processing ability, fast response, and high cost-effectiveness, which is a key technical support for achieving unmanned, clustered, and intelligent combat. Firstly, clarify and sort out the basic concepts of autonomous decision-making in unmanned clusters and the development history of major countries and regions. Subsequently, in line with the trend of modern combat style transformation, combined with the main technical methods, the basic working principles of autonomous decision-making were analyzed in depth, mainly involving multi-source information fusion, battlefield situation assessment, task allocation optimization, and cluster path planning. Finally, the future development trends of autonomous decision-making methods were analyzed from the perspectives of enhancing intelligence, improving adaptability, enhancing system stability and sound security.
Keywords. autonomous decision-making; information fusion; situation assessment; task allocation; path planning

Introduction

In the military and civilian domains of the 21st century, unmanned intelligent swarm systems are progressively showcasing their pivotal role, particularly in intricate and hazardous environments, demonstrating substantial potential and value [1]. Autonomous decision-making, characterized by robust processing capabilities, rapid responses, and high efficiency, empowers unmanned swarm systems to function in complex and dynamic environments independently, without direct human intervention [2]. They can autonomously adapt, allocate, coordinate, plan, and control, which has emerged as a crucial factor in the effective execution of tasks by unmanned systems. This significantly enhances task performance and diminishes the risks of human casualties in increasingly intricate and volatile combat scenarios as well as everyday applications [3].

Basic Concepts and Development History

Basic Concepts

Unmanned group autonomous decision-making entails the collaborative completion of intricate tasks by unmanned systems. This process operates autonomously, responding in real-time to environmental shifts, devoid of direct human intervention [6]. It encompasses various technical disciplines, including machine learning, artificial intelligence, multi-agent systems, and adaptive control. Its aim is to enhance task execution efficiency, flexibility, and resilience, particularly in unpredictable and dynamic settings [7].

Development History

A. America

B. Europe

C. Asia

In the early 21st century, research in the field of autonomous decision-making in Asia commenced comparatively later, characterized by a modest level of sophistication. Primarily, emphasis was placed on traditional control theory and algorithms, overlooking a thorough investigation into collaborative decision-making among multi-agent systems within intricate environments [12]. Over time, research endeavors gradually pivoted towards unmanned swarm autonomous decision-making methods. Successively, several nations established dedicated research institutions to delve into theoretical underpinnings and technological advancements in this domain, with a specific focus on fostering more intelligent and self-reliant unmanned swarm systems, as shown in Fig.1. In recent years, significant strides have been made by various countries in applying continuous theoretical innovation and technological breakthroughs across multiple sectors, thus emerging as a pivotal force in global research concerning unmanned swarm autonomous decision-making methods [13].

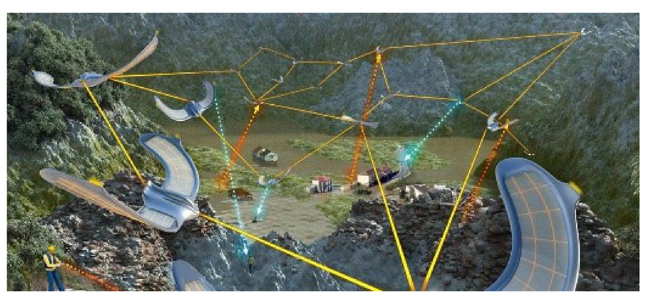

Figure 1. Schematic diagram of unmanned cluster application

D. Middle East

Basic Principles

Multi-source information fusion

A. Improving the Kalman filter

B. Deep learning

The integration of deep learning within multisource information fusion aims to harness the complementarity among various sensors and data sources to enhance the decision accuracy and robustness of autonomous systems [18]. Typically, data from multiple sensors undergo a sequence of processes including standardization, denoising, and feature extraction to establish a comprehensive perceptual environment for autonomous system analysis and decision-making, as shown in Fig.2. Features extracted from diverse information sources are subsequently merged, with these features being automatically learned and extracted through hierarchical structures in multilayer neural networks [19]. Yiannis Demiris, of Imperial College London, has devised deep learning algorithms for multisource information and sensor fusion, accentuating their application in adaptive and interactive learning. Nonetheless, mitigating the reliance on extensive datasets in complex robotic applications persists as a challenge.

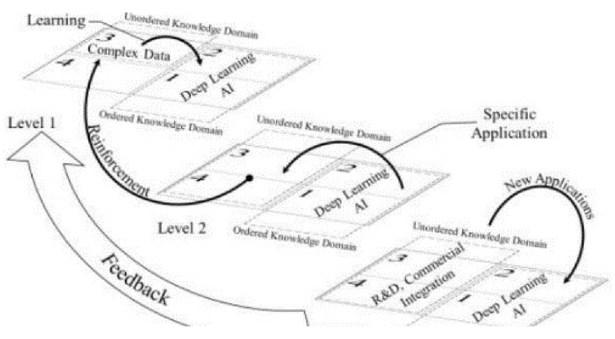

Figure 2. Schematic diagram of deep learning principles

Battlefield situation assessment

A. Fusion Bayesian networks

B. Knowledge graphs

A knowledge graph effectively organizes information via a graph structure, portraying entities as nodes and their interconnections as edges, as shown in Fig.3. Within the domain of unmanned swarm situational assessment, knowledge graph methodologies amalgamate diverse information reservoirs to establish a comprehensive knowledge framework that mirrors the drone swarm and its operational milieu [21]. The Chinese Academy of Sciences' Institute of Automation integrates environmental characteristics, task requirements, object relationships, and other pertinent information into knowledge graphs, allowing unmanned swarms to gain a more precise understanding of their operational environment.

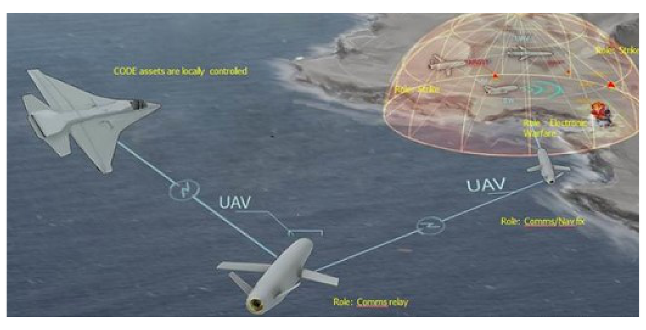

Figure 3. Schematic diagram of nodes and edges

Task Allocation Optimization

A. Market auction methods

B. Game theory

Cluster path planning

A. Image search methods

B. Bionic algorithms

Bio-inspired algorithms belong to a class of algorithms inspired by behaviors in nature, commonly used for solving path planning challenges for drone clusters. They derive insights from social behaviors and evolutionary mechanisms in the natural world to determine one or multiple optimal paths from the starting point to the destination. Particle swarm optimization mirrors the collective behaviors of birds and fish, as shown in Fig.4. Drone particles update their positions by emulating optimal peers and drawing from their own successful experiences, guiding the swarm toward an optimal state [25]. Yoshua Matsuo from the University of Tokyo advanced drone formation flight and complex maneuver coordination through bio-inspired algorithms, employing particle swarm optimization algorithms to enhance path planning efficiency and minimize conflicts and collisions.

Figure 4. Schematic diagram of unmanned cluster imitating biological particle swarm

Future development trends

Enhance intelligence level

Improve adaptability

Enhance stability

In high-intensity interference environments, ensuring the stability and reliability of unmanned swarm systems poses a significant challenge. The ability to resist interference is paramount for maintaining effective operation amidst hostile or natural disruptions. Techniques like frequency hopping and spread spectrum communication enhance resistance to signal interference, while deploying multiple communication methods, such as optical or acoustic communication, serves as alternative means. Real-time deployment of sensors and monitoring systems enables the detection of interference intensity and type, as shown in Fig.5, while predictive models forecast interference trends and impacts, facilitating timely adjustment of anti-interference strategies.

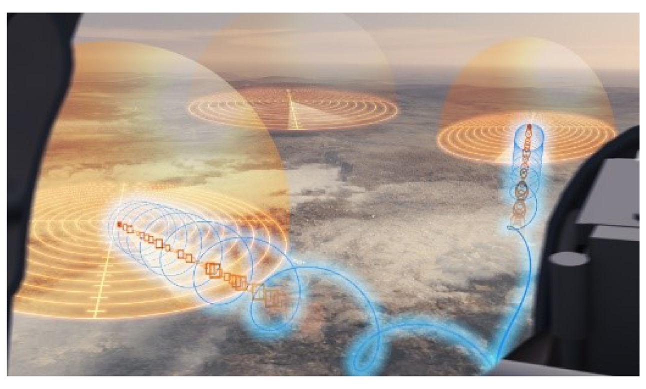

Figure 5. Schematic diagram of adaptive anti radar interference

Establish sound security mechanisms

Future development trends

Unmanned swarm autonomous decision-making technology plays a critical role in the development of unmanned, clustered, and intelligent systems. It synthesizes cutting-edge research in artificial intelligence, information fusion, autonomous control, and related disciplines, offering substantial economic and military benefits. This paper reviews current research to highlight the distinctive features and emerging trends in this area globally. It delves into the core principles of prevalent techniques in multi-source information fusion, battlefield situation analysis, task allocation optimization, and swarm trajectory planning. The goal is to furnish insights and stimulate further investigation into more intelligent, adaptable, and robust decision-making strategies that enhance security.