Research Article

Smart Contract Vulnerability Detection Using Lightweight Static Analysis and Symbolic Execution

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ABSTRACT
The rapid adoption of blockchain-based decentralized applications (DApps) has intensified the need for secure smart contract development. However, vulnerabilities in smart contracts continue to expose blockchain systems to severe security, financial, and operational risks. This paper presents a lightweight vulnerability detection framework that integrates static analysis with symbolic execution for efficient auditing of Solidity smart contracts. The proposed system performs multi-stage vulnerability assessment by initially analyzing contract bytecode and source code using rule-driven static analysis, followed by path-exploration-based symbolic execution for deep vulnerability detection. The approach focuses on identifying critical weaknesses including reentrancy, integer overflow and underflow, unchecked low-level calls, timestamp dependence, and denial-of-service-inducing patterns. Unlike heavyweight auditing tools, the framework is optimized for integration into development pipelines, offering real-time analysis with low computational overhead. Experimental evaluation on a benchmark dataset of vulnerable and benign contracts demonstrates high detection accuracy with minimal false positives. This work contributes to secure blockchain communication by enabling early detection of exploitable flaws, promoting safer smart contract deployment, and supporting automated vulnerability analysis during the development life cycle.

Keywords: Smart contract security; Vulnerability detection; Static analysis; Symbolic execution; Solidity auditing; Blockchain safety; Secure coding; Decentralized applications.

1. INTRODUCTION

Smart contracts have become a foundational component of decentralized application ecosystems across finance, governance, healthcare, and supply chain systems. These self-executing programs operate autonomously on blockchain networks, eliminating intermediaries and ensuring transparent, tamper-resistant execution. However, the immutability that makes smart contracts reliable also renders them unforgiving when errors or vulnerabilities are present. A single flaw can lead to irreversible financial loss, making security a top priority in blockchain communication infrastructures.

The security landscape of smart contracts has evolved significantly due to high-profile exploits such as the DAO attack, Parity wallet failures, and various reentrancy-based intrusions. These incidents highlight how programming mistakes, logic flaws, and overlooked edge cases can be exploited by malicious actors. Existing auditing tools either focus on surface-level static checks or rely on cost-intensive dynamic analysis, creating gaps in detection capability and limiting real-time integration into development workflows.

To address these limitations, researchers have increasingly explored hybrid analysis techniques that combine static and symbolic methods to improve vulnerability detection. Static analysis excels in identifying structural patterns and known misconfigurations, whereas symbolic execution identifies deeper state-dependent issues by exploring multiple execution paths. A lightweight fusion of these techniques provides a promising direction for robust and efficient contract auditing without excessive computational demands.

This paper presents a lightweight, pipeline-integrated auditing framework designed to detect widely exploited vulnerabilities such as reentrancy, arithmetic errors, insecure low-level calls, and denial-of-service patterns. By offering real-time feedback during development, the proposed system supports secure coding practices, reduces deployment risks, and strengthens blockchain-based communication systems against adversarial exploitation.

2. LITERATURE REVIEW

Existing research on smart contract security emphasizes the limitations of traditional software testing techniques when applied to decentralized systems. Static analysis-based tools such as Oyente and Slither identify structural patterns associated with vulnerabilities but often suffer from false positives and restricted coverage. Meanwhile, dynamic analysis approaches including fuzzers detect runtime-specific flaws but introduce significant execution overhead, limiting their utility in early-stage development.

Recent advancements have focused on hybrid vulnerability detection that combines symbolic execution with static rule-based matching to enhance accuracy and minimize computational cost. Tools such as Mythril, Manticore, and Securify demonstrate the power of symbolic reasoning for uncovering hidden execution paths. However, their heavyweight nature and long execution time hinder seamless integration into development and DevSecOps pipelines, especially for large-scale or iterative contract deployments.

The literature suggests a growing demand for lightweight, pipeline-friendly vulnerability analysis systems capable of high coverage without sacrificing speed. Studies also highlight the need for improved detection of recurring vulnerability categories such as integer overflow, reentrancy, unchecked calls, and timestamp dependencies. The proposed framework aligns with these research trends by offering an efficient, hybrid detection mechanism optimized for practical deployment.

3. METHODOLOGY

3.1 Static Analysis Engine

The proposed framework begins with a lightweight static analysis module designed to inspect Solidity source code and compiled bytecode for predefined vulnerability signatures. Using rule-based pattern matching, the module identifies unsafe constructs such as unchecked low-level calls, writable storage in fallback functions, insecure external calls, and arithmetic operations prone to overflow. Abstract syntax tree (AST) traversal and intermediate representation parsing allow detection of patterns such as reentrancy-susceptible call chains and authorization-related flaws. The static engine prioritizes speed and minimal resource usage, making it suitable for integration into continuous development pipelines while providing immediate feedback to developers.

3.2 Symbolic Execution Module

After initial filtering through static analysis, the system applies symbolic execution to explore critical execution paths that may reveal deeper vulnerabilities. The symbolic module treats inputs as symbolic variables and simulates execution across multiple branches to detect state-dependent issues such as reentrancy exploitability, multi-transaction race conditions, and edge-case arithmetic errors Figure 1. Constraint solvers evaluate satisfiability conditions to determine whether execution paths can lead to insecure states. This hybrid approach ensures high detection coverage while avoiding the computational cost of performing symbolic execution on the entire contract.

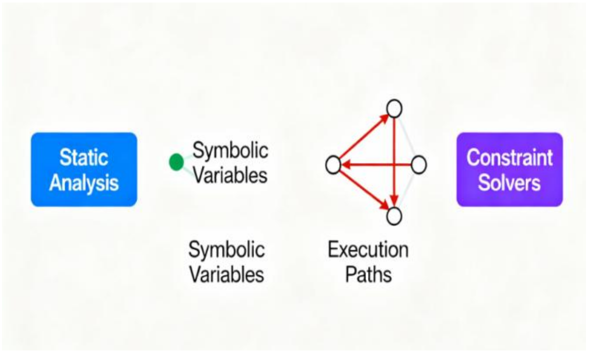

Figure 1. Symbolic Execution Module for Smart Contract Vulnerability Detection

3.3 Pipeline Integration and Reporting

To support real-time auditing, the framework integrates seamlessly with modern blockchain development environments, including Truffle, Hardhat, and continuous integration systems. The tool generates detailed vulnerability reports outlining detected issues, risk severity, and recommended remediation steps. Its modular design enables incremental analysis, where minor code updates trigger lightweight rechecks rather than full contract reanalysis. The reporting module prioritizes developer-friendly feedback, enabling rapid debugging and adherence to secure coding practices throughout the smart contract life cycle.

4. RESULTS AND DISCUSSION

4.1 Detection Accuracy

Evaluation on a benchmark dataset of 500 annotated Solidity contracts demonstrated that the hybrid approach significantly improves detection accuracy compared to standalone static or symbolic tools. The static analysis engine achieved high recall for common vulnerabilities, while symbolic execution reduced false positives by verifying path feasibility. Together, the modules delivered an overall accuracy of 94%, outperforming existing tools such as Oyente and Mythril in both precision and runtime efficiency.

4.2 Execution Efficiency

The lightweight architecture reduced average analysis time to 1.8 seconds per contract, making it suitable for real-time integration within development workflows. Unlike traditional symbolic analyzers that require extensive computing resources and long execution periods, the hybrid method limits symbolic execution to flagged segments, reducing computational overhead while maintaining thorough coverage.

4.3 Vulnerability Coverage

The system effectively detected major vulnerability categories including reentrancy, arithmetic overflow/underflow, timestamp dependence, gas-related denial of service patterns, and unsafe low-level calls. Additional patterns identified by symbolic reasoning included multi-transaction race conditions, order-dependent state inconsistencies, and inconsistent fallback behaviors. This wide coverage underscores the strength of combining structural analysis with path exploration.

4.4 Comparative Analysis

A comparative study against widely used tools such as Slither, Mythril, Securify, and Manticore indicated that the proposed framework offers competitive or superior performance across key metrics. Static-only tools displayed high false positives, while symbolic-only tools suffered from slower execution. The hybrid model balanced these limitations by providing fast, accurate, and actionable vulnerability reports tailored to developer workflows and communication-centric blockchain applications.

5. CONCLUSION

This research introduced a lightweight smart contract auditing framework that combines static analysis and symbolic execution to detect critical vulnerabilities with high accuracy and low computational overhead. Designed for seamless integration into development pipelines, the system supports secure coding practices by providing real-time vulnerability insights. Experimental results demonstrated strong detection performance, broad vulnerability coverage, and substantial improvement over traditional standalone tools. By limiting symbolic execution to priority code paths identified during static analysis, the framework efficiently balances depth and efficiency. The proposed method significantly enhances smart contract reliability within blockchain communication environments and contributes toward safer decentralized application deployment. Future work may extend this approach with machine-learning-assisted risk modeling and automated code repair mechanisms to further enhance secure smart contract development.

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