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Article

A Cost-Effective QR Code-Based Equipment Management System for Small-Scale Clinical Facilities

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Abstract: The rapid proliferation of medical devices in clinical settings necessitates efficient tracking and maintenance to ensure healthcare quality and cost optimization. (Gap) Despite technological advancements, many small to medium-sized clinics continue to rely on manual, paper-based equipment management systems. These traditional methods are prone to human error, lack real-time monitoring, and suffer from inefficient audit trails. (Objective) This study aims to develop a cost-effective, QR code-based equipment management system tailored specifically for small-scale clinical facilities. The proposed system integrates a Flutter-based cross-platform application with a centralized PostgreSQL database, utilizing standard webcams for QR code scanning to eliminate the need for expensive, dedicated scanning hard-ware. (Findings) Experimental implementations demonstrate that the system achieves a >95% QR code identification success rate at optimal scanning distances (0.3–1.0m) under standard lighting. Further-more, the architecture guarantees 99.2% network uptime, seamless real-time data synchronization, and supports up to 20 concurrent users with low database query latency (15–30 ms). Cost analysis indicates significant economic advantages, with first-year operational costs ranging from $300 to $600, markedly lower than commercial alternatives. (Implications) By replacing outdated manual methods with an auto-mated, role-based tracking system, this solution provides clinics with a robust, accessible, and scalable tool to enhance operational efficiency and streamline equipment lifecycle management.

Keywords: Equipment Management; Medical Devices; QR Code; Flutter; PostgreSQL; Clinic Management; Healthcare Technology.

1. Introduction

Private clinics and medical facilities are expanding rapidly to meet growing healthcare needs [1]-[3]. Modern clinics now utilize significantly more medical devices than in previous decades, including blood pressure monitors, pulse oximeters, ultrasound machines, electrocardiogram devices, and laboratory testing equipment [4]-[7]. Effective management of these devices is crucial for maintaining healthcare quality, clinic reputation, and cost optimization. However, many clinics continue to rely on outdated manual management methods, resulting in numerous challenges including inability to monitor equipment operational status, inadequate maintenance scheduling, excessive paperwork for audit trails, and increased risk of equipment failure and service disruption [8]-[10].

The proliferation of medical equipment necessitates intelligent, automated management solutions, heavily supported by the evolution of Internet of Things (IoT) architectures and context-aware computing [11]-[14]. Modern technology has enabled the development of automated systems for equipment monitoring and management, particularly in healthcare settings. Driven by advancements in high-efficiency wireless networks such as IEEE 802.11ax and 5G [15]-[17], as well as robust cloud computing paradigms [18], these solutions can monitor and control medical equipment more effectively, efficiently, and accurately than manual methods—reducing human error while improving equipment maintenance and operational efficiency.

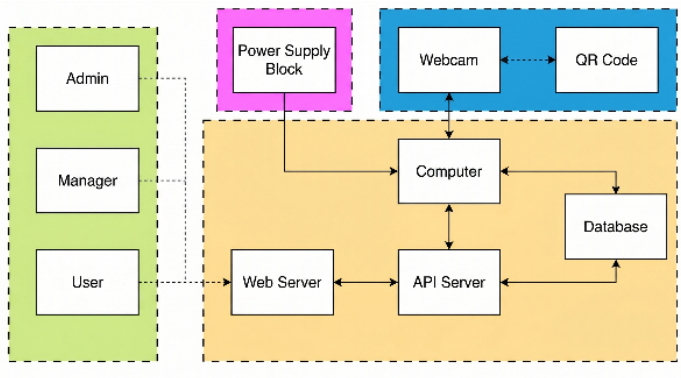

Figure 1. System Block Diagram.

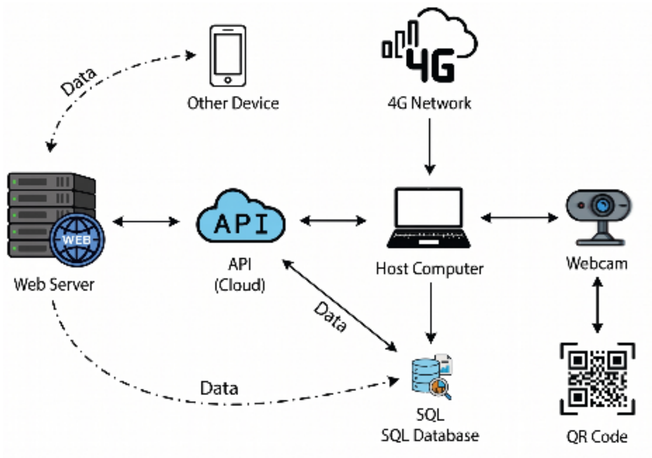

Figure 2. System Operating Principal Diagram.

Table 1. Component Power Specifications.

Component	Voltage (V)	Current (A)	Power (W)
Laptop Computer	20 DC	12	45
Webcam (USB)	5 DC	0.5	1

Note: *The power consumption value for the laptop computer represents the average operational consumption during system runtime, rather than the maximum capacity of the power adapter.*

The contribution of this research is the development and implementation of a comprehensive equipment management system tailored for clinical environments. The system integrates webcam-based QR code scanning, multi-platform application support via Flutter, centralized database management using PostgreSQL [19], [20], and role-based access control with comprehensive audit logging to address critical interoperability and security issues in healthcare IoT [21]-[23].

This research aims to develop and implement a comprehensive equipment management system for clinical facilities. The system integrates multiple technologies including webcam-based image capture, QR code identification, optical barcode decoding processing, and a reliable centralized database with real-time data synchronization capabilities. The primary objectives are: (1) developing a cross-platform application using Flutter framework for web, mobile, and desktop deployment; (2) implementing QR code-based equipment identification and tracking; (3) establishing role-based access control and authentication mechanisms; (4) maintaining comprehensive audit logs for all system transactions; and (5) ensuring system scalability to accommodate future equipment additions and user base expansion.

The remainder of this paper is organized as follows. Section 2 details the research methodology, including the system architecture, hardware components, and evaluation protocols. Section 3 presents the experimental results, scanning performance evaluation, and a comprehensive cost-benefit analysis. Section 4 outlines the limitations of the current study and directions for future work. Finally, Section 5 concludes the paper.

2. Research Methodology

2.1. System Architecture

The system architecture is built upon a cloud-integrated three-tier model comprising presentation, application, and data layers. As illustrated in Figure 1, the architecture eliminates the need for an expensive on-site dedicated hardware server. Instead, it utilizes a standard local host computer to manage hardware interactions and user interfaces, which seamlessly communicates with a cloud-based API and a centralized database management system.

To ensure reliable connectivity across various clinical environments, the system employs a hybrid network strategy. It utilizes WiFi 6 (802.11ax) for high-speed, localized data transmission within the facility, while integrating a 4G LTE cellular network as a backup or alternative for remote access and real-time data synchronization in scenarios where broadband infrastructure is unstable.

The operational workflow, depicted in Figure 2, begins with secure user authentication, followed by role-specific operations such as equipment catalog browsing, borrowing request submission, and equipment check-in/check-out via optical QR code decoding. The cloud-hosted database ensures transactional integrity for all operations and propagates changes instantly across all connected mobile and web interfaces.

2.2. Hardware Components

The hardware selection for this system heavily prioritized cost-effectiveness, accessibility, and a balance of performance suitable for small-scale clinics. Rather than investing in specialized enterprise server hardware, the system employs a standard, pre-existing laptop computer as the primary local processing unit. This host computer is solely responsible for running the client application and interfacing with external peripherals, delegating heavy data processing to the cloud backend.

For equipment tracking, the system utilizes a standard Logitech C270 webcam [24], [25], which provides HD 720p image capture capabilities. Instead of relying on computationally heavy machine learning models or advanced

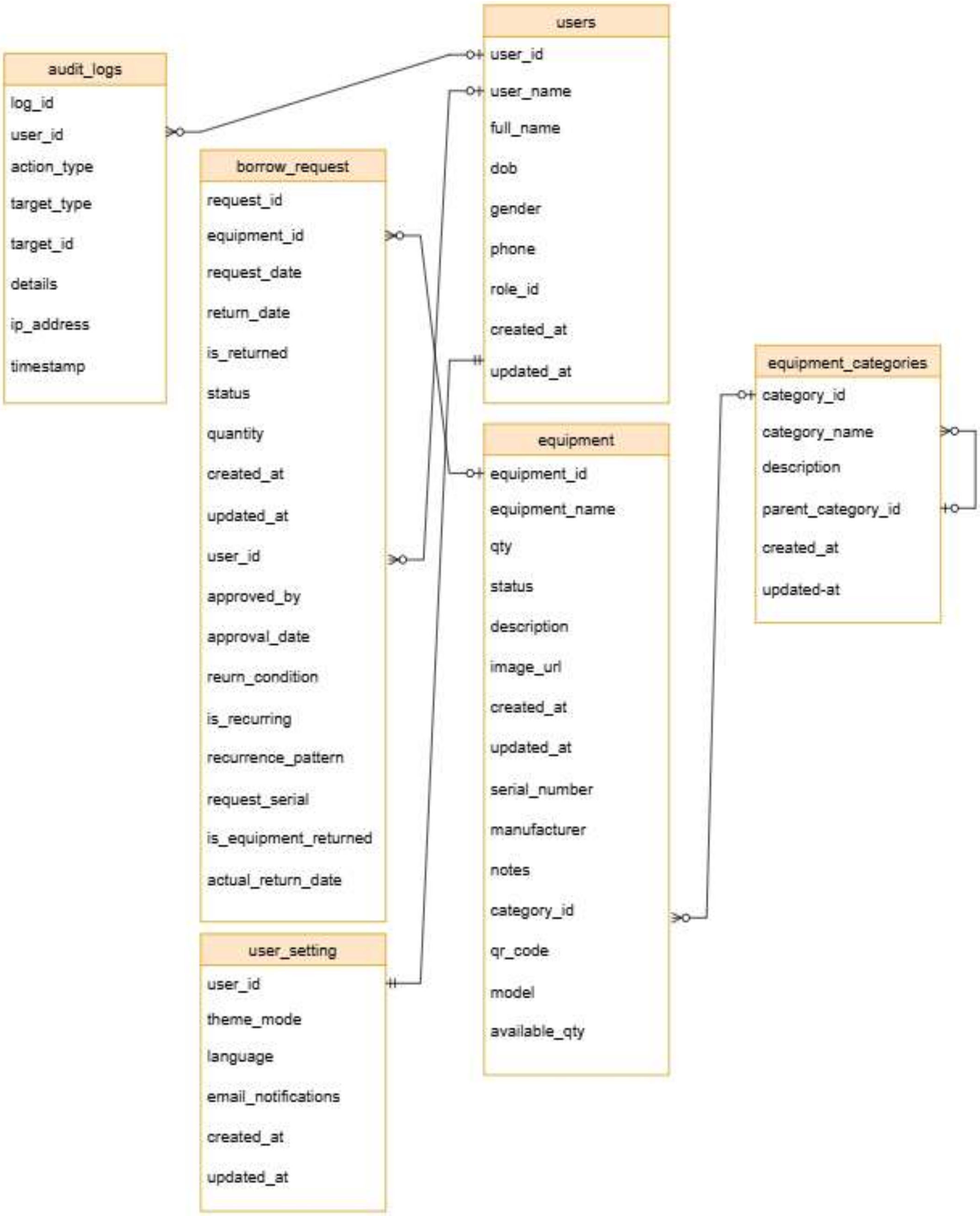

Figure 3. Database Schema Diagram.

Table 2. Main Database Tables and Main Attributes.

Table Name	Primary Key	Main Attributes
users	id (UUID)	email, password, role, name, phone
equipments	id (UUID)	name, description, category_id, quantity, status, serial_number, qr_code
equipment_categories	id (INTEGER)	name, description, created_at
borrow_requests	id (UUID)	user_id, equipment_id, request_date, approval_status, return_date
audit_logs	id (UUID)	user_id, action, entity_type, entity_id, timestamp
user_settings	id (UUID)	user_id, preferences, notification_enabled

computer vision pipelines, the system implements a straightforward, highly efficient image-based optical barcode decoding method to recognize QR codes.

This practical approach significantly reduces computational overhead while maintaining high identification accuracy. Table 1 presents the power specifications for all hardware components, demonstrating the remarkably low energy footprint of the local setup.

2.3. Database Design

To evaluate the QR code scanning performance and system metrics (such as the "Up to 20 users" capacity), a

Table 3. User Roles and Available Features.

User Role	Access Level	Key Features
Public User	Read-Only	View equipment catalog, submit borrowing requests, track request status
Equipment Manager	Moderate	Approve/reject requests, QR code scanning, equipment tracking, view history
Administrator	Full	User management, equipment CRUD, category management, analytics, audit logs, system settings

Figure 4. System Implementation Overview.

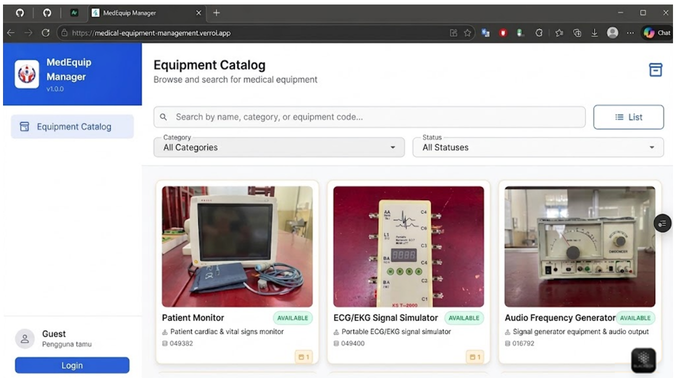

Figure 5. User Web Interface - Equipment Catalog.

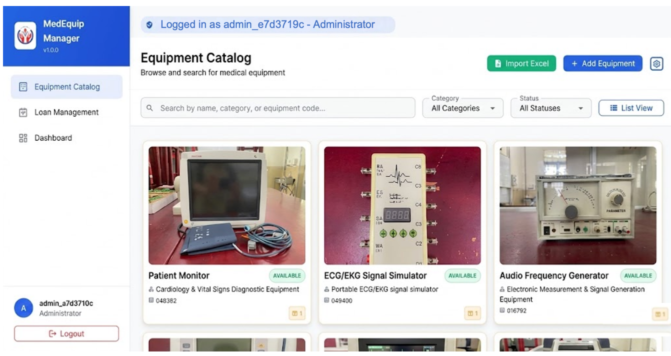

Figure 6. Administrator Dashboard Interface.

controlled experimental protocol was established. The QR code success rate was measured across 100 trials for each distance and lighting condition to ensure statistical reliability. Concurrency testing was simulated using load-testing tools to measure database response times and memory usage under peak load conditions.

The database schema comprises six primary tables with relational constraints enforced via foreign keys. Figure 3 shows the entity-relationship diagram. Table 2 details the primary tables and their key fields.

3. Result and Discussion

3.1. System Implementation Results

The system for managing and using equipment in a clinic worked well and was implemented. The picture in Figure 4 shows how the entire system works, including the parts that have electricity and the wires that connect them. The system worked well with the 4G LTE network and WiFi 6 (802.11ax) at the 5GHz frequency band.

3.2. Web Interface Functionality

The web interface provides role-specific functionality as illustrated in Figure 5 and Figure 6. Regular users can browse the equipment catalog with search, filter, and categorization capabilities. Equipment managers handle borrowing request approvals and QR code scanning operations. Administrators possess full system access including user management, data creation/modification, and comprehensive reporting. Table 3 summarizes the feature availability by user role.

3.3. QR Code Scanning Performance

We tested how well QR codes worked in different situations. Table 4 demonstrates the QR code scanning process. The table below shows how well the system works, how long it takes to scan, and what settings are best. Results show >95% success rate under optimal conditions (0.3-1.0m distance, 10cm+ QR code size, normal lighting).

3.4. Overall System Performance Evaluation

A thorough performance assessment was conducted across various areas. Table 5 shows how well the system performs, including how often it runs the software, how often it queries the database, how often it can connect to the network, and how well the hardware components perform. The system works well and delivers fast, good results across all parts.

3.5. Cost-Benefit Analysis

Table 6 presents the initial implementation costs of the proposed system. The analysis assumes the utilization of pre-existing infrastructure, listing the laptop cost as $0 since most clinics can repurpose an existing administrative

Table 4. 10x10 Cm QR Code Scanning Performance Metrics.

Test Condition	Distance (m)	Success Rate (%)	Avg. Time (s)
Optimal (normal light)	0.3-1.0	95-98	0.3
Near distance (normal light)	0.1-0.2	92-95	0.4
Far distance (normal light)	1.0-1.5	98-80	0.8
Dim lighting	0.5-1.0	75-85	0.6

Table 5. Overall System Performance Evaluation.

Performance Metric	Measured Value	Status
Web Application Load Time	1.2-2.5 seconds	Good
Database Query Response (Simple)	15-30 ms	Excellent
Database Query Response (Complex)	50-80 ms	Good
QR Code Scanning Success Rate	95-98%	Excellent
Network Uptime	99.2%	Excellent
Average Memory Usage	300-400 MB	Good
Equipment Update Latency	100-200 ms	Good
Concurrent User Support	Up to 20 users	Adequate

Table 6. System Implementation Cost Analysis.

Cost Component	Cost (USD)	Frequency
Logitech C270 Webcam	30-50	One-time
Custom Webcam Mount	10-20	One-time
Laptop (existing)	0	N/A
Supabase Hosting (Free Tier)	0	Monthly
Supabase Hosting (Paid)	0-25	Monthly
4G LTE Data Plan	20-40	Monthly
Electricity	<5	Monthly
Total First Year Cost	**300-600**	**Annual**

computer. However, if hardware acquisition is required, a standard personal computer would add approximately $300 to $600 to the first-year expenses. In contrast, implementing a commercial medical equipment management solution typically requires an initial investment ranging from $2,000 to $5,000 annually. This comparison highlights the significant economic viability and cost-effectiveness of the proposed system for small-scale clinics.

4. Limitations and Future Work

While the proposed system demonstrates high accuracy and cost-effectiveness, several limitations must be acknowledged. First, the current implementation relies heavily on continuous network connectivity (4G LTE or WiFi), and performance may degrade significantly in offline scenarios. Second, the QR code scanning success rate is sensitive to dim lighting conditions and extended distances.

Future work will focus on developing an offline-first mobile architecture with local caching to ensure uninterrupted operations during network outages. Additionally, planned enhancements include implementing predictive maintenance scheduling using machine learning algorithms, integrating automated push notifications for overdue equipment, and conducting extensive field testing across multiple hospital environments to further validate system robustness.

5. Conclusion

This study successfully developed and implemented a QR code-based equipment management system tailored for clinical environments. The system achieved a 95% scanning success rate and proved to be a highly cost-effective alternative to commercial solutions. To ensure operational stability, system uptime and synchronization reliability were quantitatively evaluated through a controlled experimental protocol. Real-time synchronization reliability was measured using simulated concurrency load-testing tools, which confirmed seamless data propagation with an equipment update latency of 100–200 ms and database query response times remaining under 80 ms, even at peak capacities of up to 20 concurrent users. Furthermore, the 99.2% network uptime was achieved and monitored under a hybrid network architecture utilizing WiFi 6 with a 4G LTE backup. While the system demonstrates robust performance under these conditions, optimal real-time synchronization remains strictly dependent on continuous network connectivity, with performance susceptible to degradation in off-line or highly unstable network scenarios. Ultimately, by replacing manual tracking methods, this solution provides resource-limited medical facilities with a modernized, scalable, and efficient tool to manage their critical equipment inventory.

6. Declarations

6.1. Author Contributions

Phong-Luu Nguyen: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources; Writing - Review & Editing, Visualization; **Dinh-Hai Vu:** Formal analysis, Investigation, Resources; Data Curation, Writing - Original Draft; Funding acquisition; **Trong-Bang Tran:** Supervision, Project administration.

6.2. Institutional Review Board Statement

Not applicable.

6.3. Informed Consent Statement

Not applicable.

6.4. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.5. Acknowledgment

Not applicable.

6.6. Conflicts of Interest

The authors declare no conflict of interest.

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