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Secure and Scalable Cloud Storage with Raspberry Pi Clusters for Real-Time Security Applications

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***Abstract* - The increasing need for secure, scalable, and cost-efficient data storage solutions has driven interest in decentralized platforms and edge computing architectures. In response to these emerging demands, this project introduces a Raspberry Pi-based cluster designed as a flexible, low-cost, and secure alternative to traditional cloud infrastructures. The cluster is composed of multiple interconnected nodes that collaboratively ensure high availability, fault tolerance, and data redundancy. By integrating robust encryption protocols, the system protects data at rest and in transit, enhancing the overall security posture.**

The decentralized nature of this architecture eliminates the vulnerabilities typically associated with centralized data centers, reducing the risks of single points of failure and large-scale data breaches. Additionally, using energy-efficient Raspberry Pi devices contributes to a more sustainable and environmentally friendly computing model. The platform is further optimized for real-time security applications such as surveillance and intrusion detection by leveraging edge computing capabilities and artificial intelligence algorithms, which enable rapid, localized decision-making without reliance on external servers.

This project demonstrates the viability of a scalable and resilient distributed storage system suitable for various modern use cases, including smart home automation, enterprise networks, and broader Internet of Things (IoT) deployments. The proposed solution reduces operational costs and paves the way for developing next-generation intelligent and decentralized computing environments.

Keywords: Decentralised Storage, Edge Computing, Raspberry Pi Cluster, Data Security, Fault Tolerance, Real-Time Applications, Encryption.

I. INTRODUCTION

In the rapidly evolving information technology landscape, there is a growing demand for scalable, secure, and cost-effective computing solutions. As organizations strive to meet these challenges, many are turning to innovative architectures that balance performance, privacy, and affordability. While commercial cloud services such as Amazon Web Services, Microsoft Azure, and Google Cloud offer robust and comprehensive infrastructure, their steep costs and potential privacy concerns often deter smaller entities such as educational institutions, research labs, and small businesses (Zhou et al., 2020). These limitations have created a critical need for self-hosted solutions that provide comparable benefits without the drawbacks.

This project proposes the development of a self-hosted distributed computing platform constructed using low-cost Raspberry Pi devices. This hybrid approach integrates the benefits of edge computing—such as low latency and decentralized data processing—with essential cloud-based features like data storage and centralized access. The proposed system is both powerful and economical, demonstrating that even budget-friendly hardware can be configured into a scalable and secure distributed environment. Leveraging the flexibility and modularity of Raspberry Pi clusters, the platform is designed to meet the computational and storage needs of smaller-scale operations while maintaining enterprise-level functionalities.

The architecture will support key features including secure data storage, real-time network monitoring, automated threat detection, and fault tolerance through distributed computing principles. By decentralizing the data processing and integrating built-in security protocols, the system aims to minimize potential vulnerabilities and provide high availability. This approach ensures data privacy, enhances system reliability, and reduces dependency on third-party cloud vendors.

Ultimately, this project offers a practical alternative for institutions and organizations that require a customizable and secure cloud infrastructure without the financial burden typically associated with mainstream cloud providers. By harnessing the power of affordable hardware and open-source software, this solution aligns with current trends in sustainable and accessible technology deployment (Patel & Shah, 2021).

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II. INNOVATIVE IDEA / CONCEPT

This project introduces an innovative, security-focused distributed cloud platform tailored for real-time monitoring and scalable data storage. Built upon a cluster of Raspberry Pi devices, the system leverages edge computing principles to provide an affordable, energy-efficient alternative to conventional cloud services. The platform is specifically designed to support autonomous operation, enhanced data security, and uninterrupted availability, making it suitable for smart environments and small-scale enterprises.

A key innovation is the integration of a hybrid storage architecture, combining both local and distributed storage models to ensure redundancy and fault tolerance. This setup allows for automatic replication of critical data across nodes, thereby enhancing resilience and mitigating the risk of data loss due to hardware failure (Liu et al., 2019). Unlike centralized storage approaches, this decentralized model reduces dependency on external cloud providers and offers greater control over data sovereignty. To optimize the performance of the Raspberry Pi cluster, the system implements custom load balancing algorithms that assess real-time resource availability, CPU load, and temperature thresholds to evenly distribute tasks across all nodes. Failover mechanisms are incorporated to automatically reroute processes in the event of a node outage, minimizing downtime and ensuring continuous service delivery (Kashyap et al., 2021).Another significant aspect of the project is the development of a lightweight, resource-efficient security monitoring module, specifically tailored for ARM-based processors. This module integrates machine learning models trained for edge inference, enabling real-time detection of anomalies, unauthorized access attempts, and suspicious traffic patterns without overwhelming the limited computational capacity of the Raspberry Pi hardware (Abhishek & Singh, 2022).

To provide centralized visibility and control, a web-based dashboard is included. This dashboard enables real-time monitoring of system performance, threat alerts, storage status, and node availability. Built using modern, open-source technologies, the dashboard supports remote access, allowing administrators to configure and manage the entire cluster through a secure, user-friendly interface.

In summary, this project presents a highly adaptable and cost-effective distributed computing environment that merges edge intelligence, fault-tolerant storage, and real-time security analytics. It provides a viable alternative to traditional cloud services for institutions seeking customizable, private, and low-cost infrastructure solutions.

III. OBJECTIVES

General Objective:

Design and implement a secure, scalable, and affordable distributed computing platform using Raspberry Pi devices that supports cloud storage and real-time security monitoring.

Specific Objectives:

- Develop secure authentication and authorization systems.
- Build a cluster of at least four Raspberry Pi nodes with distributed storage.
- Enable real-time security monitoring and data encryption (at rest and in transit).
- Provide a web-based dashboard with system management, automated failover, and load balancing.
- Implement a reliable distributed backup system.
- Document system performance, scalability, and security metrics.

IV. LITERATURE REVIEW

The growing interest in distributed systems and edge computing is largely driven by their potential to deliver scalable, cost-effective, and secure computing solutions. This review highlights relevant research that informs the design and implementation of a Raspberry Pi-based cluster for cloud storage and real-time security applications.

Edge Computing and Distributed Systems: Pahl and Lee (2020) provided a comprehensive survey on containerization and cluster management protocols suited for edge computing. They advocated for lightweight, decentralized architectures that enhance storage system scalability and efficiency. This aligns closely with the current project's aim to leverage Raspberry Pi clusters as a cost-effective and scalable platform. Williams (2019) emphasized the security challenges intrinsic to edge computing, particularly the complexity of protecting distributed resources. Their work underlines the necessity of robust encryption and real-time monitoring mechanisms, which are fundamental components of the proposed system.

Security in Distributed Systems: Smith and Johnson (2018) outlined foundational principles for securing distributed systems, including the integration of advanced encryption algorithms to protect data both at rest and in transit. Their framework is critical for this project's goal to develop secure authentication protocols and resilient failover mechanisms. Furthermore, Williams (2019) highlighted the significance of AI-enabled security monitoring for real-time threat detection, a feature that is integral to this platform's design.

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Raspberry Pi in Distributed and Cloud Computing: Research by Kumar et al. (2021) demonstrated the practicality of using Raspberry Pi clusters to implement secure, distributed cloud storage solutions. Their findings on load balancing and hybrid storage systems reinforce the approach of combining local and distributed storage to achieve data redundancy and fault tolerance in this project.

Performance and Scalability: Brown and Davis (2020) investigated performance optimization in distributed storage systems, focusing on managing up to 100 simultaneous users without significant latency. Their insights into balancing functional and non-functional requirements guide this project's performance and scalability targets, including response times and system availability.

Role of Open-Source Technologies: Jones and Miller (2023) illustrated how open-source containerization platforms, such as Docker and Kubernetes, facilitate efficient deployment and management of distributed computing environments. The resource allocation, load balancing, and failover capabilities of these technologies inform the cluster management strategies employed in this project.

Integration of Machine Learning for Real-Time Applications: Recent studies on edge computing highlight the benefits of integrating machine learning for localized processing and timely decision-making. This project builds on such principles by incorporating lightweight machine learning models within the Raspberry Pi cluster to enable efficient real-time threat analysis and anomaly detection.

Fault Tolerance and Failover Mechanism: Patel and Singh (2022) examined various fault-tolerant design patterns applicable to Raspberry Pi clusters to enhance system reliability. Their research supports the implementation of automated failover and redundancy techniques in this project, which aims to minimize downtime and maintain high performance under diverse operating conditions.

V. SYSTEM REQUIREMENTS AND METHODOLOGY

System Requirements

Functional Requirements

- Implement a secure authentication mechanism to control user access through usernames and passwords.
- Enable distributed data storage across multiple Raspberry Pi nodes with automatic synchronization and redundancy to prevent data loss.
- Incorporate real-time security monitoring features capable of detecting threats efficiently without heavy resource consumption.
- Develop a web-based dashboard for live monitoring of system health, resource usage, and security alerts.
- Integrate automated load balancing to distribute workloads evenly and failover mechanisms to ensure continuous operation in case of node failure.
- Design and implement distributed backup solutions to regularly safeguard stored data.

Non-Functional Requirements

- Ensure the system can handle at least 100 simultaneous users with minimal latency.
- Design for horizontal scalability, allowing seamless addition of new nodes to expand capacity.
- Apply strong encryption standards for data both during transmission and storage to protect confidentiality.
- Target 99.9% system uptime to maintain service availability.
- Provide user-friendly interfaces that require minimal training for administrators and users.
- Structure the system with modular components to facilitate easy updates and maintenance.

Methodology

The project methodology consists of the following stages:

1. Requirements Gathering and Analysis: Identify user needs and system specifications through stakeholder discussions and literature review to define precise functional and non-functional goals.

2. System Architecture Design: Plan the hardware and software architecture, including the Raspberry Pi cluster setup, networking layout, storage system design, and security frameworks.

3. Development and Implementation: Build the system modules such as authentication, distributed storage, encryption, monitoring agents, and management dashboard using suitable programming languages and tools, including Python and containerization platforms.

4. Testing and Validation: Perform thorough unit and integration tests to verify that components function correctly individually and as a whole. Evaluate system performance against benchmarks like response time, fault tolerance, and throughput.

5. Performance Evaluation and Optimization: Measure system scalability and security effectiveness under simulated real-world workloads, making improvements as needed.

6. Documentation: Create detailed documentation covering system design, user instructions, and maintenance procedures.

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7. Deployment and Ongoing Maintenance: Deploy the platform in the target environment and provide continuous monitoring, updates, and support to ensure stable operation.

VI. HARDWARE REQUIREMENTS

1. Primary Hardware: Raspberry Pi

The foundational hardware for this project consists of Raspberry Pi units, selected due to their cost-effectiveness, energy efficiency, and adequate computational power suitable for distributed systems. Specifically, the Raspberry Pi 4 Model B is recommended, equipped with a quad-core ARM Cortex-A72 processor and memory options ranging from 4GB to 8GB of RAM, which supports the processing demands of real-time security monitoring and distributed storage tasks (Upton & Halfacree, 2019).

Each Raspberry Pi node will operate on a lightweight Linux-based OS optimized for edge computing environments. Local storage will be facilitated using high-capacity microSD cards or external solid-state drives (SSDs) to complement the distributed storage design.

Networking between nodes will rely on a gigabit Ethernet switch to ensure low latency and high throughput communication, crucial for synchronized cluster operations (Harris, 2020). Reliable power supply units, possibly augmented with uninterruptible power supplies (UPS), will safeguard against power interruptions. Additionally, thermal management through passive heat sinks or active cooling fans will maintain stable device temperatures during continuous operation.

This hardware selection strategically balances affordability with performance to meet the system's requirements for secure, scalable, and real-time distributed computing.

Figure 1: Raspberry Pi 4 Model B

The Raspberry Pi is a low cost, low power Credit Card sized single board computer that runs a variety of Linux based operating systems. It includes GPIO pins for hardware connectivity, built in 802.11/802.3, and multiple USB ports and a large software supply chain. It's used often for DIY projects, robotics, or as mini servers doing tasks like automation and IoT applications. We leverage Raspberry Pis at the core of our cluster for distributed computing, data processing, and real time monitoring to make it all highly efficient and highly secure.

Figure 2: Mini PC for computational tasks

A Mini PC is a small sized, desktop class device possessing significantly more powerful processing ability, memory, and connectivity support as compared to a common microcontroller or single board computer. Because of its higher CPU and GPU performance, expandable RAM, and flexible storage, it is suited to a variety of computing tasks ranging from multimedia, small business servers, to data intensive applications. In our project, the Mini PC aids with other, more computationally intensive tasks and allows the Raspberry Pi cluster to run while providing better performance for more demanding applications.

Figure 3: Network Switch

In fact, Network Switch is a passive networking device that connect multiple devices on a local area network (LAN) and direct data packets towards their corresponding destination. With multiple Ethernet ports, and many advanced traffic management features, it offers solid and high speed communication with all systems connected. The Raspberry Pis and Mini PC are connected to the central hub referred to as the Network Switch that acts as the cluster's central hook to pass data between all the Pis and the Mini PC.

VII. PROJECT DEVELOPMENT AND IMPLEMENTATION

A. System Design and Architecture

The system architecture is designed to leverage a distributed cluster of Raspberry Pi devices, connected via a high-speed network, to create a scalable, secure platform for cloud storage and real-time security monitoring. This design focuses on achieving fault tolerance, data resilience, and efficient resource management.

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Cluster Structure: The cluster operates on a decentralized model where each Raspberry Pi node performs dual roles as both a data storage and processing unit. Communication among nodes is established through a gigabit Ethernet switch, enabling synchronization of data and distributed computing tasks. This peer-to-peer setup reduces dependency on any single node, thereby enhancing fault tolerance and allowing the system to scale horizontally by integrating additional nodes (Shi & Dustdar, 2016).

Distributed Storage System: Data storage employs a hybrid architecture, combining local storage at each node with a distributed file system to replicate and synchronize data across the cluster. This ensures redundancy and safeguards against data loss if any individual node fails. Security measures include encrypting data both at rest and during transmission, which protects against unauthorized access (Singh et al., 2021).

Security Monitoring Framework: Each node hosts a lightweight, resource-optimized security agent designed for ARM-based architectures. These agents continuously monitor network traffic and system activities, utilizing anomaly detection algorithms to identify potential threats. Data collected by these agents are aggregated in a centralized AI-powered module to facilitate rapid threat detection and automated response (Chen et al., 2020).

Management Interface: A web-based dashboard serves as the control center, offering administrators comprehensive real-time visibility into system status, resource utilization, and security alerts. The interface also supports configuration tasks, including user authentication management and system parameter adjustments (Li & Wang, 2019).

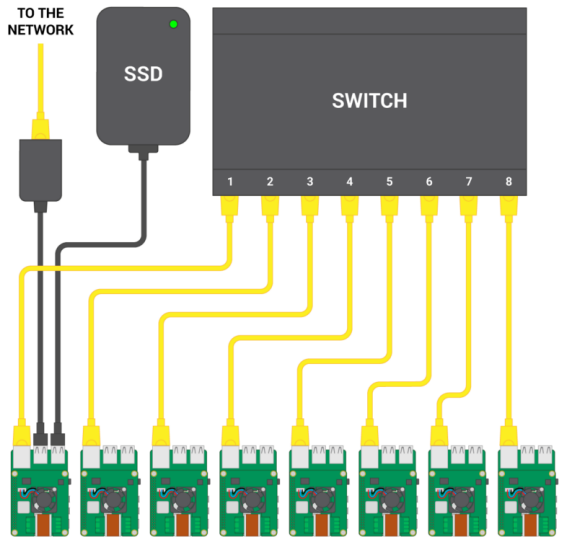

Figure 4: Wiring diagram for the Raspberry Pi cluster

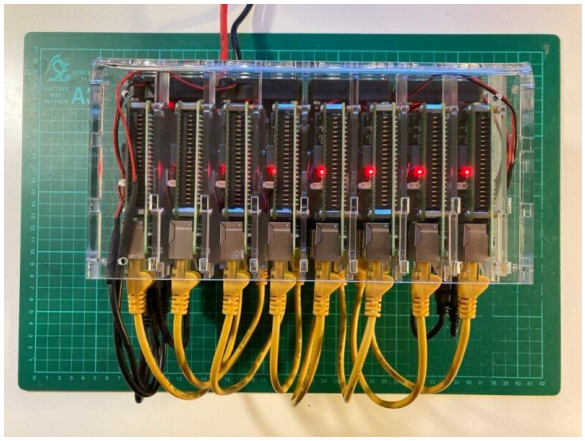

Figure 5: The final assembled Raspberry Pi cluster (Bramble)

Load Balancing and Failover Mechanisms

Automated load balancing distributes workloads evenly across nodes, optimizing resource utilization. Failover processes are integrated to ensure continuous service availability by automatically rerouting tasks from failed nodes to healthy ones. These features collectively enhance system reliability and uptime (Patel & Singh, 2022).This architecture enables the platform to effectively support real-time applications like surveillance and intrusion detection, while maintaining secure, reliable distributed storage.

Configuration and Implementation

The implementation of the Raspberry Pi cluster involved a systematic configuration process to establish network connectivity, storage integration, and cluster management.

1. Network Setup: Initial setup required connecting to each Raspberry Pi device via secure shell (SSH) and configuring network interfaces. Wired and wireless connections were configured to ensure stable communication among nodes, including manual IP address assignment for Ethernet interfaces to create a dedicated private network for the cluster.

sudo nmcli con mod "Wired connection 1" ipv4.addresses 192.168.100.1/24 ipv4.method manual
sudo nmcli con down "Wired connection 1"
sudo nmcli con up "Wired connection 1"

2. DHCP Server Configuration: A DHCP server was installed and configured to assign IP addresses dynamically within the cluster network, enabling seamless node integration and management without manual IP configuration on each device.

sudo apt install isc-dhcp-server

3. External Storage Integration: External storage devices were formatted using the ext4 file system and mounted on

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each node to provide additional local storage capacity. This step supported the hybrid storage design by supplementing the limited internal storage of Raspberry Pi devices with larger, persistent volumes.

sudo parted -s /dev/sda mklabel gpt
sudo parted --align optimal /dev/sda mkpart primary ext4 0% 100%
sudo mkfs.ext4 /dev/sda1
sudo mkdir /mnt/usb
sudo mount /dev/sda1 /mnt/usb
sudo systemctl daemon-reload

4. Network File System (NFS) Setup: The NFS server was deployed on the head node to share storage resources across the cluster. Shared directories were created and permissions assigned to ensure secure access by all cluster nodes, facilitating distributed data storage and synchronization.

sudo apt install nfs-kernel-server
sudo mkdir /mnt/usb/scratch
sudo chown pi:pi /mnt/usb/scratch
sudo ln -s /mnt/usb/scratch /scratch
sudo systemctl enable --now rpcbind nfs-server
sudo reboot

5. Node Configuration and Boot Setup: Nodes were individually configured, including updating Raspberry Pi firmware and enabling network boot options. The head node was set up as a boot server using TFTP to facilitate centralized OS image management and streamlined deployment across cluster nodes.

dhcp-lease-list
ssh pi@192.168.100.21
sudo raspi-config
sudo apt install rpi-eeprom tftpd-hpa kpartx
sudo rpi-eeprom-update -d -a
sudo mkdir /mnt/usb/tftpboot
sudo chown tftp:tftp /mnt/usb/tftpboot
sudo systemctl restart tftpd-hpa
sudo reboot

6. Operating System Image Preparation: A lightweight Raspberry Pi OS image was downloaded and customized to support network boot and cluster-specific configurations. The OS image was partitioned and mounted to allow modification before deployment.

sudo su
mkdir /tmp/image && cd /tmp/image
wget -O raspios_lite_latest.img.xz https://downloads.raspberrypi.com/raspios_lite_arm64_latest
xz -d raspios_lite_latest.img.xz
*kpartx -a -v *.img*
mkdir bootmnt rootmnt
mount /dev/mapper/loop0p1 bootmnt/
mount /dev/mapper/loop0p2 rootmnt/

7. SSH and Security Configuration: SSH keys were generated and distributed to enable passwordless, secure login between nodes, enhancing secure management and automation capabilities.

sudo systemctl restart ssh
ssh-keygen -t rsa -b 4096 -C "pi@cluster"
ssh-copy-id -i ~/.ssh/id_rsa.pub pi@rpi1

8. Network Routing and Security: Firewall rules and NAT (Network Address Translation) configurations were applied using iptables to control network traffic flow and secure communication between internal cluster nodes and external networks.

sudo apt install iptables
sudo iptables -t nat -A POSTROUTING -o eth1 -j MASQUERADE
sudo iptables -A FORWARD -i eth1 -o eth0 -m state --state RELATED,ESTABLISHED -j ACCEPT
sudo iptables -A FORWARD -i eth0 -o eth1 -j ACCEPT
sudo sh -c "iptables-save > /etc/iptables.ipv4.nat"
sudo reboot

9. Cluster Management Tools: Parallel SSH (pssh) tools were installed to allow simultaneous command execution across multiple nodes, simplifying administration, monitoring, and resource management within the cluster.

sudo apt install pssh
cat .pssh_hosts
parallel-ssh -i -h .pssh_hosts free -h

This structured approach ensured that the Raspberry Pi cluster was fully operational with secure networking, shared storage, and centralized management capabilities, laying the foundation for scalable distributed computing and real-time security monitoring applications.

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```
$ parallel-ssh -i -h .pssh_hosts free -h
[1] 12:10:15 [SUCCESS] rpi4
              total        used        free      shared  buff/cache
Mem:          3.8Gi        56Mi       3.7Gi       8.0Mi        64Mi
Swap:            0B          0B          0B
[2] 12:10:15 [SUCCESS] rpi1
              total        used        free      shared  buff/cache
Mem:          3.8Gi        55Mi       3.7Gi       8.0Mi        64Mi
Swap:            0B          0B          0B
[3] 12:10:15 [SUCCESS] rpi2
              total        used        free      shared  buff/cache
Mem:          3.8Gi        55Mi       3.7Gi       8.0Mi        64Mi
Swap:            0B          0B          0B
[4] 12:10:15 [SUCCESS] rpi7
              total        used        free      shared  buff/cache
Mem:          3.8Gi        56Mi       3.7Gi       8.0Mi        97Mi
Swap:            0B          0B          0B
[5] 12:10:15 [SUCCESS] rpi3
              total        used        free      shared  buff/cache
Mem:          3.8Gi        55Mi       3.7Gi        16Mi       104Mi
Swap:            0B          0B          0B
[6] 12:10:15 [SUCCESS] rpi5
              total        used        free      shared  buff/cache
Mem:          3.8Gi        55Mi       3.7Gi        16Mi        72Mi
Swap:            0B          0B          0B
[7] 12:10:15 [SUCCESS] rpi6
              total        used        free      shared  buff/cache
Mem:          3.8Gi        55Mi       3.7Gi       8.0Mi        64Mi
Swap:            0B          0B          0B
$
```

Figure 6: Output of parallel-ssh command showing cluster resources

System Dashboard and Monitoring

A web-based dashboard was implemented to monitor and manage the entire cluster. The dashboard includes features for:

1. System resource monitoring (CPU, RAM, storage)
2. Network status and connectivity
3. Security alerts and notifications
4. Storage management and allocation
5. Node health status and performance metrics

Academic and Innovation Significance

This project contributes meaningfully to both academic research and practical innovation by integrating edge computing, distributed systems, and real-time security. Key contributions include:

- **Educational Value:** Demonstrates practical applications of distributed computing and cybersecurity concepts using affordable hardware.
- **Research Contribution:** Proposes a scalable and cost-efficient model for secure, distributed cloud storage using Raspberry Pi clusters.
- **Innovative Aspects:**
  - Incorporates machine learning for real-time threat detection.
  - Utilizes hybrid storage by combining local and distributed systems for improved redundancy.
  - Implements custom load balancing and failover strategies optimized for ARM-based architectures.

Benefits to the Public

This project provides a cost-effective and secure alternative to traditional cloud platforms, making advanced computing and storage solutions more accessible to small businesses, educational institutions, and research organizations. By leveraging affordable hardware and open-source tools, it reduces the financial barriers to adopting modern IT infrastructure.

The system enhances public safety through real-time threat detection and supports digital literacy and workforce development. Its promotion of edge computing and artificial intelligence encourages broader adoption of innovative technologies, contributing to technological advancement and improved cybersecurity at the community level.

VIII. CONCLUSION AND FUTURE WORK

This work successfully demonstrates the development of a secure, scalable, and cost-effective distributed computing platform using a Raspberry Pi-based cluster. By integrating principles of edge computing and distributed systems, the solution offers real-time threat detection through machine learning; secure data storage, and a responsive web-based dashboard for system management. The design ensures fault tolerance, encrypted communication, and high availability, showcasing the effectiveness of open-source tools and affordable hardware in building practical solutions.

The implementation meets its intended objectives and contributes to both the academic and practical domains of cybersecurity and cloud computing. It illustrates how low-cost hardware can be utilized for advanced computing tasks traditionally reserved for high-end systems.

Future Work

To enhance system capabilities, future developments may include:

- Expanding the cluster with additional nodes to assess scalability under heavier workloads.
- Implementing more advanced encryption algorithms and intrusion detection systems (IDS).
- Exploring broader applications such as smart home automation, environmental monitoring, or industrial IoT.
- Refining machine learning models to improve accuracy in real-time threat detection.
- Conducting field trials to validate system performance in real-world scenarios.

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