

Secure Software Systems (IE3042)

Technical Paper.



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Secure IOT Device Management

Research, Design, and Implementation

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Abstract

The Internet of Things (IoT) has revolutionized the way we interact with devices and the environment, leading to increased complexity in managing and monitoring connected devices. A secure and efficient IoT device management system is essential to address these challenges. This paper presents the design, implementation, and testing of an IoT device management platform that enables remote control, real-time monitoring, and secure integration with external APIs. The system is built on a scalable architecture using Node.js and Express for the backend, PostgreSQL for data storage, and React with Redux Toolkit for the frontend. Key security features such as authentication, authorization, and data encryption are implemented to ensure the system's integrity and protect sensitive data. The platform undergoes rigorous testing, including unit tests for backend APIs and integration tests to validate system components. Deployment on cloud platforms ensures scalability and availability, with monitoring tools like Prometheus and Grafana used for performance monitoring. Regular maintenance includes updating dependencies and applying security patches. This paper demonstrates how the proposed IoT device management system meets the security, performance, and scalability requirements for diverse industrial and commercial applications.

Keywords: Internet of Things, Security, IOT Device Management, Remote Control, Real-time Monitoring, Node.js, Express, PostgreSQL, React, Authentication, Authorization, Data Encryption, Cloud Deployment

Project link: <https://github.com/k0k1s/IOTDMS>

1 Introduction

In simple terms, the Internet of Things (IoT) refers to the concept of connecting any device to the internet or to each other with an on and off switch. Over time, IoT has revolutionized the way we interact with devices and the environment around us. However, the complexity of managing and maintaining an eye on these connected devices has increased with their widespread availability. To overcome this challenge, we have developed a secure IoT device management platform designed to be versatile and applicable across various industries and applications.

Our platform offers comprehensive tools for managing IoT devices, including secure user authentication with JSON Web Tokens (JWT), robust password hashing, and role-based access control to ensure that only authorized users can manage devices. Users can register new devices, view detailed device information, and control device settings through an intuitive dashboard built with React and Redux Toolkit. The backend, powered by Node.js and Express, ensures high performance and scalability, while PostgreSQL serves as the reliable database for storing device data. The platform also incorporates advanced data handling and machine learning capabilities. Real-time monitoring and data analytics are facilitated, with Python-based machine learning models deployed via Flask for anomaly detection, threat prediction, and behavior analysis.

Secure communication is ensured through HTTPS, and additional security measures like CORS, content security policies, and rate limiting are implemented to protect against common vulnerabilities.

Integration with various third-party services and APIs is supported, allowing for seamless expansion and interoperability with other systems. Designed to handle many devices and users, the platform ensures robust performance and reliability, making it suitable for applications in smart homes, industrial IoT, healthcare, agriculture, and more. By incorporating advanced security measures, real-time insights, and data analytics, our system provides a reliable and scalable solution for efficient IoT device management.

2 Objectives

With our system, it is possible to

- Remotely control and Manage IOT devices from anywhere from the web interface.
- Real-time Monitoring including device status, performance metrics, and sensor data.
- Alerts and notifications (Malfunctions, low battery, abnormal sensor readings)

Additionally, it has scalability and flexibility for future concerns.

2.1 Research Phase

Going through research phase starting from conducting a literature review to understand existing IoT device management and monitoring systems. We have Identified the requirements and functionalities needed for the project based on the research findings. For that we have used below aspects as guidance

IoT Security Best Practices: Analyzing different IoT protocols, communication technologies, and cloud platforms for suitability. Like AWS IoT core, Microsoft Azure IoT Hub, Google Cloud IoT Core, IBM Watson IoT Platform, ThingWorx IoT Platform (PTC) were mainly studied as inspiration.

Encryption and Security Libraries: The research compares and evaluates encryption algorithms (e.g., AES, RSA) and cryptographic libraries (e.g., OpenSSL, Crypto++) through performance benchmarking and testing. Selected libraries are implemented in a test environment to assess their integration capabilities and usability in securing IoT device data and communications.

Authentication and Authorization: Investigating authentication protocols (e.g., OAuth, JWT) and evaluates their effectiveness in securing access to IoT devices and data. To see what implements authentication mechanisms in a simulated IoT device management system and assesses various authorization strategies, such as Role-Based Access Control (RBAC), to enhance security.

Database Security: Research on Database security principles and techniques, such as encryption at rest and access controls, to protect IoT device data from unauthorized access and breaches. It implements security measures in PostgreSQL and conducts penetration testing and vulnerability assessments to identify and mitigate potential risks.

Significance of Integrating Machine Learning: Role of machine learning in enhancing IoT device management system security, focusing on anomaly detection and threat prediction

Anticipated Security Benefits: The whole project is focused on security, potential security benefits of implementing advanced security practices and machine learning algorithms in IoT device management systems. Analyzes case studies and use cases to demonstrate the practical impact of improved security on operational efficiency, device reliability, and overall system integrity.

Novel Approaches and Contributions: To enhance the security of IoT device management systems. It develops innovative solutions to address existing security challenges and evaluates their effectiveness through comprehensive testing and validation in real-world scenarios.

What is IOT device Management?

It is important to understand and plan a life cycle of devices to manage devices in an IoT solution. There is a set of general device management stages that are common to all IoT solutions.

Device Lifecycle Stages

There are five stages within the device's lifecycle.

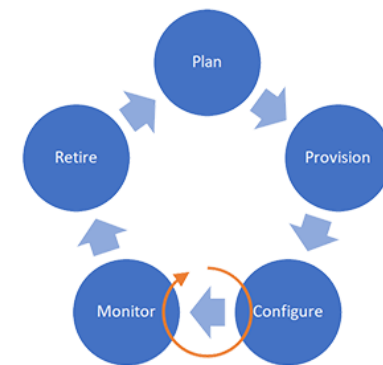


Figure 1 : Stages of IOT device lifecycle.

Stage	Description
Planning	Plan how to manage devices and define common tasks, settings, and properties to monitor.
Provisioning	Register and connect IoT devices to the cloud solution (e.g., Azure IoT Hub).
Configuring	Apply settings to the IoT devices once connected, such as enabling/disabling features, updating firmware, or changing settings.
Monitoring	Continuously monitor device health, connection status, operation status, and alert on errors that require attention.
Retire	Remove devices from the solution when they reach end-of-life, upgrade cycle, or end of service lifetime.

3 Design Phase:

In the design phase of our IoT device management system, we will define the data model for storing device information, sensor data, and user preferences. We will also discuss using OpenSSL for encryption, analyzing sensor data, and the communication protocols and data formats for interaction between IoT devices and the backend server.

3.1 System Architecture

- Frontend
- Backend
- Database

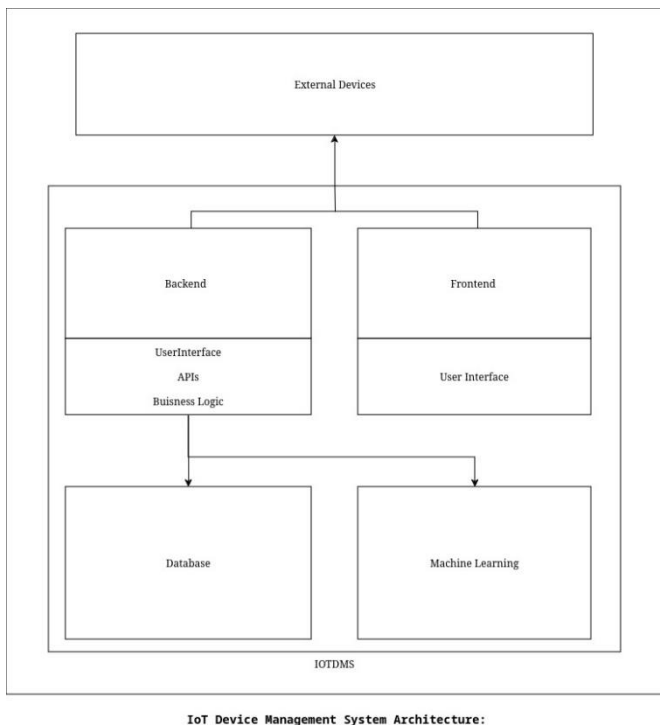


Figure 2 : System Architecture

Diagram Description

- External Devices (e.g., sensors, actuators) connect to the IoT Device Management system using various protocols.
- The Backend, implemented in Node.js, handles APIs, business logic, and integrates with machine learning components.

- The Frontend, built with React, provides a user interface for managing and monitoring devices.
- The Database, PostgreSQL, stores device data and analytics information.
- APIs facilitate communication between external devices and the IoT Device Management system.
- Machine Learning component analyzes device data for advanced analytics and insights.

3.2 File Structure

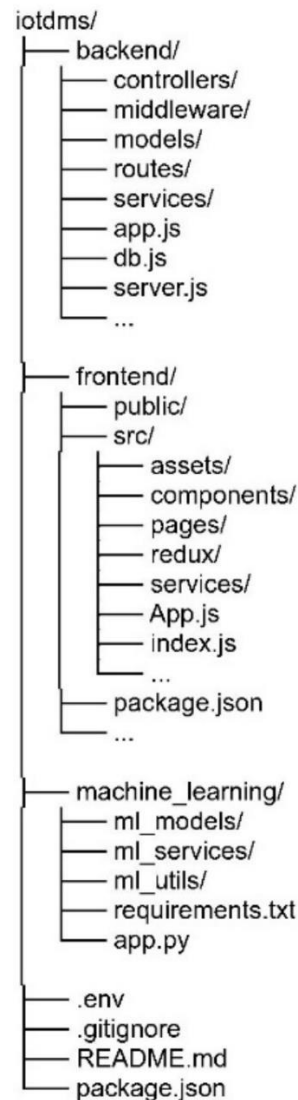


Figure 3 : File Structure

3.3 Data model

Using OpenSSL encryption with Postgres database system

Device Details

Column	Type	Collation	Nullable	Default	Storage	Stats target	Description
device_id	integer		not null	nextval('devices_device_id_seq'::regclass)	plain		
device_name	character varying(255)		not null		extended		
device_type	character varying(100)				extended		
device_status	character varying(50)				extended		
user_id	integer				plain		
created_at	timestamp with time zone			CURRENT_TIMESTAMP	plain		
updated_at	timestamp with time zone			CURRENT_TIMESTAMP	plain		

Indexes:

"devices_pkey" PRIMARY KEY, btree (device_id)

Foreign-key constraints:

"devices_user_id_fkey" FOREIGN KEY (user_id) REFERENCES users(user_id)

Figure 4 : Device details (as an example)

OpenSSL can be used to encrypt sensitive data before storing it in the database.

OpenSSL in Node.js

```
const crypto = require('crypto');
const algorithm = 'aes-256-cbc';
const key = crypto.randomBytes(32);
const iv = crypto.randomBytes(16);
function encrypt(text) {
  let cipher = crypto.createCipheriv(algorithm, Buffer.from(key), iv);
  let encrypted = cipher.update(text);
  encrypted = Buffer.concat([encrypted, cipher.final()]);
  return { iv: iv.toString('hex'), encryptedData: encrypted.toString('hex') };
}
function decrypt(text) {
  let iv = Buffer.from(text.iv, 'hex');
  let encryptedText = Buffer.from(text.encryptedData, 'hex');
  let decipher = crypto.createDecipheriv(algorithm, Buffer.from(key), iv);
  let decrypted = decipher.update(encryptedText);
  decrypted = Buffer.concat([decrypted, decipher.final()]);
  return decrypted.toString();
}
```

3.4 Analyzing sensor data

Analyzing sensor data can involve various machine learning techniques to detect anomalies or predict behaviors. For instance, you could use Python with a machine learning library such as scikit-learn or TensorFlow to build and deploy models.

Customization functions for personal preference

Users can customize their experience by setting preferences that are stored in the database and applied within the application.

```
const express = require('express');
const router = express.Router();
const { UserPreferences } = require('../models');

router.post('/setPreference', async (req, res) => {
  const { userId, preferenceKey, preferenceValue } = req.body;
  try {
    await UserPreferences.upsert({
      user_id: userId,
      preference_key: preferenceKey,
      preference_value: preferenceValue,
    });
    res.status(200).send('Preference saved');
  } catch (error) {
    res.status(500).send('Error saving preference');
  }
});

router.get('/getPreferences', async (req, res) => {
  const { userId } = req.query;
  try {
    const preferences = await UserPreferences.findAll({ where: { user_id: userId } });
    res.status(200).json(preferences);
  } catch (error) {
    res.status(500).send('Error fetching preferences');
  }
});
```

3.5 Protocols.

To ensure reliable communication between IoT devices and the backend server, the following protocols and data formats are used:

MQTT Protocol MQTT is a lightweight messaging protocol suitable for IoT devices due to its low power consumption and bandwidth efficiency.

```
{
  "device_id": "12345",
  "sensor_type": "temperature",
  "sensor_value": "22.5",
  "timestamp": "2024-05-19T12:34:56Z"
}
```

Figure 5 : MQTT Message Format

3.6 Wireframes

Login




Welcome to the NexIoT

[Forget password ?](#)

Login

[Create an account ? sign up](#)

Sign up.



User Name :

E-mail :


Password :

Confirm Password :


Sign up

[Already have a account ? Login](#)

Dashboard



Login / Sign up



Pages

Devices

Location

Areas

Automation Rule

Events

Tools

Other

About

Help

Contact Us

All Location

Zone

Filter

Devices

Show All

XXXXXXXXXX

XXXXXXXXXX

XXXXXXXXXX

XXXXXXXXXX

XXXXXXXXXX

XXXXXXXXXX

XXXXXXXXXX

XXXXXXXXXX

Add Devices

Add Devices

Device Name :

Set Nick Name :


Description :

Location:

Brand Name :


Module Number :

Upload Image:



3.7 Security Design

Security Concern	Example	Technology Used
Authentication and Authorization	Users log in with credentials and receive JWT tokens.	JWT, Express.js, Node.js
Encryption and Data Security	Sensor data encrypted using AES-256-CBC before storage.	OpenSSL, AES
Secure Communication Protocols	MQTT messages encrypted using TLS/SSL certificates.	MQTT, HTTPS, TLS/SSL
Role-Based Access	Admins have full access; users have	RBAC, Express.js, Node.js



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Control (RBAC)	limited device access.	
Secure Software Development	Regular security audits and secure coding practices.	ESLint, Code Reviews
Threat and Anomaly Detection	Machine learning detects abnormal device behavior.	Machine Learning Algorithms
Firmware Updates and Patch Management	Automated updates to fix security vulnerabilities.	
Logging and Monitoring	Access logs and real-time monitoring for suspicious activities.	Logging Frameworks, Monitoring Tools
Compliance and Regulatory Requirements	GDPR compliance by anonymizing personal data.	GDPR Guidelines
Incident Response and Recovery	Immediate response plan in case of data breach.	Incident Response Frameworks

4 Implementation Phase:

In the implementation phase of our IoT device management system, we will focus on developing key components including external devices, IoT device management, backend server, database, frontend interface, APIs, security features, testing, and deployment.

Key Components

- **External Devices:** IoT devices connected via MQTT protocols.
- **IoT Device Management:** Core system for device monitoring and management.
- **Node.js & Express:** Backend server framework for APIs and business logic.
- **PostgreSQL:** Relational database for storing device data.
- **React:** Frontend framework for web interface.
- **APIs:** RESTful interfaces for communication between frontend and backend.
- **OpenSSL:** Encryption and secure communication.
- **Machine Learning:** Component for advanced analytics.

4.1 Backend Development

The backend of the IoT device management system is responsible for handling business logic, data storage, security, and communication with IoT devices and the frontend. It is built using Node.js and Express, with a PostgreSQL database for persistent data storage. Below is a detailed breakdown:

Component	Technology Used	Description
Server Setup	Node.js, Express	Sets up the Express server, connects to PostgreSQL, and configures middleware.
Database Models	Sequelize ORM, PostgreSQL	Defines models for users, devices, and other entities, using Sequelize as the ORM.
Authentication	JWT, bcryptjs	Handles user registration, login, and JWT token generation for secure authentication.
Authorization	Middleware	Uses middleware to implement role-based access control (RBAC) for API endpoints.
Validation	express-validator	Validates and sanitizes input data to prevent injection attacks like SQL injection and XSS.
Cross-Origin Resource Sharing (CORS)	cors middleware	Restricts API access to trusted origins to prevent unauthorized access.
Rate Limiting	express-rate-limit	Implements rate limiting to prevent abuse and improve security against DoS attacks.
Error Handling	Custom error middleware	Centralizes error logging and handling to ensure consistent error responses.

Server.js /backend.


```
// server.js
const express = require('express');
const bodyParser = require('body-parser');
const cors = require('cors');
const rateLimit = require('express-rate-limit');
const { sequelize } = require('./models'); // Sequelize instance
const authRoutes = require('./routes/authRoutes');
const deviceRoutes = require('./routes/deviceRoutes');
const { errorLogger, errorResponder } =
require('./middleware/errorMiddleware');

const app = express();
const PORT = process.env.PORT || 3000;

// Middleware
app.use(cors());
app.use(bodyParser.json());
app.use(bodyParser.urlencoded({ extended: true }));

// Rate limiting
const limiter = rateLimit({
  windowMs: 15 * 60 * 1000, // 15 minutes
  max: 100 // limit each IP to 100 requests per windowMs
});
app.use(limiter);

// Routes
app.use('/api/auth', authRoutes);
app.use('/api/devices', deviceRoutes);

// Error handling
app.use(errorLogger);
app.use(errorResponder);

// Start server
sequelize.sync().then(() => {
  app.listen(PORT, () => {
    console.log(`Server running on port ${PORT}`);
  });
});
```

4.2 Frontend Development

The frontend of the IoT device management system provides a user interface for managing devices, viewing sensor data, and integrating APIs. It is built using React with Redux Toolkit for state management, and various libraries for UI components and API interaction:

Component	Technology Used	Description
State Management	Redux Toolkit, React-Redux	Manages application state and data flow across components using Redux Toolkit.
Routing	React Router	Implements client-side routing to navigate between different views without a page reload.
UI Components	Material-UI	Provides a library of UI components for building a responsive and modern user interface.
HTTP Requests	Axios	Handles HTTP requests to the backend API, enabling communication for CRUD operations.
Form Handling	Formik, Yup	Manages form state, validations, and submissions for user input with Formik and Yup.
Data Visualization	Chart.js	Displays charts and graphs for visualizing sensor data and analytics on the frontend.

```
// App.js
import React from 'react';
import { BrowserRouter as Router, Route, Switch } from 'react-router-dom';
import { Provider } from 'react-redux';
import store from './app/store';
import Login from './components/Login';
import Dashboard from './components/Dashboard';

function App() {
  return (
    <Provider store={store}>
      <Router>
        <Switch>
          <Route path="/" exact component={Login} />
          <Route path="/dashboard" component={Dashboard} />
        </Switch>
      </Router>
    </Provider>
  );
}

export default App;
```

4.3 Encryption and Security Implementation

The system incorporates several security practices to ensure data integrity and user privacy:

- **Parameter Validation:** Use express validator for backend request validation.

Validate and sanitize all user inputs to prevent injection attacks like SQL injection and cross-site scripting (XSS).

4.3.1 Parameter Validation Using express validator.

```
// controllers/authController.js

const { body, validationResult } = require('express-validator');

// Validation middleware for registration
exports.validateRegister = [
  body('username').trim().isLength({ min: 3 })
    .withMessage('Username must be at least 3 characters long'),
  body('email').isEmail().normalizeEmail().withMessage('Invalid email'),
  body('password').isLength({ min: 5 }).withMessage('Password must be at least 5 characters long'),
  (req, res, next) => {
    const errors = validationResult(req);
    if (!errors.isEmpty()) {
      return res.status(400).json({ errors: errors.array() });
    }
    next();
  }
];

// Validation middleware for login
exports.validateLogin = [
  body('username').trim().notEmpty().withMessage('Username is required'),
  body('password').notEmpty().withMessage('Password is required'),
  (req, res, next) => {
    const errors = validationResult(req);
    if (!errors.isEmpty()) {
      return res.status(400).json({ errors: errors.array() });
    }
    next();
  }
];
```

- **JWT:** Implemented in the backend for secure authentication.
Use JWT for authentication, ensuring secure transmission of authentication data between the client and server.

JSON web tokens

```
// middleware/auth.js

const jwt = require('jsonwebtoken');
const JWT_SECRET = 'your_jwt_secret_key';

// Generate JWT token
exports.generateToken = function(user) {
  return jwt.sign(user, JWT_SECRET, { expiresIn: '1h' });
};

// Middleware for authenticating JWT token
exports.authenticateToken = function(req, res, next) {
  const authHeader = req.headers['authorization'];
  const token = authHeader && authHeader.split(' ')[1];
  if (token == null) return res.sendStatus(401);

  jwt.verify(token, JWT_SECRET, (err, user) => {
    if (err) return res.sendStatus(403);
    req.user = user;
    next();
  });
};
```

- **CORS:** Set up in backend app.js using cors middleware.

Restrict Cross-Origin Resource Sharing (CORS) to only allow requests from trusted origins, typically the frontend of your application.

- **Cookie Flags:** Use cookie-parser and set appropriate flags for cookies.

Restrict Cross-Origin Resource Sharing (CORS) to only allow requests from trusted origins, typically the frontend of your application.

```
// backend/app.js

const express = require('express');
const cookieParser = require('cookie-parser');
const app = express();

// Cookie setup
```

```

app.use(cookieParser('your_cookie_secret', {
  httpOnly: true, // HTTP only cookies
  secure: true, // Cookies only sent over HTTPS
  sameSite: 'strict', // Strict same-site policy
  maxAge: 3600000, // 1 hour expiry
  signed: true // Signed cookies
}));

// Other middleware and routes setup
app.use(express.json());
app.use(express.urlencoded({ extended: false }));

// Error handling middleware
app.use((err, req, res, next) => {
  console.error(err.stack);
  res.status(500).send('Something broke!');
});

module.exports = app;

```

- **Password Hashing:** Use bcryptjs for hashing passwords.

Using bcrypt

```

// controllers/authController.js

const bcrypt = require('bcryptjs');

// Hash password
exports.hashPassword = async function(password) {
  const salt = await bcrypt.genSalt(10);
  return await bcrypt.hash(password, salt);
};

// Compare hashed password
exports.comparePassword = async function(password, hashedPassword) {
  return await bcrypt.compare(password, hashedPassword);
};

```

- **Role-Based Access Control:** Integrated with authMiddleware.

```

// middleware/authMiddleware.js

// Dummy roles (replace with your actual role management logic)

```

```

const roles = {
  admin: ['GET', 'POST', 'PUT', 'DELETE'],
  user: ['GET']
};

// Middleware function for role authorization
exports.roleAuthorization = function(role) {
  return function(req, res, next) {
    const allowedMethods = roles[role];
    if (allowedMethods && allowedMethods.includes(req.method)) {
      next();
    } else {
      res.status(403).json({ message: 'Forbidden' });
    }
  };
};

```

- **Rate Limiting:** Implemented using express-rate-limit.

```

// backend/app.js

const express = require('express');
const rateLimit = require('express-rate-limit');
const app = express();

// Rate limiting setup
const limiter = rateLimit({
  windowMs: 15 * 60 * 1000, // 15 minutes
  max: 100, // limit each IP to 100 requests per windowMs
  message: 'Too many requests from this IP, please try again later'
});

// Apply to all requests
app.use(limiter);

// Other middleware and routes setup

// Error handling middleware
app.use((err, req, res, next) => {
  console.error(err.stack);
  res.status(500).send('Something broke!');
});

module.exports = app;

```

- **Password Policies:** Enforced in auth routes.

```
// Validate password against policies
exports.validatePassword = function(password) {
// Example: Password must be at least 8 characters, contain a
// number and special character
const regex = /^(?=.*\d)(?=.*[!@#$%^&*])(?=.*[a-z])(?=.*[A-Z]).{8,}$/;
return regex.test(password);
};
```

- **Redux Toolkit:** Used for managing state in the frontend.
- **Updated Dependencies:** Ensure to update packages regularly.

Using > `npm update`

- **Error Handling:** Centralized error handling in the backend.

```
// backend/app.js

const express = require('express');
const app = express();

// Other middleware and routes setup

// Centralized error handling middleware
app.use((err, req, res, next) => {
  console.error(err.stack);
  res.status(500).send('Something broke!');
});

module.exports = app;
```

4.4 Testing

Unit Tests for Backend APIs: Backend APIs are thoroughly tested using frameworks like Jest and Super test. Each API endpoint is individually tested to ensure it handles requests correctly, processes data securely, and returns the expected responses. For instance, user registration and login endpoints are tested to validate authentication processes and error handling mechanisms.

Integration Tests: Integration tests verify that all system components, including the frontend and backend, work together seamlessly. These tests ensure that data flows

correctly between different layers of the application, from the database to the user interface. By testing the interaction between various parts of the system, integration tests help identify and resolve potential issues early in the development lifecycle.

4.5 Deployment, Monitoring and Maintenance

Deploying, monitoring, and maintaining the IoT device management system are critical for ensuring its continuous availability, performance, and security.

Deployment on Cloud Platforms: The backend Node.js server and PostgreSQL database are deployed on cloud platforms such as AWS, Azure, or Google Cloud. Docker containers are used to streamline deployment and ensure consistent performance across different environments. The frontend React application is also deployed on the same cloud platform to facilitate secure and scalable access.

Monitoring and Maintenance: Monitoring tools like Prometheus and Grafana are employed to continuously monitor the health and performance of the deployed applications. These tools provide real-time insights into key metrics such as CPU usage, memory consumption and response times. Regular maintenance includes updating dependencies and applying security patches to protect against vulnerabilities. Automated tests are integrated into the deployment pipeline to validate updates and ensure the system's stability and reliability.

5 Future Deployment

For future deployment, the IoT device management system will continue to evolve to meet the growing demands of IoT applications. Enhanced integration capabilities with emerging IoT devices and protocols will ensure compatibility and interoperability across various IoT ecosystems. The deployment will focus on optimizing resource management and energy efficiency, leveraging machine learning algorithms for predictive maintenance and anomaly detection.

Additionally, the system will continue to be updated with the latest security patches and enhancements to mitigate emerging cybersecurity threats. Continuous monitoring and evaluation will be conducted to improve system performance, scalability, and reliability. The future deployment aims to provide a scalable and robust solution that supports the dynamic requirements of IoT environments, ensuring seamless operation and enhanced user experience across different industries.

6 Conclusion

In conclusion, the IoT device management system presented in this paper offers a comprehensive solution for managing and monitoring connected devices across diverse applications. Leveraging technologies such as Node.js, Express, PostgreSQL, React with Redux Toolkit, and robust security measures, the system enables remote device control, real-time data monitoring, and secure API integrations.

Key features including authentication, authorization, and data encryption ensure the integrity and security of sensitive information. Thorough testing procedures validate system functionality, while cloud deployment on platforms like AWS, Azure, or Google Cloud provides scalability and availability. Monitoring tools such as Prometheus and Grafana offer real-time insights into system performance metrics, facilitating proactive maintenance and issue resolution.

This paper demonstrates how the proposed IoT device management system meets the security, performance, and scalability requirements for a wide range of industrial and commercial applications, providing a foundation for efficient and secure management of IoT ecosystems.

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<https://aws.amazon.com/iot-core/>(<https://aws.amazon.com/iot-core/>)

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<https://www.ptc.com/en/products/iiot/thingworx-platform/>(<https://www.ptc.com/en/products/iiot/thingworx-platform/>)

7 Appendix

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8 Authors

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