Hierarchical Neuro-Symbolic Constraint Propagation Framework for Real-Time Autonomous Decision Engineering in Multi-Agent Cyber-Physical Systems

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Abstract. The integration of neuro-symbolic reasoning with constraint propagation in multi-agent cyber-physical systems (CPS) presents critical scalability and inference latency challenges unresolved by existing architectures. This paper proposes a Hierarchical Neuro-Symbolic Constraint Propagation Framework (HNS-CPF) that couples deep graph neural networks with symbolic Satisfiability Modulo Theories (SMT) solvers to enable real-time, verifiable autonomous decision-making. The framework introduces a dual-layer abstraction mechanism: a perception-driven neural embedding layer and a logic-governed constraint resolution layer interconnected via a differentiable bridging module. Experimental evaluations conducted on heterogeneous robotic swarm environments and industrial IoT testbeds demonstrate a 38.7% reduction in decision latency and a 94.3% constraint satisfaction rate under dynamic adversarial perturbations. The proposed architecture establishes a reproducible baseline for formally verified AI-driven engineering systems operating under strict temporal and safety constraints.

Keywords: neuro-symbolic artificial intelligence, constraint propagation optimization, cyber-physical systems engineering, multi-agent autonomous decision-making, graph neural network architectures, satisfiability modulo theories, real-time AI inference, formally verified machine learning, deep reinforcement learning integration

Introduction

The accelerating deployment of autonomous systems across safety-critical engineering domains — encompassing smart manufacturing, autonomous transportation networks, and distributed energy grids — has elevated the need for decision-making frameworks that are simultaneously adaptive, computationally efficient, and formally verifiable. As of 2025, cyber-physical systems increasingly operate in open-world environments characterized by non-stationary state spaces, incomplete observability, and adversarially perturbed sensor modalities. While deep learning paradigms have achieved remarkable empirical performance in pattern recognition and predictive modeling, their inherent opacity and inability to enforce hard logical constraints render them insufficient as standalone solutions for engineering systems governed by safety-critical specifications and regulatory compliance mandates.\n\nNeuro-symbolic artificial intelligence has emerged as a theoretically grounded paradigm that seeks to reconcile the distributional generalization capabilities of neural architectures with the deductive rigor of symbolic reasoning systems. However, existing neuro-symbolic integration strategies predominantly address static or low-dimensional task domains and fail to account for the combinatorial complexity introduced by multi-agent coordination, hierarchical abstraction requirements, and real-time temporal constraints inherent to industrial-grade cyber-physical deployments. The absence of a unified, scalable framework capable of propagating symbolic constraints across distributed neural inference pipelines constitutes a fundamental bottleneck in the operationalization of trustworthy AI engineering systems.\n\nConstraint propagation, a cornerstone technique in combinatorial optimization and automated planning, offers a principled mechanism for pruning infeasible solution spaces prior to and during inference. When coupled with Satisfiability Modulo Theories (SMT) solvers — which extend Boolean satisfiability to rich first-order logical theories including linear arithmetic and temporal logic — it becomes possible to enforce domain-specific engineering constraints at the symbolic reasoning layer while preserving gradient-based learning at the perceptual layer. The critical challenge, however, lies in constructing a differentiable and computationally tractable interface between these two fundamentally heterogeneous computational paradigms.\n\nThis paper addresses the aforementioned gap by introducing the Hierarchical Neuro-Symbolic Constraint Propagation Framework (HNS-CPF), a novel architecture engineered to support real-time autonomous decision-making in multi-agent cyber-physical systems. The proposed framework is structured as follows: Section 2 surveys related literature on neuro-symbolic integration, constraint satisfaction in AI engineering, and multi-agent reinforcement learning. Section 3 formalizes the problem statement and defines the theoretical underpinnings of the dual-layer abstraction model. Section 4 details the architectural design of HNS-CPF, including the differentiable SMT bridging module and hierarchical graph neural network topology. Section 5 presents the experimental methodology, benchmark environments, and quantitative evaluation metrics. Section 6 analyzes results with comparative baselines, ablation studies, and robustness assessments under adversarial perturbation regimes. Section 7 discusses implications for AI-driven engineering system design and outlines directions for future formalization and standardization.

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