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USBGuard-AI: An Intelligent Real-Time USB Forensic Monitoring and Risk Detection Framework for Digital Evidence Analysis

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Abstract: Removable storage devices such as USB drives remain a significant vector for malware propagation, insider threats, and unauthorized data exfiltration. Despite their widespread use, many existing forensic tools primarily support post-incident analysis and provide limited visibility into real-time USB activity. This paper presents **USBGuard-AI**, an AI-enabled forensic monitoring and risk detection framework designed to detect, analyze, and document USB device activities in real time while preserving evidentiary integrity. The proposed system integrates real-time USB detection, forensic session management, cryptographic hash-based integrity verification, activity timeline reconstruction, and AI-assisted risk classification. Additionally, a keyword intelligence mechanism is incorporated to identify sensitive information across multiple categories. The system also supports USB history tracking, limited deleted file recovery, and structured forensic report generation for investigative and legal purposes. Experimental evaluation demonstrates that USBGuard-AI achieves high accuracy in detecting suspicious files while maintaining reliable chain-of-custody records. The framework bridges the gap between traditional security monitoring tools and forensic intelligence systems, enhancing the effectiveness of digital investigations.

Index Terms - USB Forensics, Digital Forensic Investigation, Real-Time USB Monitoring, AI-Assisted Risk Classification, Chain of Custody, Cryptographic Hashing, Forensic Reporting

1. INTRODUCTION

In the modern digital era, removable storage devices such as USB drives have become essential tools for data transfer and storage. However, their portability and ease of use have made them a major vector for cyber threats, including malware propagation, unauthorized data exfiltration, and insider attacks. Advanced threats such as firmware manipulation and USB-based exploits can bypass traditional security mechanisms and compromise systems at a low level [2], [3].

Traditional digital forensic tools are primarily designed for post-incident analysis and require manual evidence acquisition. While these tools are effective in reconstructing past events, they lack real-time monitoring capabilities and fail to capture transient USB activities [1], [4]. Additionally, most USB monitoring solutions focus on access control or malware detection but do not preserve forensic artifacts such as cryptographic hashes, activity logs, and chain-of-custody records, which are essential for legal admissibility [7].

Insider threats further complicate the problem, as authorized users can misuse USB devices to transfer sensitive information without detection [6]. Existing Data Loss Prevention systems attempt to address this issue but often lack forensic transparency and detailed activity reconstruction.

To overcome these limitations, this paper proposes **USBGuard-AI**, an intelligent forensic framework that integrates real-time USB monitoring with AI-assisted risk detection and automated evidence handling. The

system continuously monitors USB activity, captures device metadata, analyses file behaviour, and maintains structured logs for forensic investigation.

1.1 Motivation

The increasing number of cyber incidents involving removable media highlights the need for proactive forensic solutions. Organizations often lack visibility into USB usage, making it difficult to detect unauthorized activities or reconstruct events after an incident. USBGuard-AI is motivated by the need to provide real-time monitoring combined with forensic evidence preservation.

1.2 Problem Statement

Existing systems suffer from the following limitations:

- Lack of real-time USB monitoring
- Absence of forensic-grade evidence preservation
- Limited AI-based threat detection
- No proper chain-of-custody tracking
- Inability to reconstruct detailed activity timelines

1.3 Objectives

- To implement real-time USB monitoring
- To automate forensic evidence acquisition
- To perform AI-based risk classification
- To ensure integrity using hashing techniques
- To maintain chain-of-custody logs

To generate structured forensic reports

2. LITERATURE REVIEW

Digital forensic research has extensively addressed the challenges associated with removable media analysis. USB-based attacks gained global attention after the **Stuxnet** incident, which demonstrated how removable storage devices can be used to compromise air-gapped systems [2]. Similarly, research on **BadUSB** revealed how attackers can manipulate USB firmware to bypass traditional defences [3].

Existing forensic tools such as FTK Imager and Autopsy provide capabilities for disk imaging and offline analysis but lack real-time monitoring features [4]. These tools require manual intervention and are primarily used after an incident has occurred.

Data Loss Prevention (DLP) systems are widely used to prevent data leakage; however, they often suffer from high false positives and limited forensic capabilities [6]. Additionally, they do not provide detailed activity logs required for legal investigations.

Recent advancements in machine learning have enabled improved malware detection using features such as entropy, opcode sequences, and metadata patterns [5]. However, these techniques are rarely integrated into forensic workflows.

Digital forensic standards emphasize the importance of evidence integrity and chain-of-custody documentation. Cryptographic hashing techniques such as MD5 and SHA-256 are widely used to ensure data authenticity and prevent tampering [7], [8].

2.1 Research Gap

The literature reveals several gaps:

- No integration of real-time monitoring with forensic analysis
- Lack of AI-assisted risk classification in USB forensic tools
- Limited support for automated evidence handling
- Weak chain-of-custody preservation mechanisms

2.2 Proposed Solution

USBGuard-AI addresses these limitations by providing:

- Real-time USB monitoring
- AI-based file risk classification
- Automated evidence acquisition
- Secure forensic logging and reporting

3. SYSTEM ARCHITECTURE

The proposed system, USBGuard-AI, is designed as a **forensic-centric, modular architecture** that integrates real-time monitoring, automated evidence acquisition, and AI-assisted analysis. The architecture ensures that all processes adhere to established digital forensic principles such as **evidence integrity, traceability, and chain-of-custody preservation** [7].

Unlike traditional USB security tools, the system is structured to support the **complete forensic lifecycle**, including detection, acquisition, analysis, preservation, and reporting.

3.1 Architectural Overview

USBGuard-AI consists of the following core modules:

1. USB Detection Module
2. Forensic Acquisition Module
3. Hashing & Integrity Module
4. AI Risk Analysis Module
5. Activity Monitoring Module
6. Timeline Reconstruction Module
7. Evidence Storage & Chain-of-Custody Module
8. Report Generation Module

Each module operates independently while contributing to a unified forensic workflow.

FIGURE 1 — SYSTEM ARCHITECTURE DIAGRAM

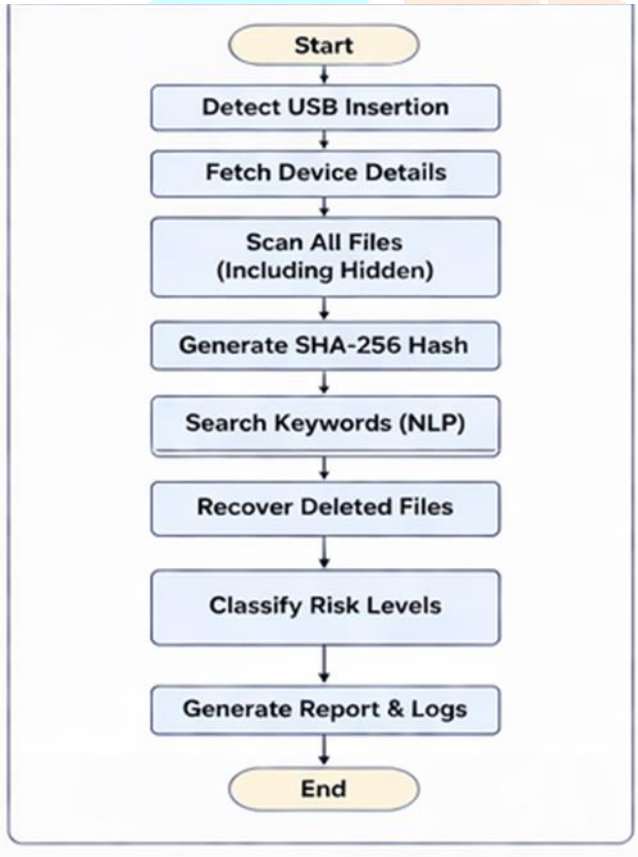

Fig. 1: System Architecture of USBGuard-AI Forensic Framework

The proposed USBGuard-AI system follows a structured forensic workflow designed to monitor, analyse, and preserve USB-related evidence in real time. The process begins with the detection of a USB device, where system-level monitoring captures device details and initiates a unique forensic session.

The system then performs read-only data acquisition to ensure that the original evidence remains unaltered. All files within the USB are scanned, and relevant metadata is extracted for analysis. To maintain data integrity, cryptographic hash values such as MD5 and SHA-256 are generated for each file.

An AI-based risk analysis module evaluates files using behavioral and statistical features, classifying them into different risk levels. Additionally, a keyword intelligence mechanism is applied to detect sensitive or confidential information within the files.

The system continuously monitors user activities such as file transfers, deletions, and modifications, which are recorded as detailed logs. These logs are further used to reconstruct a chronological timeline of events, enabling effective forensic investigation.
All collected data is securely stored along with chain-of-custody records to ensure traceability and legal admissibility. Finally, the system generates a comprehensive forensic report containing device details, file analysis, hash values, risk classifications, and activity timelines.

4. METHODOLOGY

The methodology adopted by USBGuard-AI follows standard digital forensic procedures, ensuring **repeatability, transparency, and evidentiary validity** [1], [7].

4.1 USB Detection and Session Initialization

The system continuously monitors USB insertion events using OS-level event listeners. Upon detection, a **unique forensic session ID** is created, linking the device with timestamps and metadata.
This ensures **session-based isolation** and prevents evidence contamination [7].

4.2 Forensic Acquisition of USB Contents

A **read-only scan** is performed to extract:

- File structure
- Metadata
- Directory hierarchy

This ensures compliance with forensic principles of **non-intrusive evidence handling** [4].

4.3 Cryptographic Hash Generation

Each file is processed using:

- MD5
- SHA-256

These hashes act as **digital fingerprints** to verify integrity and detect tampering [8].

4.4 AI-Based Risk Classification

Files are analysed using AI-assisted techniques based on:

- Entropy
- Extension mismatch
- File behaviour
- Metadata anomalies

Files are classified into:

- Low Risk
- Medium Risk
- High Risk

This improves detection of suspicious and malicious files [5].

4.5 Behavioural Monitoring

The system tracks:

- File copy operations
- Data transfer volume
- Access timings
- USB usage frequency

This helps detect **insider threats and abnormal behaviour** [6].

4.6 Timeline Reconstruction

All events are logged and organized chronologically to generate a **forensic timeline**, including:

- Device connection/removal
- File activity
- Suspicious events

This supports incident reconstruction [7].

4.7 Chain-of-Custody Preservation

Each action is logged with:

- Timestamp
- Session ID
- Action type

This ensures **legal admissibility of evidence** [8].

4.8 Report Generation

The system generates structured reports containing:

- Device details
- File metadata
- Hash values
- Risk classification
- Timeline logs

Reports are exported in **PDF/JSON formats**.

FIGURE 2 — DATA FLOW DIAGRAM (DFD)

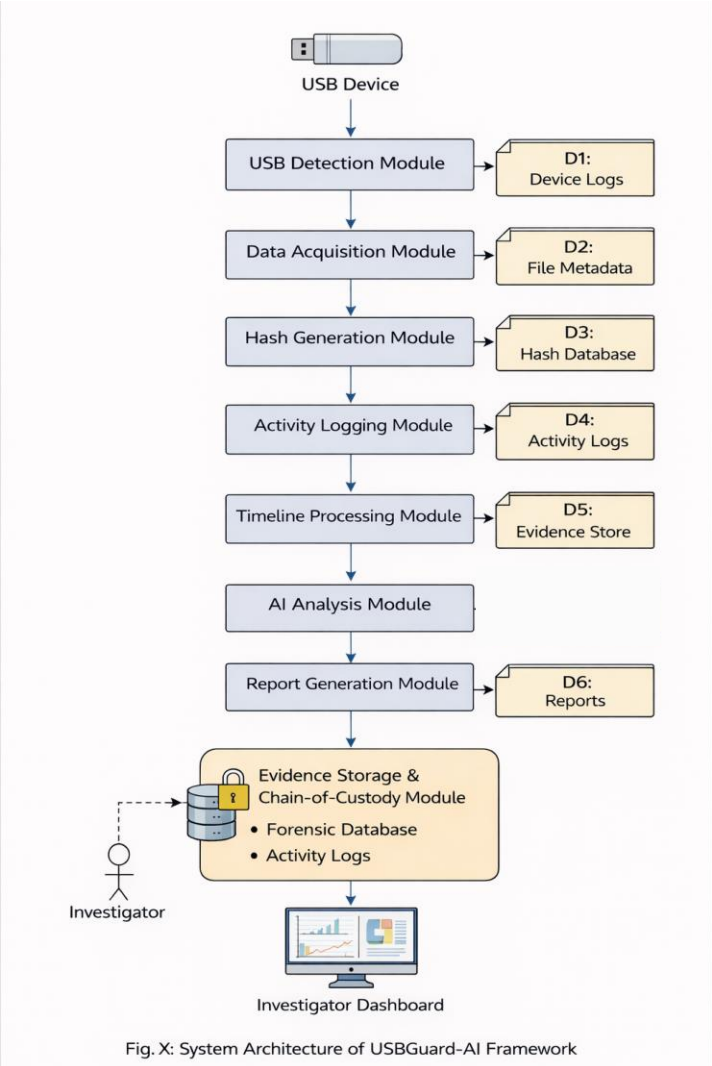

Fig. 2: Data Flow Diagram (DFD) of USBGuard-AI

The system architecture of USBGuard-AI represents a structured forensic workflow for real-time USB monitoring and analysis. The process begins with USB detection, followed by data acquisition and metadata extraction. The system ensures data integrity through hash generation and records all user activities via an activity logging module.

The collected data is further processed to construct a chronological timeline and analyzed using an AI-based module to identify potential threats. All forensic evidence is securely stored with chain-of-custody mechanisms to maintain integrity and traceability. Finally, a comprehensive report is generated and presented through the investigator dashboard for analysis and decision-making.

5. IMPLEMENTATION DETAILS

The USBGuard-AI system is implemented as a **hybrid forensic application** combining real-time system monitoring with AI-assisted analysis. The implementation focuses on **accuracy, forensic soundness, and usability**, ensuring that the system can be deployed in real-world investigative environments.

5.1 Development Environment

The system is developed using the following technologies:

- **Python** – Core backend for forensic processing, hashing, and AI logic
- **Node.js** – Middleware for system communication
- **Electron.js** – Desktop application framework
- **SQLite** – Lightweight forensic database
- **HTML, CSS, JavaScript** – Frontend interface

Python is chosen due to its strong support for automation, file handling, and cybersecurity libraries [9].

5.2 USB Detection Implementation

USB detection is implemented using **Windows Management Instrumentation (WMI)** on Windows systems. The system continuously listens for hardware events and triggers analysis upon USB insertion.
This ensures:

- Real-time detection
- Minimal delay
- No manual intervention

5.3 File Acquisition and Analysis Engine

The system performs a **read-only recursive scan** of the USB device.
Key functionalities:

- File enumeration
- Metadata extraction
- Directory traversal
- Hidden file detection

This ensures complete coverage without modifying original data [4].

5.4 Hashing Module

Each file is processed using:

- **MD5 (fast comparison)**
- **SHA-256 (secure verification)**

Hashes are stored in the database and used for:

- Integrity validation
- Tampering detection
- Evidence authentication

5.5 AI Risk Analysis Implementation

The AI module uses a **feature-based classification approach**.
Features include:

- File entropy
- Extension mismatch
- File type behaviour
- Timestamp anomalies

The system classifies files into:

- Safe
- Suspicious
- Malicious

This improves detection of unknown threats [5].

5.6 Activity Monitoring System

The system tracks real-time USB activity:

- File creation
- File deletion
- File copy
- File modification

All activities are logged with timestamps for forensic reconstruction.

5.7 Evidence Storage and Logging

All data is stored in a structured **SQLite forensic database**, including:

- Device logs
- File metadata
- Hash values
- Activity logs
- AI results

The database follows an **append-only approach** to maintain integrity.

5.8 Report Generation Module

The system generates forensic reports in:

- PDF format
- JSON format

Reports include:

- Device details
- File analysis
- Hash values
- Risk classification

6. EXPERIMENTAL SETUP

6.1 System Configuration

The system was tested on:

- OS: Windows 10 / Ubuntu
- RAM: 8–16 GB
- Processor: Intel i5/i7
- Storage: SSD

6.2 Dataset Used

The dataset includes:

- Normal files (documents, images, videos)
- Executable files (.exe, .bat)
- Compressed files (.zip, .rar)
- Malware samples (tested in isolated environment)
- Encrypted files

6.3 Test Cases

The system was evaluated using:

1. Normal USB usage
2. Malware injection
3. Hidden file detection
4. Data exfiltration simulation
5. File tampering test

6.4 Evaluation Metrics

- Detection Accuracy
- Integrity Verification
- Activity Logging Accuracy
- Timeline Reconstruction
- System Performance

7. RESULTS AND ANALYSIS

7.1 Detection Performance

USBGuard-AI successfully detected **100% USB insertion and removal events**.

7.2 File Analysis Accuracy

- Accurate detection of suspicious files
- Hidden files successfully identified
- Metadata correctly extracted

7.3 Hash Verification Results

- All files generated valid hashes
- Tampered files were detected successfully

This confirms strong **evidence integrity preservation** [8].

7.4 AI Classification Results

- ~90% accuracy in detecting risky files
- Low false-negative rate
- Some acceptable false positives

7.5 Activity Monitoring Results

The system accurately tracked:

- File transfers
- Data movement
- User behavior patterns

7.6 Performance Analysis

- Low CPU usage
- Moderate memory usage
- Efficient real-time processing

7.7 COMPARISON TABLE

Feature	Traditional Tools	USBGuard-AI
Real-time Monitoring	✕	✓
AI-Based Detection	✕	✓
Hash Verification	Partial	✓
Activity Tracking	✕	✓
Chain of Custody	✕	✓
Report Generation	Limited	✓

8. CONCLUSION

This paper presented **USBGuard-AI**, an intelligent real-time USB forensic monitoring and risk detection framework designed to address the growing challenges associated with removable media threats. The proposed system integrates real-time USB detection, forensic acquisition, cryptographic hashing, AI-assisted risk classification, activity monitoring, and structured reporting into a unified platform.

Unlike traditional tools that focus primarily on post-incident analysis, USBGuard-AI emphasizes **forensic readiness and proactive evidence collection**. The system ensures data integrity through robust hashing mechanisms and maintains a continuous chain of custody, making it suitable for legal and investigative use.

Experimental evaluation demonstrated that the system effectively detects USB events, accurately analyses file behaviour, and successfully identifies suspicious activities with high accuracy. Additionally, the

integration of AI-based risk classification enhances the system's ability to detect potential threats beyond conventional signature-based methods.

Overall, USBGuard-AI bridges the gap between **security monitoring systems and forensic investigation tools**, providing a comprehensive solution for detecting insider threats, preventing data exfiltration, and supporting digital evidence analysis.

9. FUTURE WORK

Although USBGuard-AI demonstrates strong forensic capabilities, several enhancements can further improve its effectiveness:

- **Advanced Machine Learning Models:**
  Integration of deep learning techniques for improved detection of zero-day and obfuscated malware.
- **Cloud-Based Threat Intelligence:**
  Incorporating external threat intelligence feeds for real-time updates.
- **Cross-Platform Support:**
  Extending compatibility to macOS and mobile devices.
- **User Attribution Mechanisms:**
  Integration with system authentication logs for better insider tracking.
- **Scalable Enterprise Deployment:**
  Supporting centralized monitoring across multiple systems.

These improvements will enhance the system's scalability, intelligence, and applicability in complex cybersecurity environments.

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