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Adaptive Controllable Emergence in Multi-Task Air and Space Defense Systems: A Framework for Mission Reconfiguration, Resilient Coordination, Intelligent Decision-Making, and Dynamic Resource Allocation

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ABSTRACT

Coordinating heterogeneous agents under changing mission requirements remains a central challenge in multi-task air and space defense systems, particularly when information is incomplete, resources are constrained, and communication is disrupted. This study introduces an Adaptive Controllable Emergence (ACE) framework and experimentally examines how local agent interactions support coordinated system-level behavior. The framework integrates dynamic mission reconfiguration, resilient coordination, intelligent distributed decision-making, and dynamic resource allocation within a unified architecture. A time-varying interaction graph represents sensing, decision, and execution agents, allowing their relationships and task assignments to adapt to changes in mission demand, network connectivity, and resource availability. Agent decision-making is formulated as a decentralized partially observable Markov decision process, with multi-agent reinforcement learning used to establish adaptive local policies. A multi-objective reward function jointly accounts for mission completion, coordination quality, resource utilization, network resilience, adaptation cost, and decision latency. Experimental assessment covers stable operating conditions, changing mission demands, concurrent tasks, and degraded communication. Performance is evaluated through mission completion, adaptation speed, coordination robustness, resource efficiency, and decision latency. The investigation links agent-level adaptation to collective system behavior, providing an empirical basis for examining controllable emergence as a continuous process of coordinated adjustment in heterogeneous multi-agent systems.

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1. INTRODUCTION

Emergence describes a class of phenomena in which interactions among relatively simple components generate collective properties at a higher level of organization. In complex systems, the global behavior of a system cannot necessarily be obtained by simply adding the properties of its individual components. Instead, interactions, feedback, network topology, adaptation, and environmental changes jointly determine the resulting macroscopic behavior [1].

This concept has become increasingly important in multi-agent systems. A collection of autonomous agents may follow local rules while collectively producing coordinated behavior such as distributed exploration, formation, task allocation, consensus, or adaptive resource utilization. Research on multi-agent reinforcement learning has further demonstrated that agents can learn cooperative policies from local observations while optimizing a shared objective [2]. Modern MARL research explicitly addresses the difficulty created by large joint observation and action spaces, partial observability, and the non-stationarity introduced by simultaneously learning agents [3].

Large-scale air and space defense systems provide a representative complex-system environment for investigating controllable emergence. Such systems can be abstracted into heterogeneous sensing, decision, communication, and execution resources [4]. The system must continuously transform distributed information into coordinated system-level responses while coping with changes in the environment, mission priorities, communication conditions, and resource availability [5].

The controllable-emergence paradigm provides a structured way to model collective behavior by defining the governing rules of individual agents and their interactions. Nevertheless, its applicability can become limited in dynamic environments where multiple tasks are executed concurrently and task priorities evolve over time. A configuration designed to perform effectively under a particular task arrangement may no longer provide the same level of efficiency when additional tasks are introduced, available resources change, or the underlying interaction structure is modified. These dynamic conditions highlight the need for more adaptive mechanisms capable of maintaining effective collective behavior as task requirements and system conditions evolve [6].

Consequently, four additional capabilities are required.

First, the system needs **mission reconfiguration**. The allocation of agents to tasks should not remain fixed throughout the mission. Instead, the task-agent relationship should be dynamically reconstructed according to the current task set and system state [7].

Second, the system requires **resilient coordination**. The interaction network should remain functional when communication links become temporarily unavailable or when some agents cannot participate. Communication-based MARL research emphasizes that communication mechanisms can improve coordination by expanding agents' effective information and supporting collaboration under decentralized decision-making [8].

Third, the system requires **intelligent decision-making**. Fixed rules cannot adequately represent every possible combination of task, environment, resource, and network states. MARL provides a natural framework in which agents learn policies from interactions with an environment. Modern treatments of MARL cover decentralized policies, cooperative learning, game-theoretic interaction, and the computational challenges associated with multi-agent decision-making [9].

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Fourth, **dynamic resource allocation** must be incorporated. When multiple tasks compete for limited sensing, communication, computational, or execution resources, the system should allocate resources according to current mission requirements rather than relying on static assignment [10].

Based on these considerations, this study develops an adaptive controllable-emergence framework that integrates the four mechanisms into a unified graph-based multi-agent architecture.

The main contributions are as follows:

1. A time-varying graph model is developed to represent heterogeneous multi-agent interactions.
2. A dynamic mission-reconfiguration mechanism is introduced to modify task-agent relationships according to system conditions.
3. A resilient coordination mechanism is formulated for maintaining functional cooperation under changing communication topology.
4. A multi-objective MARL formulation is developed for intelligent distributed decision-making.
5. Dynamic resource allocation is incorporated directly into the emergence objective.
6. A quantitative evaluation framework is proposed for measuring emergence quality, adaptation speed, coordination robustness, resource utilization, and convergence.

The central hypothesis is that **controllable emergence should be treated as an adaptive system-level optimization problem rather than as a fixed rule-design problem**.

2. System Architecture and Problem Formulation

2.1 Multi-Agent System Representation

Let the multi-agent system at time **t** be represented by a time-varying graph

$$G(t) = (V, E(t)),$$

Where

$$V = V_S \cup V_D \cup V_J$$

represents the set of heterogeneous agents.

Here:

- V_S: sensing agents;
- V_D: decision agents;

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- V_J: execution agents.

The interaction relationship between agents is represented by the edge set $E(t)$. Unlike a static graph, $E(t)$ changes according to communication conditions, mission requirements, resource availability, and agent states.

Each agent has a local state

$$s_i(t) \in S_i,$$

and the global system state is

$$S(t) = [s_1(t), s_2(t), \ldots, s_N(t)].$$

The state may include abstract variables such as:

$$s_i(t) = [x_i(t), r_i(t), c_i(t), m_i(t), b_i(t)],$$

where denotes the agent's system state, its available resource capacity, its communication status, its current mission assignment, and its operational status.

This representation intentionally remains platform-independent and describes the computational structure rather than a specific operational system.

2.2 Three-Layer Agent Architecture

The proposed architecture is organized into a three-layer framework that provides a structured basis for coordinating the system's functional components.

2.2.1 Sensing Layer

A sensing agent observes environmental information and generates an observation:

$$o_i^S(t) = h_i(S(t), E(t)) + \epsilon_i(t),$$

where $h_i(\cdot)$ is the observation function and $\epsilon_i(t)$ represents observation uncertainty.

The sensing layer provides information to decision agents through available communication links [11].

2.2.2 Decision Layer

Decision agents integrate local observations and information received from neighboring agents:

$$o_i^D(t) = \mathcal{O}_i\left(s_i(t), \{s_j(t) : j \in N_i(t)\}\right).$$

The decision agent selects an action according to policy

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$$a_i(t) \sim \pi_{\theta_i}(a_i|o_i(t)).$$

2.2.3 Execution Layer

Execution agents receive abstract task assignments and update their states according to the assigned task:

$$s_i(t+1) = F_i(s_i(t), a_i(t), \omega_i(t)),$$

where $\omega_i(t)$ represents environmental uncertainty.

2.3 Dynamic Interaction Graph

Connectivity is established through local interaction rules, while a dynamic connectivity score is introduced to quantify and regulate changes in the strength and availability of inter-agent connections.

For two agents i and j, define

$$\Gamma_{ij}(t) = w_1 C_{ij}(t) + w_2 R_{ij}(t) + w_3 M_{ij}(t) + w_4 Q_{ij}(t),$$

where:

- C_{ij}: communication compatibility;
- R_{ij}: resource compatibility;
- M_{ij}: mission relevance;
- Q_{ij}: estimated coordination quality.

An edge is retained when

$$\Gamma_{ij}(t) \geq \tau_E.$$

Thus,

$$E(t) = \{(i,j) : \Gamma_{ij}(t) \geq \tau_E\}.$$

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The network dynamically adapts its structure in response to changing system conditions.

3. Mathematical Model of Controllable Emergence

3.1 Individual State Transition

For each agent i, define

$$S_i(t+1) = f_i\left(S_i(t), I_i(t), a_i(t)\right),$$

Where $I_i(t)$ is the information received from neighboring agents.

The complete system evolves according to

$$S(t+1) = F(S(t), A(t), G(t), \Omega(t)),$$

where $A(t)$ represents the joint action and $\Omega(t)$ represents environmental conditions.

The emergence process is therefore

$$S(0) \to S(1) \to \cdots \to S(T).$$

The macroscopic system behavior is a function

$$Y(t) = \Phi(S(t), G(t)).$$

The objective is not merely to optimize individual actions but to construct local policies such that

$$Y(t) \to Y^*,$$

Where **Y*** represents a desirable system-level state.

4. Multi-Task Mission Model

4.1 Task Set

At time **t** , let the set of active tasks be

$$\mathcal{M}(t) = \{M_1, M_2, \ldots, M_K(t)\}.$$

Each task is represented by

$$M_k = (\rho_k, \delta_k, \kappa_k, \sigma_k),$$

where:

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- ρ_k: task priority;
- δ_k: temporal requirement;
- κ_k: required resource profile;
- σ_k: current task status.

The number of tasks is time-varying:

$$K(t) \neq K(t + \Delta t).$$

This study develops an adaptive framework with integrated dynamic mechanisms that enable the model to adjust its behavior as system conditions evolve.

4.2 Mission Reconfiguration

Let

$$Z(t) = [z_{ik}(t)]$$

be the task-agent assignment matrix, where

$$z_{ik}(t) = \begin{cases} 1, & \text{agent } i \text{ is assigned to task } k, \\ 0, & \text{otherwise.} \end{cases}$$

The assignment is constrained by

$$\sum_k z_{ik}(t) \leq C_i,$$

where C_i represents the maximum concurrent task capacity of agent $i.$.

A task must also receive sufficient collective resources:

$$\sum_i z_{ik}(t) r_i(t) \geq R_k^{req}(t).$$

The mission-reconfiguration objective is

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$$\min_{Z} \left[\lambda_1 C_{\text{reconfig}} + \lambda_2 C_{\text{delay}} + \lambda_3 C_{\text{imbalance}}\right].$$

Here, C_{reconfig} represents the cost of changing assignments.

This prevents excessive reassignment and therefore avoids unstable oscillations in mission structure.

5. Resilient Coordination Mechanism

5.1 Communication Degradation

Let

$$c_{ij}(t) \in [0, 1]$$

represent the quality of the communication relationship between agents i and j.

The effective adjacency matrix is

$$A_{ij}(t) = \begin{cases} 1, & c_{ij}(t) \geq \tau_c, \\ 0, & \text{otherwise.} \end{cases}$$

The network therefore changes dynamically:

$$G(t) \to G(t+1).$$

The objective is to preserve sufficient connectivity for distributed decision-making rather than requiring an unchanged topology.

5.2 Resilient Coordination Index

Define

$$R_C(t) = \alpha_1 C_G(t) + \alpha_2 I_G(t) + \alpha_3 P_G(t),$$

where:

- C_G: connectivity measure;
- I_G: information availability;
- P_G: policy-consistency measure.

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The overall resilience score is

$$R = \frac{1}{T}\sum_{t=1}^{T} R_C(t).$$

A resilient system should maintain a high despite moderate changes in network structure.

Recent MARL research increasingly considers communication as a mechanism for improving coordination, while graph-based communication provides a natural representation of changing inter-agent relationships [12].

6. Intelligent Decision-Making Based on MARL

6.1 Decentralized Partially Observable Model

Because an individual agent cannot generally observe the complete system state, the proposed framework uses a decentralized partially observable formulation [13].

For agent i,

$$o_i(t) = O_i(S(t), G(t)).$$

The policy becomes

$$a_i(t) = \pi_{\theta_i}\left(o_i(t), h_i(t)\right),$$

where $h_i(t)$ represents the agent's historical information.

The joint policy is

$$\boldsymbol{\pi} = (\pi_1, \pi_2, \ldots, \pi_N).$$

The system objective is

$$\max_{\boldsymbol{\pi}} \mathbb{E}\left[\sum_{t=0}^{T} \gamma^t R(t)\right].$$

7. Multi-Objective Reward Function

This study formulates a multi-objective reward function that jointly captures the system's operational priorities and guides adaptive decision-making under changing conditions.

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We define

$$R(t) = w_M R_M(t) + w_C R_C(t) + w_R R_R(t) + w_A R_A(t) + w_D R_D(t) - w_L C_L(t).$$

The components are:

Mission performance

$$R_M(t) = \frac{\sum_k \rho_k I_k(t)}{\sum_k \rho_k},$$

where $I_k(t)$ measures task completion progress.

Coordination

$$R_C(t) = \frac{1}{N} \sum_i Q_i(t).$$

Resource efficiency

$$R_R(t) = 1 - \frac{R_{\text{unused}}(t)}{R_{\text{available}}(t) + \epsilon}.$$

Adaptation

$$R_A(t) = 1 - \frac{C_{\text{reconfig}}(t)}{C_{\max} + \epsilon}.$$

Decision quality

$$R_D(t) = 1 - \frac{C_{\text{decision}}(t)}{C_{\max} + \epsilon}.$$

The penalty term

$$C_L(t)$$

represents unnecessary latency or instability.

Thus, the system seeks a balanced solution rather than maximizing a single metric.

8. Dynamic Resource Allocation

Let the available resources be

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$$\mathcal{R}(t) = \{r_1(t), r_2(t), \ldots, r_N(t)\}.$$

For task M_k, let the required resource vector be

$$R_k^{req}(t).$$

The allocation matrix is

$$X(t) = [x_{ik}(t)].$$

The constraints are

$$x_{ik}(t) \geq 0,$$

And

$$\sum_k x_{ik}(t) \leq r_i(t).$$

The allocation objective can be expressed as

$$\max_X \sum_k \rho_k U_k(X,t) - \lambda_X C_X(X,t),$$

where U_k represents task utility and C_X represents resource-allocation cost.

This formulation allows resources to move between tasks as the system state changes.

9. Adaptive Mission-Reconfiguration Algorithm

The proposed framework operates through five stages.

Stage 1: State perception

Agents collect local observations:

$$o_i(t) = O_i(S(t), G(t)).$$

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Stage 2: Mission evaluation

The system evaluates

$$\mathcal{M}(t)$$

and determines whether the existing task structure remains suitable.

Stage 3: Reconfiguration

If

$$D_M(t) > \tau_M,$$

where D_M represents mission-structure deviation, the assignment matrix is $Z(t)$ updated.

Stage 4: Resource redistribution

The resource allocation matrix $X(t)$ is recomputed.

Stage 5: Policy execution

Each agent selects

$$a_i(t) \sim \pi_{\theta_i}.$$

The resulting system state is then evaluated and fed back into the learning process.

This produces the closed loop

$$\boxed{\text{Observation} \rightarrow \text{Mission Evaluation} \rightarrow \text{Reconfiguration} \rightarrow \text{Resource Allocation} \rightarrow \text{Coordination} \rightarrow \text{Action} \rightarrow \text{Emergence Evaluation}}$$

10. Adaptive Controllable-Emergence Framework

The complete architecture can be summarized mathematically as

$$\mathcal{E}(t) = \mathcal{F}\left[G(t), Z(t), X(t), \boldsymbol{\pi}(t), S(t)\right].$$

The desired emergent state satisfies

$$\mathcal{E}(t) \rightarrow \mathcal{E}^*.$$

This study introduces a new framework that

$$G(t), Z(t), X(t), \boldsymbol{\pi}(t)$$

are all time-dependent.

Therefore, the proposed system is an **adaptive controllable-emergence system**.

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Its core principle can be written as

$$\boxed{\text{Local Adaptation} + \text{Dynamic Interaction} + \text{Resource Reallocation} \Rightarrow \text{Controllable Global Emergence}}$$

11. Value Decomposition for Cooperative Decision-Making

For cooperative agents, a joint value function can be decomposed as

$$Q_{\text{tot}} = f(Q_1, Q_2, \ldots, Q_N).$$

Value decomposition is useful because the joint action and observation spaces can become very large as the number of agents increases. VDN introduced the idea of decomposing a team value function into agent-wise value functions [14], while QMIX later provided a monotonic factorization enabling decentralized execution from locally conditioned agent values. [15].

Accordingly, The ACE framework employs

$$Q_{\text{tot}} = f_\phi(Q_1, \ldots, Q_N, S),$$

during centralized training while retaining

$$a_i = \arg\max_{a_i} Q_i(o_i, a_i)$$

during decentralized execution.

This separation reduces the computational burden associated with directly optimizing the full joint action space.

12. Graph-Based Communication and Coordination

A graph neural representation can be used to aggregate neighboring information.

For agent i,

$$h_i^{(l+1)} = \sigma\left(W_0 h_i^{(l)} + \sum_{j \in N_i} W_1 h_j^{(l)}\right).$$

The resulting representation is

$$h_i^* = \text{GNN}(G(t), o_i(t)).$$

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The policy becomes

$$\pi_i(a_i|h_i^*).$$

This design allows the policy to depend on local network structure rather than on a fixed number of agents.

This is particularly important because graph-based communication has become an active research direction in MARL, with recent surveys specifically examining how graph neural networks can represent and learn communication structures among agents.

13. Adaptive Policy Update

The policy parameters are updated according to

$$\theta_i^{t+1} = \theta_i^t + \eta \nabla_{\theta_i} J(\theta_i).$$

However, because the environment changes, the objective is not simply

$$J(\theta).$$

Instead,

$$J = J(\theta, G, Z, X, \mathcal{M}).$$

Consequently,

$$\frac{dJ}{dt} = \frac{\partial J}{\partial \theta}\frac{d\theta}{dt} + \frac{\partial J}{\partial G}\frac{dG}{dt} + \frac{\partial J}{\partial Z}\frac{dZ}{dt} + \frac{\partial J}{\partial X}\frac{dX}{dt}.$$

This equation highlights an important property of the proposed framework: **system adaptation occurs simultaneously at the policy, network, mission, and resource levels.**

14. Emergence Quality Metric

To quantify emergence, define

$$E_Q = \beta_1 P_M + \beta_2 P_C + \beta_3 P_R + \beta_4 P_A - \beta_5 C_S,$$

where:

- P_M : mission performance;
- P_C : coordination performance;
- P_R : resource efficiency;

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- P_A: adaptation performance;
- C_S: system instability.

The overall emergence quality is

$$EQ \in [0,1].$$

A high value means that the system simultaneously satisfies multiple system-level requirements.

15. Convergence and Adaptation Analysis

Let

$$D(t) = \|Y(t) - Y^*\|.$$

The adaptation time is defined as

$$T_A = \min\{t : D(\tau) \leq \epsilon,\ \forall \tau \geq t\}.$$

The smaller T_A, the faster the system adapts to a change.

For network resilience, define

$$\Delta G = d(G(t), G(t + \Delta t)),$$

where $d(\cdot,\cdot)$ represents a graph-distance measure.

The resilience objective is therefore

$$\min |E_Q(G) - E_Q(G')|$$

for moderate structural perturbations

$$G \to G'.$$

This provides a mathematical interpretation of resilient emergence: **the desired macroscopic behavior should remain relatively stable even when the microscopic interaction structure changes.**

16. Simulation Framework

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The experimental framework is designed around a multi-agent configuration that enables the investigation of controllable emergent behavior under varying operating conditions. Rather than restricting the evaluation to a single fixed configuration, the present study examines the framework across multiple dynamic scenarios in which agent interactions, task requirements, and system conditions can change over time.

16.1 Experimental Scenarios

Scenario A: Static Single-Task Environment

The task set remains constant:

$$\mathcal{M}(t) = \mathcal{M}_0.$$

This scenario establishes the baseline.

Scenario B: Multi-Task Environment

Multiple tasks coexist:

$$|\mathcal{M}(t)| > 1.$$

Agents must allocate resources across tasks.

Scenario C: Dynamic Task Arrival

At time t_c,

$$\mathcal{M}(t_c^+) \neq \mathcal{M}(t_c^-).$$

The system must reconfigure.

Scenario D: Communication Degradation

A subset of graph edges is temporarily removed:

$$E(t_c^+) \subset E(t_c^-).$$

The system must reconstruct sufficient coordination relationships.

Scenario E: Resource Reduction

The available resource changes:

$$R(t_c^+) < R(t_c^-).$$

The system must redistribute resources among tasks.

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Scenario F: Combined Perturbation

Mission structure, resources, and network topology change simultaneously.

This is the most demanding test of adaptive controllable emergence.

17. Evaluation Metrics

17.1 Task Completion Rate

$$TCR = \frac{N_{\text{completed}}}{N_{\text{total}}}.$$

17.2 Mission Reconfiguration Time.

$$MRT = t_{\text{stable}} - t_{\text{change}}.$$

17.3 Resource Utilization

$$RU = \frac{R_{\text{used}}}{R_{\text{available}}}.$$

17.4 Coordination Robustness

$$CR = \frac{E_Q^{perturbed}}{E_Q^{normal}}.$$

17.5 Decision Latency

$$DL = \frac{1}{N}\sum_i (t_i^{decision} - t_i^{observation}).$$

17.6 Adaptation Efficiency

$$AE = \frac{\Delta E_Q}{T_A}.$$

17.7 Emergence Quality

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$$EQ = w_1 TCR + w_2 CR + w_3 RU + w_4 AE - w_5 DL.$$

18. Baseline Algorithms

The contribution of the proposed framework is evaluated through a comparative analysis against the following baseline configurations:

1. **Fixed-rule controllable emergence (FR-CE).**
2. **Static MARL without mission reconfiguration (MARL-S).**
3. **MARL with dynamic resource allocation (MARL-DRA).**
4. **MARL with resilient coordination (MARL-RC).**
5. **Proposed Adaptive Controllable Emergence framework (ACE).**

All comparisons were conducted under suitable environmental conditions using consistent evaluation metrics.

The central experimental hypothesis is:

$$EQ_{ACE} > EQ_{MARL-DRA}, EQ_{MARL-RC}, EQ_{MARL-S}, EQ_{FR-CE}.$$

All numerical results were obtained from experimental measurements collected during the study.

19. Ablation Study

An ablation analysis systematically excluded one mechanism at a time to quantify its individual contribution to the overall performance of the ACE framework.

ACE without mission reconfiguration

$$ACE - MR$$

ACE without resilient coordination

$$ACE - RC$$

ACE without dynamic resource allocation

$$ACE - DRA$$

ACE without adaptive policy learning

$$ACE - APL$$

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The performance difference can be measured as

$$\Delta_i = EQ_{ACE} - EQ_{ACE-i}.$$

A large indicates that the corresponding mechanism contributes substantially to controllable emergence.

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20. Discussion

The proposed framework changes the interpretation of controllable emergence in three important ways.

First, emergence is no longer considered a static property of a fixed network. Instead,

$$E_Q = E_Q(t).$$

The emergent behavior can therefore evolve as the environment changes.

Second, the network topology itself becomes part of the decision process:

$$G(t+1) = \mathcal{G}(G(t), S(t), \mathcal{M}(t), R(t)).$$

This means that coordination is not merely performed over a predefined network; the interaction structure can adapt to system requirements.

Third, mission assignment and resource allocation are coupled with policy learning:

$$\pi \leftrightarrow Z \leftrightarrow X \leftrightarrow G.$$

This coupling is essential in multi-task systems because optimizing one component independently can produce undesirable global behavior.

For example, maximizing task completion without considering resource constraints may lead to resource concentration. Conversely, maximizing resource utilization without considering mission priorities may reduce overall system effectiveness. Similarly, maximizing communication connectivity without considering decision relevance can produce unnecessary communication overhead.

The proposed multi-objective formulation addresses this problem by explicitly incorporating these factors into a common optimization framework.

21. Theoretical Significance

The theoretical contribution of this work lies in connecting three levels of system description:

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$$Microsoft\ agent\ policy \rightarrow mesoscopic\ interaction\ network \rightarrow macroscopic\ emergen\ behavior$$

At the microscopic level, agents select actions.

At the mesoscopic level, agents form dynamic relationships.

At the macroscopic level, the system exhibits mission-level behavior.

The proposed framework therefore considers controllable emergence as a hierarchical mapping:

$$\mathcal{P} \times \mathcal{G} \times \mathcal{Z} \times \mathcal{X} \rightarrow \mathcal{Y},$$

where

- $\mathcal{P}$: policy space;
- $\mathcal{G}$: graph space;
- $\mathcal{Z}$: mission-assignment space;
- $\mathcal{X}$: resource-allocation space;
- $\mathcal{Y}$: emergent-behavior space.

The controllability problem can therefore be written as

$$\exists(\mathcal{P}, \mathcal{G}, \mathcal{Z}, \mathcal{X}) : \mathcal{Y} \approx \mathcal{Y}^*.$$

This provides a general mathematical definition of adaptive controllable emergence.

22. Practical Computational Implications

The framework is also compatible with centralized-training/decentralized-execution architectures. Such architectures are widely used because centralized information can be available during training while decentralized policies are required during execution. QMIX, for example, explicitly addresses this relationship through monotonic value factorization.

The framework can therefore be implemented using several algorithmic families, including:

- value decomposition;
- actor-critic methods;
- graph-based MARL;
- attention-based communication;
- multi-objective reinforcement learning;
- evolutionary optimization for resource assignment.

The appropriate algorithm should depend on the size of the agent population, degree of observability, computational budget, and degree of cooperation.

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23. Limitations

Several limitations should be recognized.

First, the mathematical model remains an abstraction of a real air and space defense system. Real systems involve heterogeneous physical dynamics, regulatory constraints, cybersecurity considerations, hardware limitations, and highly uncertain environments.

Second, the proposed framework assumes that the reward components can be appropriately normalized and weighted. In practice, determining the optimal values of

$$w_M, w_C, w_R, w_A, w_D$$

is itself a multi-objective optimization problem.

Third, MARL training can suffer from non-stationarity because every agent's policy may change simultaneously. Multi-agent actor-critic research has identified non-stationarity and increasing policy-gradient variance as important challenges in multi-agent learning.

Fourth, the exponential growth of the joint state-action space remains a fundamental limitation.

If each **q** agent has possible states and there are **N** agents,

$$|\mathcal{S}| = q^N.$$

This exponential relationship motivates value decomposition, graph representations, parameter sharing, and hierarchical decision-making.

24. Future Research

Future research should focus on five directions.

24.1 Hierarchical Emergence

A hierarchical architecture could separate:

24.2 Meta-Learning

Meta-learning could allow agents to rapidly adapt to previously unseen task configurations.

24.3 Graph-Structure Learning

Instead of manually defining G(t), the system could learn the most useful interaction topology.

24.4 Safe and Explainable MARL

Decision-making should include constraints that prevent unstable or undesirable behaviors and provide interpretable explanations for major policy changes.

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24.5 Digital-Twin Evaluation

A high-fidelity digital simulation environment could be used to test the framework under diverse system configurations before any physical implementation.

25. Conclusion

This study introduces an Adaptive Controllable Emergence (ACE) framework for multi-task air and space defense systems. Its architecture integrates four interdependent mechanisms—mission reconfiguration, resilient coordination, intelligent decision-making, and dynamic resource allocation—to support adaptive system behavior under changing operational conditions.

The system is represented as a time-varying heterogeneous graph in which sensing, decision, and execution agents interact through dynamically changing relationships. Multi-task mission requirements are represented through a dynamic assignment matrix, while resource allocation is modeled as a constrained optimization problem. Resilient coordination is achieved by allowing the interaction topology to adapt to changes in communication and system conditions. Intelligent decision-making is formulated through decentralized partially observable multi-agent reinforcement learning.

The central mathematical innovation is the coupling of policy, network, mission, and resource spaces:

$$\boxed{\pi \leftrightarrow G \leftrightarrow Z \leftrightarrow X \rightarrow E_Q}$$

where represents agent policies, the interaction network, mission assignment, resource allocation, and the resulting emergent-system quality.

This formulation changes controllable emergence from a static problem of designing fixed local rules into an adaptive process in which the system continuously reorganizes its microscopic policies and interactions in response to changing macroscopic requirements.

The resulting framework provides a unified basis for investigating how large-scale multi-agent systems can achieve stable, efficient, and adaptive collective behavior under multiple simultaneous tasks. Its principal scientific value is not restricted to air and space defense; the same framework can be generalized to other complex distributed systems involving heterogeneous agents, dynamic tasks, partial observability, limited resources, and changing interaction networks.

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Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

(ACE): Adaptive Controllable Emergence; (FR-CE): Fixed-rule controllable emergence; (ACE): Adaptive Controllable Emergence framework.

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All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

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Conflicts of Interest:

"The authors declare no conflict of interest."

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