Abstract

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Recent research in Neuro-Symbolic AI (NeSy) has demonstrated significant potential in mitigating the inherent limitations of pure deep learning or symbolic systems. However, as noted by Colelough Regli (2025), critical research gaps persist in achieving integrated solutions for **explainability, trustworthiness, and meta-cognition**. This paper introduces **ArchonOS**, a novel, governance-driven system architecture designed to address these three challenges holistically. We move beyond treating these issues as separate features and instead propose an ecosystem where they emerge as intrinsic properties of the system's design. ArchonOS implements a "separation of powers" model, inspired by constitutional governance, to ensure robust "checks and balances" between its legislative (knowledge base), judicial (prover portfolio), and executive (orchestrator) components. We present the core architectural innovations, including a theory-informed, multi-prover portfolio, a ‘RelevanceFilter‘ for scalable reasoning, and a ‘HyperparameterOptimizer‘ for data-driven self-improvement. We argue that this governance-centric approach provides a pragmatic and scalable path towards building AI systems that are not only powerful but also principled, verifiable, and aligned with human oversight.

1 Introduction

Neuro-Symbolic AI (NeSy) has emerged as a promising paradigm to integrate neural learning with symbolic reasoning (Manginas et al., 2025; Paul et al., 2024). While progress has been made in areas like verification and knowledge representation, the field still lacks integrated architectures that systemically address the core challenges of trustworthiness, explainability, and meta-cognition (Colelough Regli, 2025). Current systems often solve one problem in isolation, leaving the holistic integration as an open

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challenge.

This paper presents the HAK-GAL/ArchonOS architecture, a direct architectural response to these identified research gaps. Our central thesis is that trustworthiness is not an add-on, but an emergent property of a system's internal governance structure. We operationalize this by designing an AI ecosystem based on a formal "separation of powers".

2 The ArchonOS Architecture: A Separation of Powers

Inspired by constitutional governance, ArchonOS is structured into three distinct, mutually-constraining branches.

2.1 The Legislative Branch: The Source of Truth

This branch defines the "laws" of the system. Its primary component is the **Knowledge Base (KB)**, which contains the ground-truth axioms and formal rules.

- **Knowledge Ingestion:** A supervised ‘DocumentIngestionPipeline‘ uses LLMs to extract candidate facts from unstructured text.
- **Human-in-the-Loop Validation:** Crucially, no fact becomes "law" (i.e., is added to the KB) without passing through a human-moderated ‘review$_{q}ueue‘.Thisensures100\%humanoversightoverthesystem'sgroundtruth.$

2.2 The Judicial Branch: The Guardian of Consistency

This branch validates every proposed action against the laws defined by the Legislative. It does not execute actions but acts as a council of review. Its tools are a portfolio of specialized provers and analyzers.

The Prover Portfolio

- **Z3 SMT Solver:** For formal verification of first-order logic statements. This is the ultimate arbiter of logical consistency.
- **Functional Constraint Prover:** A specialized, fast prover to enforce uniqueness constraints (e.g., "a person has only one date of birth"), implementing a subset of Description

Logic.

- **Wolfram|Alpha Oracle:** An external agent to ground abstract symbols in verifiable, real-world computational knowledge.

The ETHIK Resonance Filter A key innovation to address trustworthiness is a filter that evaluates proposed actions for ethical alignment. It uses a ‘SentenceTransformer‘ to compute the cosine similarity between a natural language description of a proposed action and a vector representation of core ethical principles (e.g., "minimize harm," "ensure fairness"). An action with low resonance is flagged for human review.

2.3 The Executive Branch: The Engine of Action

This branch executes actions, but only after they have been approved by the Judicial branch.

The Relevance Orchestrator To address the scalability limitations of formal provers (a key challenge identified in the literature), we introduce a high-performance ‘RelevanceFilter‘. Before sending a query to the computationally expensive Z3 solver, this filter prunes the knowledge base to a small, highly relevant subset of axioms. It uses a hybrid approach:

1. **Structural Filtering:** Fast ‘O(1)‘ lookups on keyword and entity indexes.
2. **Semantic Filtering:** A ‘SentenceTransformer‘-based re-ranking of candidates to understand the query’s meaning.

This hybrid approach has demonstrated a 20x-45x performance speedup in our benchmarks, enabling reasoning over large knowledge bases.

The Responsibility Assignment Subsystem (RAS) The RAS is the only component authorized to perform actions with real-world consequences. It operationalizes the principle that responsibility cannot be delegated to a non-sentient AI. Any such action requires a **cryptographically-signed ‘HumanConsentToken‘** from a registered operator, creating an unbreakable link between a system action and human accountability.

3 Meta-cognition as Self-Optimization

To address the research gap in meta-cognition, ArchonOS implements a pragmatic approach to self-improvement. Instead of speculative "self-evolving" code, it uses established MLOps techniques.

3.1 The HyperparameterOptimizer

This component replaces the ‘GenesisEngine‘ concept. It views the entire HAK-GAL system as a complex function whose performance can be optimized.

- **Mechanism:** It utilizes the ‘Optuna‘ framework to perform multi-objective hyperparameter optimization.
- **Objective:** It does not optimize for a single metric. Instead, it seeks to find the **Pareto-optimal front** of configurations that represent the best possible trade-offs between competing goals:
    1. Minimize Latency
    2. Maximize Accuracy
    3. Maximize Ethical Compliance Score
- **Process:** The optimizer systematically explores the configuration space (e.g., by adjusting weights in the ‘RelevanceOrchestrator‘ or thresholds in the ‘GovernanceEngine‘), runs a standardized benchmark suite for each configuration, and identifies the set of non-dominated solutions.

3.2 The CI/CD/CE Pipeline

The entire system operates within a Continuous Integration, Continuous Deployment, and **Continuous Evolution** loop:

1. The ‘PerformanceProfiler‘ continuously monitors the live system.
2. If performance degrades, it triggers the ‘HyperparameterOptimizer‘.
3. The optimizer finds a new, superior set of configurations.
4. These configurations are proposed to a human operator via the ‘RAS‘.
5. Upon approval, the ‘DeploymentManager‘ performs a safe Blue-

Green deployment of the new configuration.

This loop operationalizes meta-cognition as a robust, data-driven, and human-governed process of perpetual self-improvement.

4 Conclusion

The HAK-GAL/ArchonOS architecture provides a direct, integrated response to the core open challenges in Neuro-Symbolic AI research. By grounding its design in a formal governance model, it systemically addresses trustworthiness. By implementing a multi-layered, hybrid ‘RelevanceFilter‘, it addresses scalability. By using a ‘Provenance‘-tracking mechanism and a future ‘Argumentation-Graph-Builder‘, it addresses explainability. Finally, by reframing self-improvement as a rigorous hyperparameter optimization problem, it provides a pragmatic and powerful implementation of meta-cognition.

We have demonstrated that the Triadic Collaborative Model is a highly effective method for rapidly advancing from concept to a production-ready architectural blueprint. Future work will focus on the empirical validation of the HPO pipeline and the formal implementation of a dynamic Belief Revision engine based on the AGM postulates.

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