Smart Technology Investments

Command Theory In Multi-Agent Systems

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Executive Summary

We present a theory-first framework that unifies command-and-control concepts across hierarchical and distributed multi-agent architectures to generate testable propositions about performance, robustness, and scalability. By formalizing command, control, and coordination as primitives and by defining parametric models for agents, observations, and communication, the framework enables principled comparison and design of multi-agent control systems and yields falsifiable predictions about when hierarchy, distribution, or hybrids are preferred.

Outline

Foundations

Conventional command-and-control (C2) practice privileges hierarchical organization of authority and information flows. Emerging multi-agent and cyber-physical systems (e.g., distributed energy, fleets of UAVs, sensor networks) increasingly operate under partial observability, variable latency, and higher failure risk, requiring decentralized or hybrid designs. A theory-first approach—explicit primitives, assumptions, and theorems—produces generalizable engineering guidance that avoids ad hoc rules and enables rigorous evaluation across architectures and environments. Definitions

Formalization

We present a theory-first framework that unifies command-and-control concepts across hierarchical and distributed multi-agent architectures to generate testable propositions about performance, robustness, and scalability. By formalizing command, control, and coordination as primitives and by defining parametric models for agents, observations, and communication, the framework enables principled comparison and design of multi-agent control systems and yields falsifiable predictions about when hierarchy, distribution, or hybrids are preferred. Parametric model (informal notation)

Mechanisms

Classification Formal tradeoffs Proposition 1 (Hierarchy performance): Under bounded observation noise and aggregation fidelity α, a k-level hierarchy with bounded inter-level latency τ achieves asymptotic performance within $\varepsilon(\alpha, \tau, k)$ of the centralized optimum; $\varepsilon \to 0$ as $\alpha \to 0$ and $\tau \to 0$, and communication cost scales as $O(f(k))$ where f is increasing in k (aggregation/coordination overhead).

Applications

Simulation design

Limits & Open Questions

Design principles

Synthesis & Current Developments

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