Smart Embedded System for Token-Based Airplane Restroom Management

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Abstract
In 2019, the International Civil Aviation Organization (ICAO) reported that scheduled air services carried approximately 4.5 billion passengers globally, marking a 3.6% increase from the previous year. The number of departures reached 38.3 million, a 1.7% rise compared to 2018 [1]. This data underscores the extensive utilization of aircraft and the significant volume of passengers in the aviation industry. With the number of passengers per plane being large on most airplanes and restrooms being limited, one common problem is efficient restroom management in airplanes. This is necessary to enhance passenger experience and reduce unnecessary congestion. This paper proposes an intelligent embedded system for token-based toilet reservations in airplanes. This proposal suggests a system comprising embedded sensors, real-time monitoring, and a digital token system to streamline restroom usage. By automating this reservation, passengers can find a comfortable way to access restrooms. Such a system will have passengers book restroom access via seatback screens or mobile applications, ensuring fair and orderly utilization. This fairness in access will enhance the overall passenger experience, improve hygiene, minimize wait times, and enhance comfort.

Keywords: Embedded System, Token-Based Reservation, Airplane Restroom, Occupancy Sensors, AI-Powered Management, Passenger Experience, In-Flight Services

I. INTRODUCTION

Modern aircraft accommodate hundreds of passengers, often leading to restroom congestion and inconvenience. Traditionally, we rely on an implicit agreement that a first-come, first-serve mechanism accesses these restrooms. However, this can cause confusion and inconvenience to passengers, especially on long-haul flights. Also, older people can find it inconvenient to keep standing and waiting for restroom access. This paper explores integrating embedded systems with real-time monitoring and artificial intelligence (AI) to create a more effective and robust restroom management system. The proposed system is designed to provide practical relief from these inconveniences, making restroom usage more efficient and less stressful. In the following sections, we will look at the architecture of such a design, important components, benefits, challenges, and the future of such an application.

II. SYSTEM DESIGN AND ARCHITECTURE

The proposed system comprises the following components:

- Digital Token System: Passengers request access to the restroom via in-flight seatback systems, handsets, or a mobile app, which assigns a priority number.

- Real-Time Monitoring: Embedded sensors detect restroom occupancy status and communicate with the reservation system, ensuring accurate tracking.
- Automated Notifications: Passengers receive alerts in their seatback monitors or phones when their turn approaches to minimize wait times and prevent unnecessary queuing.
- Priority Access: Priority queues can provide special provisions for elderly passengers, children, and individuals with medical conditions, allowing them faster access.
- Display Panels: Restroom availability and queue status are displayed at different strategic locations within the aircraft, ensuring clarity for all the passengers.
- AI-Based Prediction System: Machine learning algorithms predict restroom demand and adjust the queue dynamically to balance usage efficiently.

Provided below in figure 1 is a flow chart of how the proposed system will function.

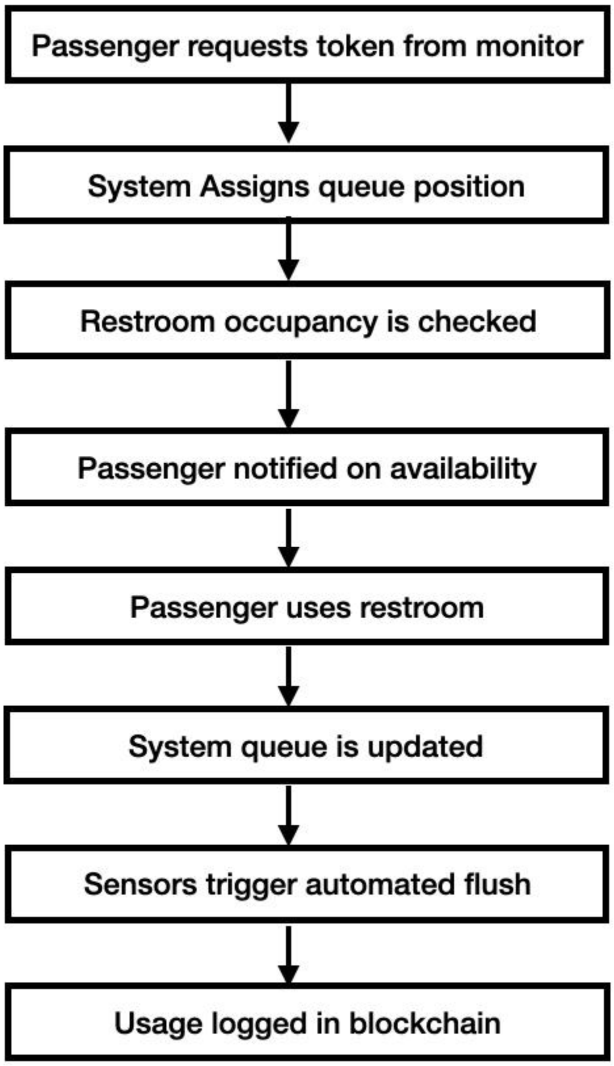

Figure 1: Flowchart of proposed system

III. EMBEDDEDSYSTEM AND SENSOR INTEGRATION

This proposal for a restroom reservation system uses embedded systems and sensors to streamline restroom management. These technologies enable real-time monitoring, hygiene assessment, and smooth data processing, making the system more efficient and automated.

A. Occupancy Detection and Monitoring

The proposed system employs infrared and load-based occupancy sensors to monitor real-time restroom usage. These sensors will detect human presence through passive infrared (PIR) motion detection or variations in weight pressure. Upon detecting occupancy, the sensors communicate with the embedded processing unit, which updates the system's queue status and prevents redundant requests. This ensures real-time dynamic queue management and prevents passengers from congesting the restroom area and causing inconvenience to fellow passengers in nearby seats.

B. Hygiene Monitoring and Automated Sanitation

One method discussed in [4] is soliciting visitor feedback through a dedicated device (smiley box) fitted in the restroom.In our proposed system we want to automate the system without violating user privacy. Hygiene monitoring sensors are integrated within the restroom to assess air quality, surface contamination levels, and general cleanliness. These sensors include gas sensors to detect odors, optical sensors for surface contamination, and humidity sensors to monitor moisture levels. When sanitation thresholds drop below predefined standards, an alert is automatically triggered to notify the flight crew for immediate action.

Additionally, the embedded system features an automated flushing mechanism that activates either through capacitive touch sensors or a programmed timer. This ensures the toilet flushes automatically after each use, maintaining hygiene standards and reducing the need for manual intervention. Integrating IoT-enabled sanitation monitoring allows the system to transmit real-time cleanliness data, enabling predictive maintenance and timely crew interventions to uphold restroom hygiene.

C. Data Processing and System Integration

A microcontroller-based processing unit manages sensor inputs and transmits real-time data to the aircraft's central system. This unit interfaces with the queue-based token management system, updating passenger queue positions based on restroom availability. The embedded system also leverages machine learning algorithms to dynamically predict restroom demand patterns and optimize queue distribution.

IV. TOKEN-BASED RESERVATION MECHANISM

From a study done across 10 transcontinental flights, it was found that half of the passengers did not use restroom during flight (42-58 %), 38 percent used it once , 9% used it twice and 3% used it more than twice [3]. This indicates how important is to have efficient queue management policies in-place to overcome such limitations in airplanes.

The smart token-based reservation system leverages real-time data processing, embedded computing, and AI-driven queue management to enhance efficiency and minimize congestion around restrooms. Various components of the token-based network are listed below.

A. Token Request and Assignment

Passengers initiate a restroom request via the in-flight entertainment system or a dedicated mobile application. The request is processed by an onboard embedded controller, which assigns the passenger a unique digital token.

B. Dynamic Queue Management

Once a token is assigned, the system places the passenger in a dynamic queue, continuously adjusting queue positions based on:

- Real-time restroom occupancy data from embedded sensors.
- Passenger seat location and estimated travel time to the restroom.
- Urgency levels are determined by AI-based predictive models analyzing passenger movement patterns.

To ensure fair and accurate queue management, these models consider flight duration, passenger load, and past usage patterns. The system calculates each passenger's estimated wait time and communicates this information via digital displays or notifications on the entertainment system or mobile application.

C. Notification and Access Control

As a passenger's turn approaches, the system triggers automated notifications through visual or audio alerts. The notification provides restroom location guidance and a usage window for passengers to utilize their reserved slot.

The restroom door should have an NFC, QR Code, or unique identifier-based access control system that verifies the digital token before granting entry. If a passenger fails to use their token within the allocated time, the system re-assigns the token to the following individual in the queue and puts this person at the end of the queue again. This process ensures continuous restroom availability and prevents misuse, enhancing the system's fairness.

V. AI-BASED OPTIMIZATION

Research has shown that on long-haul flights, lavatories are occupied between 63% and 72% of the flight time [2]. Such high occupancy rates highlight the need for AI-driven queue optimization to reduce wait times and improve passenger convenience.

The proposed systememploys artificial intelligence to enhance restroom accessibility, optimize resource allocation, and streamline passenger experience through data-based decisions. AI models will continuously analyze passenger movement patterns, restroom usage trends, and occupancy data to make real-time adjustments for queue management and efficiency improvements.

A. Predictive Analytics for Demand Forecasting

AI-driven predictive analytics utilize historical restroom usage data, passenger count, and flight duration to anticipate peak demand periods. By leveraging time-series analysis and pattern recognition, the system dynamically adjusts queue positions and optimizes restroom usage time and availability, ensuring a smooth passenger experience.

B. Adaptive Queue Management

Machine learning models continuously refine queue management strategies based on real-time data streams from embedded sensors. By analyzing passenger movement patterns, AI dynamically adjusts queue priorities, optimizing restroom access based on factors such as:

- Passenger medical conditions.
- Seat location and restroom proximity.
- Flight conditions and turbulence patterns.

This approach minimizes congestion, reduces restroom bottlenecks, and ensures equitable access for all passengers.

C. AI-Assisted Hygiene Monitoring

AI-powered hygiene assessment integrates real-time sensor data from air quality monitors, humidity detectors, and optical cleanliness sensors to evaluate restroom conditions. The proposed system will apply computer vision and anomaly detection algorithms to detect cleanliness issues, triggering predictive maintenance requests for cleaning crews.

Automating hygiene monitoring and integrating AI-driven sanitation scheduling ensures high cleanliness standards while reducing unnecessary manual interventions.

D. Personalized Restroom Recommendations

The AI system personalizes restroom usage recommendations based on passenger behavior and preferences. By analyzing past restroom usage frequency, seat location, and urgency, the system suggests optimal restroom availability slots to passengers, reducing unnecessary waiting times and improving passenger satisfaction.

By integrating advanced AI methodologies, the restroom reservation system enhances efficiency, optimizes resource utilization, and improves overall user experience, creating a seamless and data-driven restroom access framework.

VI. BENEFITS AND CHALLENGES

A. Benefits

- Reduces restroom congestion and passenger discomfort, ensuring smoother access.
- Ensures fair and organized restroom access by systematically managing queues.
- Improves in-flight hygiene and cleanliness through automated monitoring and AI-driven scheduling.
- Enhances overall passenger satisfaction and reduces stress related to restroom access.

B. Challenges

- Ensuring seamless integration with existing in-flight systems without significant infrastructural changes.
- Managing exceptions for emergency restroom access while maintaining fairness in the queue. One of the restrooms can still operate on a first-come, first-serve basis.
- Addressing potential connectivity and user adoption issues, especially for non-tech-savvy passengers.
- Overcoming resistance from airline operators who may be reluctant to adopt new restroom management systems.
- Training airline crew to efficiently manage and assist passengers with the token-based restroom system.

VII. FUTURE ENHANCEMENTS

- Voice-Controlled Assistance: Implementing voice-command systems for accessibility features, allowing hands-free token requests.
- IoT-Based Sanitation Monitoring: Advanced IoT sensors to monitor air quality, odor levels, and cleanliness, ensuring optimal restroom conditions.
- AI-Powered Personalization: Machine learning models to personalize restroom recommendations like time slots to passengers based on individual preferences and needs.
- Mobile App Integration: Seamless integration with airline apps, enabling passengers to manage restroom reservations from their devices.
- Integrating Blockchain: Using smart contracts to automate prioritization for passengers with special needs. Store tokens and usage logs in blockchain for secure access and fool-proof data analaytics for the AI models

VIII. CONCLUSION

The implementation of the smart token-based restroom reservation system presents several challenges, such as adaptability, emergencies, and reliability testing, that need to be addressed before widespread usage.

To facilitate a smoother transition and allow evaluation of this proposed system's effectiveness, one restroom on the aircraft needs to be maintained on a first-come, first-serve basis. This approach ensures that passengers have an alternative option while data is collected to refine and improve the system.

Future research will focus on AI-driven optimization, predictive analytics for demand forecasting, IoT-based hygiene monitoring systems, blockchain integration, and expanded accessibility features to further enhance in-flight restroom management. Enhancements such as AI-powered sentiment analysis and real-time feedback collection will also be explored to improve system responsiveness and passenger satisfaction.

IX. REFERENCES

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