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Editorial

Institutionalized and systematized gaming for multi-agent systems

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Multi-agent system gaming (MASG) is widely applied in military intelligence, information networks, unmanned systems, intelligent transportation, and smart grids, exhibiting systematic and organizational characteristics. It requires the multi-agent system perceive and act in a complex dynamic environment and at the same time achieve a balance between individual interests and the maximization of group interests within the system. Some problems include complex system structure, uncertain game environment, incomplete decision information, and unexplainable results. As a result, the study of multi-agent game has transformed from a traditional simple game to a game facing a high-dimensional, continuous, and complex environment, which prompts an urgent need for institutionalized and systematized gaming (InSys gaming). With this background, several important tendencies have emerged in the development of InSys gaming for multi-agent systems:

1. Analyzing the evolution law of MASG and establishing the InSys gaming theory model for multi-agent systems

The organized and systematic MASG has orderly and structured characteristics, so it is necessary to establish a system game model. To study political, military, economic, and other systemic confrontation gaming problems, the first step is to analyze the system's internal evolution characteristics and external interaction information. In addition, establishing the evolution model of InSys gaming and studying the elements, relationships, and criteria of the game evolution help provide theoretical support for the system design, decision-making planning, and other research in this field.

2. Combining several artificial intelligence learning algorithms to achieve collaborative decision-making of multi-agent systems

The current mainstream artificial intelligence learning methods all have application advantages in specific scenarios. In solving InSys gaming problems, we can combine the environmental representation ability of deep learning and the decision generation ability of reinforcement learning (RL). For example, by building a digital simulation training environment, intelligent decision algorithms and unsupervised training methods can be designed to generate a multi-agent system's collaborative decision in a complex and unknown environment.

3. Adopting a hierarchical task planning and decision-making action architecture to reduce the complexity of collaborative decision-making algorithms

With the increase of the scale of multi-agent systems, the problems of node coupling, observation uncertainty, and interaction disorder faced by collaborative decision-making have become increasingly prominent. The complexity of solving its systematic and organized game problems has increased significantly.

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A multi-agent hierarchical algorithm architecture is constructed through game task decomposition, long-term planning, and real-time action decision-making. It can effectively reduce the complexity of the search process of a collaborative decision-making algorithm. In addition, it is a feasible idea for solving an organized and systematic game.

4. Establishing the robustness analysis framework of the algorithm model to solve the model deviation between data-driven methods and the actual scene

When the training data deviates from the actual scene for data-driven methods, the algorithm's performance will be degraded. Thus, it is necessary to study the robustness analysis framework of data-driven methods. For example, a robust algorithm model and an actual data fine-tuning method are designed to reduce the performance loss of the trained algorithm. This strategy helps support the actual deployment of data-driven methods.

Game theory has become a basic analytical framework for solving problems in strategic politics, military confrontation, market economy, and so on. The object of analysis is characterized by complex systematization and organization and has been highly concerned with and valued by academic and industrial circles alike. A multi-agent system is used to model the organized and systematic game, combined with an artificial intelligence method to solve the game decision-making problem, providing a new idea for developing theories, methods, and technologies in this field.

In this context, the journal *Frontiers of Information Technology & Electronic Engineering* has organized a special feature on institutionalized and systematized gaming (InSys gaming) for multi-agent systems. This special feature covers multi-agent evolutionary game, unmanned aerial vehicle (UAV) formation control, autonomous multi-agent planning, collaborative control, swarm intelligence, and multi-agent RL framework design. After a rigorous review process, eight papers have been selected, including two perspective articles and six research articles.

Jun LU and his collaborators explored the existence and practice of games from the understanding process of gaming, elaborating the difficult problems of a complex and changing environment, dynamic heterogeneity of systems, and limited computational and perceptual capabilities of a single individual in multi-intelligence games, and proposed a theoretical framework of multi-intelligence, multi-agent evolutionary games. Multi-agent evolutionary game application practice was introduced with the next-generation early warning and detection system as an example, which is essential for studying organized and systematic game behavior in a high-dimensional complex environment.

To provide a quick overview of multi-agent study with a particular focus on agent collaboration and gaming, You HE and his collaborators reviewed multi-intelligence collaboration and gaming technologies from three perspectives: task challenges, technical directions, and application areas. Therein, typical research problems and challenges in recent work on multi-agent systems were analyzed, some promising research directions on multi-agent collaboration and gaming tasks were discussed, and the outlooks on the application directions in this field were given.

Multi-agent cooperative games provide an effective tool for studying multi-agent optimal control problems, relying on solving the coupled Hamilton–Jacobi (HJ) equations. Hongyang LI and Qinglai WEI proposed a new optimal synchronization control method with input saturation to address the coupled HJ equations that limit the applications of cooperative game theory in synchronization control problems. They transformed the optimal synchronization control problem into a multi-agent nonzero-sum game problem by introducing the multi-agent theory and then solved the Hamilton–Jacobi–Bellman (HJB) equation with a non-quadratic input energy term to achieve the Nash equilibrium. Meanwhile, they proposed a new model-free off-policy RL method that allows the iterative control rate to converge to the Nash equilibrium without considering the system model information, and provided methodological support for simultaneous control of the multi-agent system with saturated inputs.

Haibin DUAN and his collaborators investigated a distributed game strategy for UAV formation with external disturbances and obstacles. Their strategy involves a distributed model predictive control (MPC) framework and Levy flight based pigeon inspired optimization (LFPIO). First, they proposed a non-singular fast terminal sliding mode observer (NFTSMO) to estimate the influence of disturbances. Second, a distributed MPC framework was established, where each UAV exchanges messages only with its neighbors. Moreover, the cost function of each UAV was designed, by which the UAV formation problem was transformed into a game problem. Finally, LFPIO was developed to solve the Nash equilibrium. Numerical simulation was conducted, and the efficiency of LFPIO-based distributed MPC was verified through comparative experiments.

Multi-agent RL is challenging in practice, partially because of the gap between simulated and real-world scenarios. Jian ZHAO and his collaborators derived a formal concept of a cooperative multi-agent RL system with unexpected crashes to address this problem. They designed a virtual coach-assisted multi-agent RL framework, which can further stimulate the phenomenon that agents in actual operation may "crash" unexpectedly during coordination, and provided a research framework for solving the discrepancies between multi-agent system simulation and the reality.

Xiwang DONG and his collaborators investigated the multi-agent differential game problem and its application in cooperative synchronization control. A systematic design and analysis method of multi-agent differential game was presented, and a data-driven approach based on RL technology was given. First, it was established that distributed controllers have difficulty reaching the global Nash equilibrium for differential games due to the coupling of networked interactions. Second, alternative local Nash solutions were derived by decomposing the game problem and defining the concept of best response. An off-policy RL algorithm using adjacent interaction data was then constructed to update the controller without a system model, demonstrating stability and robustness. A global Nash equilibrium was achieved by modifying the differential game configuration of the coupled exponential functions. At the same time, distributed cooperative control ensured stability, and an equivalent parallel RL method was developed. Simulation results illustrated the effectiveness of the learning process and the strength of synchronous control.

Sliding mode control (SMC) has significant advantages against system uncertainty and the influence of external disturbances, especially for the closed-loop system. Ruizhuo SONG and his collaborators developed a new consistency control scheme for the finite-time leader-follower consensus of discrete second-order multi-agent systems under external disturbance constraints. The traditional sliding-mode convergence law was used to create the adaptive controller, which can effectively reduce the jitter and invariance phenomena of perturbations. At the same time, finite-time stability was proved using discrete Lyapunov functions, which provides theoretical support for the solution of the consistency problem of infinite time for multiple intelligence.

The cooperative multi-agent planning problem is one of the representative tasks that can reflect the coordination and cooperation ability of multi-agent systems. Weining LU and his collaborators combined the graph neural network (GNN) with a task-oriented knowledge fusion sampling method to address this problem. They proposed a new collaborative planning architecture which can build a general model for the collective planning of any number of agents, and designed a task-oriented sampling method aggregating available knowledge from specific directions. This strategy provides a research framework for multi-agent game collaborative planning problems in unknown complex environments.

Overall, a broad spectrum of current research topics relevant to the theory and techniques of InSys gaming are covered in this special feature, from multi-agent system gaming theory and application to InSys gaming methods and others. We hope that this collection of diverse but interconnected topics will benefit those interested in InSys gaming or related areas.

Finally, we would like to express our special gratitude to the authors and reviewers for their support and valuable contributions to this special feature, the Editors-in-Chief Profs. Yunhe PAN and Xicheng LU, and the editorial staff.

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