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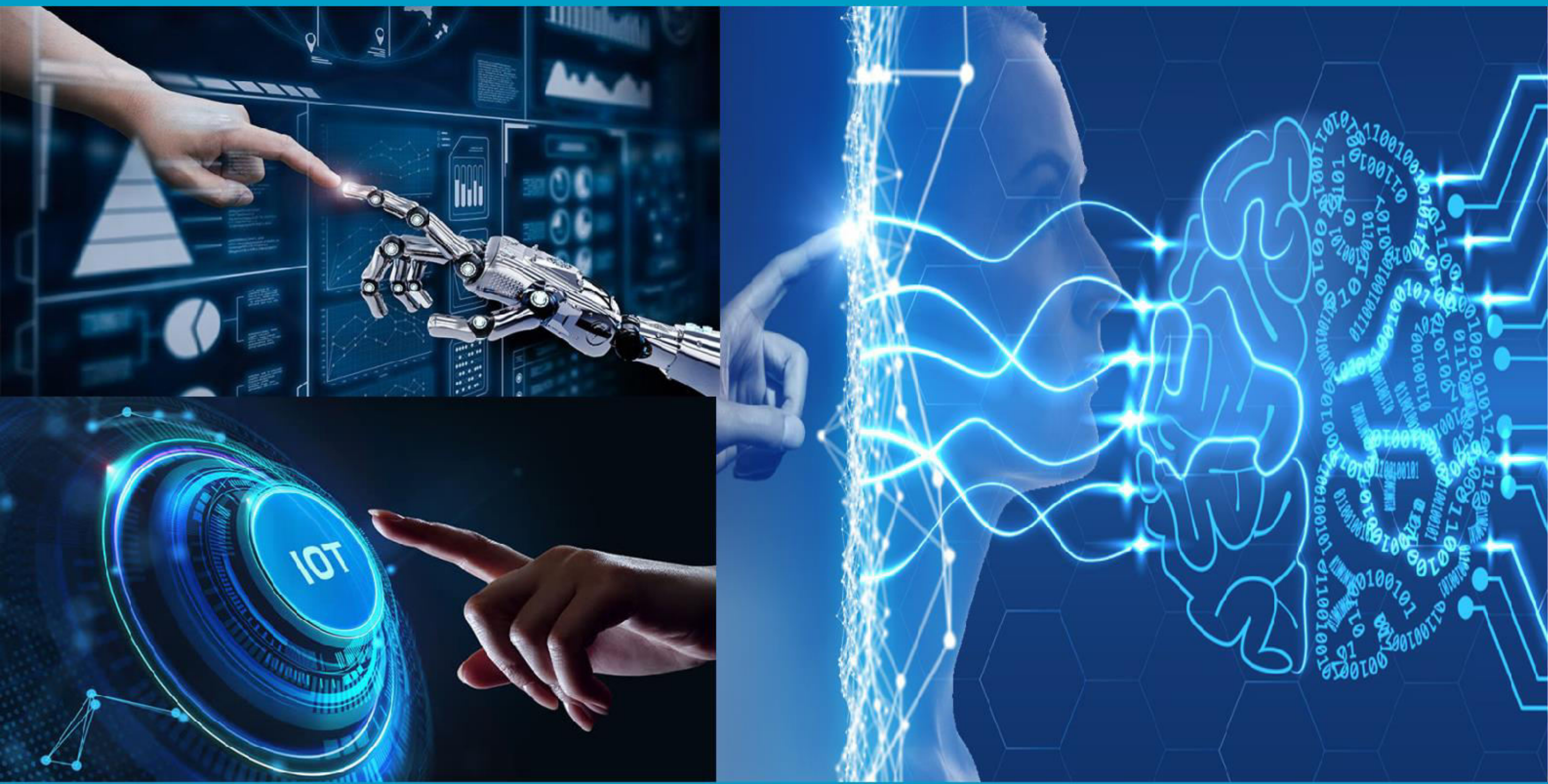

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Causal Inference for Mean Field Multi-Agent Reinforcement Learning

Vaishnavi Jarande, Vishal Jadhav

Department of Computer Engineering, K J College of Engineering and Management research, Pune, India

ABSTRACT: Multi-agent reinforcement learning (MARL) has gained significant attention due to its applications in complex, interactive environments. Traditional MARL approaches often struggle with scalability and non-stationarity as the number of agents increases. Mean Field Reinforcement Learning (MFRL) provides a scalable alternative by approximating interactions using aggregated statistics. However, existing MFRL models fail to capture causal relationships between agent interactions, leading to suboptimal decision-making. In this work, we introduce **Causal Mean Field Multi-Agent Reinforcement Learning (Causal-MFRL)**, which integrates causal inference techniques into the mean field framework. By leveraging causal graphs and counterfactual reasoning, Causal-MFRL improves policy learning and enhances the interpretability of agent behaviors. We evaluate our approach on standard MARL benchmarks, demonstrating superior performance in efficiency, robustness, and generalization.

I. INTRODUCTION

Multi-agent systems are ubiquitous in fields such as robotics, traffic control, and game theory. Traditional MARL methods, which rely on explicit modeling of interactions between agents, face challenges in large-scale settings due to exponential complexity. MFRL simplifies this by treating interactions as an average influence, reducing computational burdens. However, existing MFRL methods overlook the causal dependencies among agent actions and rewards, leading to inefficient learning and limited interpretability. This paper proposes a novel **Causal-MFRL** framework that integrates causal inference into mean field MARL, enabling better decision-making and policy generalization.

II. BACKGROUND AND RELATED WORK

- **Multi-Agent Reinforcement Learning (MARL):** Overview of common approaches such as independent Q-learning, centralized training with decentralized execution (CTDE), and mean field reinforcement learning.
- **Mean Field Reinforcement Learning (MFRL):** Explanation of the mean field approximation in MARL, its benefits, and limitations.
- **Causal Inference in Reinforcement Learning:** Introduction to causal graphs, structural causal models (SCMs), and counterfactual reasoning.
- **Existing Challenges:** Discussion of the limitations of standard MFRL approaches, particularly their inability to model causality.

III. CAUSAL MEAN FIELD MULTI-AGENT REINFORCEMENT LEARNING (CAUSAL-MFRL)

- **Causal Graph Representation:** Introducing causal models to represent interactions between agents and environment states.
- **Counterfactual Reasoning in MARL:** Using counterfactuals to infer the true effect of agent actions.
- **Integration with Mean Field Approximation:** Enhancing MFRL by incorporating causal dependencies to improve decision-making and policy optimization.
- **Algorithmic Framework:** Formal description of the Causal-MFRL learning algorithm, including policy updates and reward shaping.

IV. EXPERIMENTAL EVALUATION

- **Benchmark Environments:** Evaluation on multi-agent particle environments, predator-prey simulations, and traffic control scenarios.
- **Performance Metrics:** Comparison of training efficiency, convergence rates, reward maximization, and generalization capabilities.
- **Ablation Studies:** Assessing the impact of causal inference components on policy learning.

- **Interpretability Analysis:** Demonstrating how causal modeling improves understanding of agent behaviors.

V. RESULTS AND DISCUSSION

- **Improved Policy Learning:** Empirical evidence of enhanced learning efficiency compared to standard MFRL.
- **Robustness to Non-Stationarity:** Evaluation of how causal reasoning helps mitigate non-stationary environments.
- **Scalability Considerations:** Discussion on how Causal-MFRL scales with increasing agent numbers.

VI. CONCLUSION AND FUTURE WORK

We introduced **Causal-MFRL**, a novel framework that integrates causal inference into mean field MARL to improve learning efficiency and interpretability. Our experiments demonstrate that causal modeling enhances policy optimization and generalization in multi-agent environments. Future work includes extending causal reasoning to partially observable settings and exploring applications in real-world domains.

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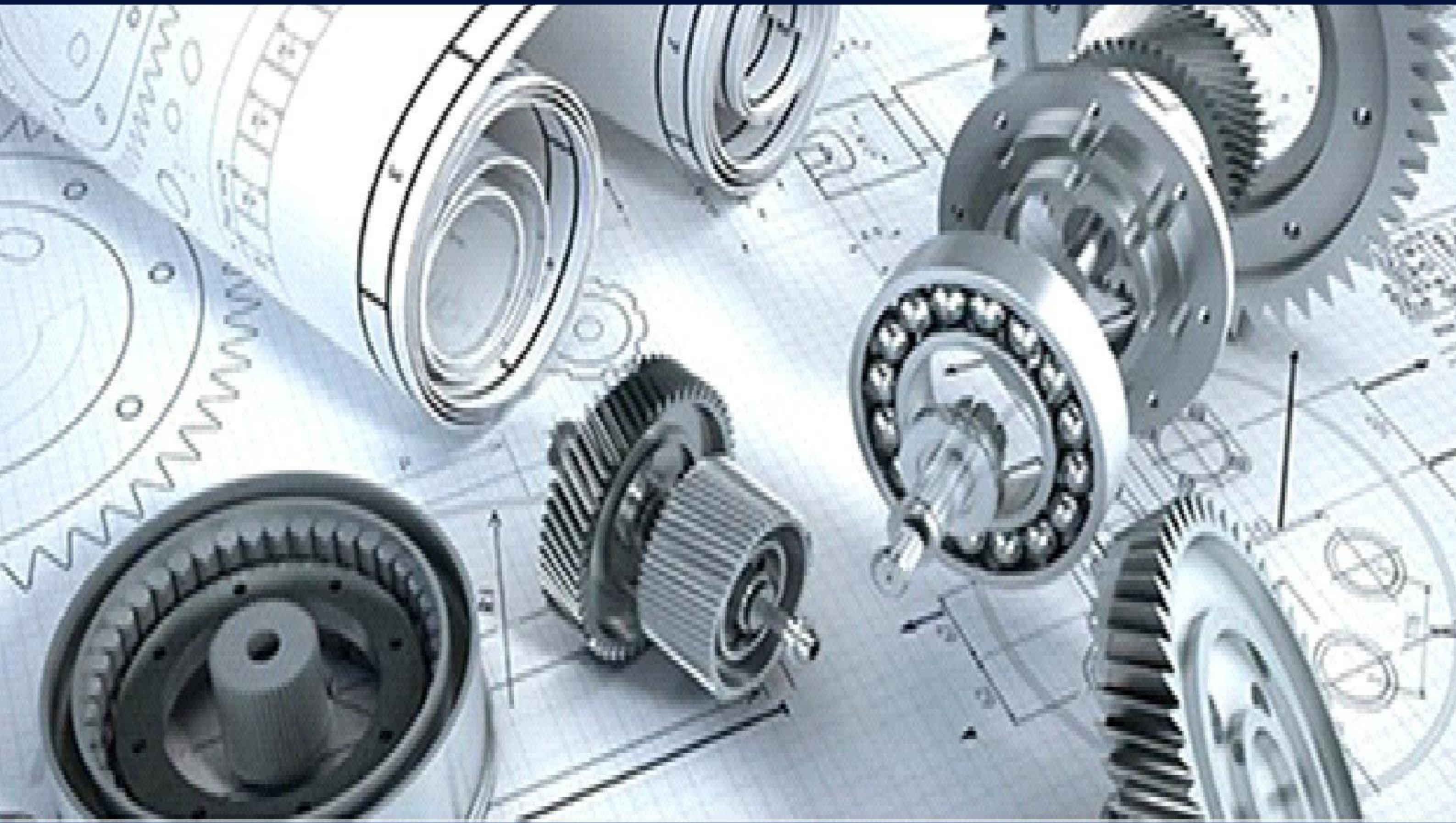

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