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IoT-Based Voice Communication Control System for ATC Radar Simulator Support

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Abstract−The Voice Communication Control System (VCCS) used in the Air Traffic Control (ATC) Radar Simulator plays an essential role in supporting communication between ATC trainees and pseudo pilots during simulation-based training. However, the existing proprietary VCCS faces obsolescence issues, limited component availability, and high maintenance costs, creating challenges for long-term operational sustainability. This study proposes an Internet of Things (IoT)-based VCCS prototype as an alternative communication control solution using embedded wireless control and Android-based human-machine interfaces. The system was developed using a prototype-based approach consisting of requirements identification, conceptual architecture design, implementation, and iterative testing. Functional testing was conducted to evaluate core communication control features, followed by reliability and performance evaluation through 100 operational testing cycles. The results show that the developed prototype successfully fulfilled all primary functional requirements, including wireless connectivity, channel switching, push-to-talk control, digital volume adjustment, and voice communication. Reliability testing demonstrated an operational reliability of 96%, while cost analysis showed a cost efficiency of 91.05% compared to conventional proprietary VCCS systems. These findings indicate that the proposed IoT-based VCCS provides a practical, reliable, and economically sustainable solution for communication control modernization in aviation training environments.

Keywords: IoT-based VCCS; Air Traffic Control Radar Simulator; Voice Communication Control System; Reliability Analysis; Maintenance Sustainability

1. INTRODUCTION

Air Traffic Control (ATC) radar simulators play a crucial role in training cadets and air traffic personnel to operate in complex and dynamic airspace scenarios. These simulators are designed to replicate real operational environments by providing aircraft movement visualization, radar tracking, traffic sequencing, conflict detection, and communication-based coordination tasks. Through simulator-based training, ATC students are exposed to high-density traffic situations, abnormal flight conditions, and emergency scenarios without compromising actual flight safety. Such training environments are essential for developing decision-making skills, communication discipline, and situational awareness required in real ATC operations. According to previous studies, simulator-based learning significantly improves procedural understanding and operational readiness of air traffic personnel (Sharma et al., 2024).

To support realistic training sessions, an auxiliary communication subsystem known as the Voice Communication Control System (VCCS) is used to facilitate voice communication between ATC students acting as radar controllers and pseudo pilots simulating aircraft operations. In a typical training scenario, the radar simulator provides aircraft movement and traffic visualization, while the VCCS enables verbal interaction that closely resembles real air-to-ground communication. This interaction includes instruction delivery, pilot readback, route clearance, altitude assignment, handoff coordination, and emergency communication handling. Therefore, the VCCS functions as a supporting communication infrastructure rather than as an embedded core component of the radar simulator itself. The availability and reliability of the VCCS directly influence the effectiveness of simulator-based ATC training because communication failures may interrupt scenario execution and reduce training realism.

In many training facilities, conventional proprietary VCCS units have become increasingly difficult to maintain due to hardware obsolescence, limited spare part availability, vendor dependency, and high replacement costs. Many legacy systems were designed using closed proprietary architectures, making hardware repair and software modification difficult without support from the original manufacturer. As these systems age, maintenance complexity increases and operational downtime becomes more frequent. This creates significant operational risks because failures in the communication subsystem can disrupt ATC simulation sessions, reduce training continuity, and increase maintenance costs. Consequently, there is a growing need for an alternative communication architecture that is more sustainable, easier to maintain, and economically feasible for long-term deployment.

With the increasing adoption of the Internet of Things (IoT), it is now feasible to design more flexible, cost-effective, and wireless systems that can replace legacy communication infrastructure. IoT technology enables real-time control and monitoring of interconnected devices using lightweight embedded controllers and wireless communication frameworks, supporting flexible and distributed system operation (Li et al., 2024; Malkawi et al., 2023). In control and automation systems, IoT architectures offer several advantages, including modular scalability, remote accessibility, simplified maintenance, and distributed communication control. These characteristics make IoT particularly suitable for replacing conventional wired control systems that rely on rigid hardware configurations.

The NodeMCU ESP8266 is a low-cost Wi-Fi-enabled microcontroller that can be easily programmed using the Arduino IDE and offers sufficient processing capability for embedded control applications (Likhitha U. N. et al., 2024).

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Its built-in wireless communication capability enables direct integration with mobile-based control interfaces and networked devices without requiring expensive proprietary hardware. Programming environments such as Arduino IDE simplify firmware development, while Android-based applications such as Virtuino provide intuitive graphical user interfaces for real-time control, monitoring, and status visualization (Syahban & Misbah, 2025). The combination of ESP8266-based embedded control and Android-based user interfaces creates an attractive platform for modern communication control systems requiring mobility, flexibility, and ease of maintenance.

Prior research has demonstrated the efficacy of IoT-based solutions in domains such as industrial automation (Arun et al., 2024; Rathee et al., 2021), smart learning environments (Likhitha U. N. et al., 2024; Pancane et al., 2025), and avionics systems (Tavana et al., 2021). These studies indicate that IoT architectures can improve system flexibility, monitoring capability, and operational efficiency through wireless communication and distributed control. However, limited studies have specifically addressed the application of IoT as a replacement architecture for obsolete proprietary Voice Communication Control Systems (VCCS) used in ATC radar simulator training environments.

This study proposes the design and implementation of an IoT-based Voice Communication Control System (VCCS) as a sustainable replacement for legacy proprietary communication systems supporting ATC radar simulator training. The proposed system utilizes commercially available components, including the NodeMCU ESP8266, Android-based control panels, Wi-Fi communication, and UHF transceiver modules to provide wireless communication control across four operational channels. The contributions of this research are threefold. First, this study introduces an open and modular VCCS architecture that improves maintainability and reduces dependency on proprietary hardware. Second, the developed system is experimentally validated through reliability and performance testing in an ATC simulator training environment, demonstrating stable communication performance and high switching accuracy. Third, the proposed architecture provides significant economic benefits, achieving approximately 91.05% cost efficiency compared to conventional proprietary VCCS systems. These contributions demonstrate the feasibility of IoT-based communication control as a practical, scalable, and cost-effective solution for aviation training environments.

2. RESEARCH METHODOLOGY

This study adopts an applied prototype development approach grounded in the Design Science Research (DSR) methodology to design, develop, and evaluate an Internet of Things (IoT)-based replacement system for the Voice Communication Control System (VCCS) used to support Air Traffic Control (ATC) radar simulator training. The DSR methodology was selected because this research focuses on developing a functional engineering artifact intended to solve practical problems associated with legacy proprietary VCCS systems. The research process follows iterative development stages consisting of requirements identification, conceptual architecture design, system implementation, testing and refinement, and prototype validation. As illustrated in Figure 1, each stage was systematically conducted to ensure that the developed system satisfies operational, technical, and reliability requirements within the intended training environment.

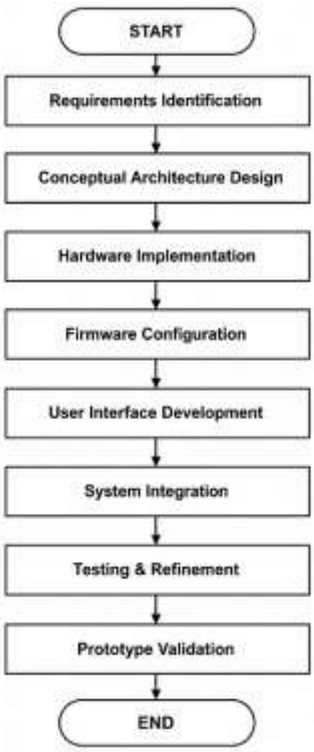

Figure 1. Flowchart of VCCS Prototype Development Design

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2.1 Prototype Development Framework

The development of the proposed IoT-based Voice Communication Control System (VCCS) followed a prototype-based engineering framework to ensure systematic design, implementation, testing, and validation. This framework was selected because the study focuses on developing a functional communication control prototype intended to replace legacy proprietary VCCS systems used in ATC radar simulator training environments. As illustrated in Figure 1, the development process consists of two primary design stages: requirements identification and conceptual architecture design. These stages establish the technical and operational foundation for subsequent implementation, testing, and prototype validation. The framework enables iterative refinement throughout development to ensure that the resulting system satisfies communication reliability, usability, and maintainability requirements.

2.1.1 Requirements Identification

The requirements identification stage was conducted through direct observation of the existing proprietary Voice Communication Control System (VCCS) used to support Air Traffic Control (ATC) radar simulator training. The observation focused on system operation, communication workflow, hardware condition, and control panel functionality to identify technical limitations and operational constraints of the legacy system.

The observation revealed several major limitations, including hardware obsolescence, limited spare part availability, high maintenance complexity, and restricted flexibility due to the conventional wired architecture. These issues may reduce communication reliability and disrupt training continuity (Tavana et al., 2021; Whitworth et al., 2021). Based on these findings, the proposed system was required to support wireless communication control, real-time channel switching across four communication channels, stable communication performance, and reduced dependency on proprietary hardware. Modularity, scalability, and maintainability were also established as key design requirements, consistent with core principles of IoT-based distributed control systems (Lea, 2020; Pancane et al., 2025).

2.1.2 Conceptual Architecture Design

Based on the identified system requirements, a conceptual architecture was designed to support wireless communication control, modular deployment, and simplified maintenance of the proposed IoT-based VCCS. The architecture adopts an Internet of Things (IoT) approach to enable distributed communication control through networked embedded devices, which improves scalability and system interoperability compared to conventional wired control systems (Li et al., 2024; Malkawi et al., 2023).

As illustrated in Figure 2, the proposed architecture consists of three functional layers: the user control layer, the IoT control layer, and the voice communication layer. The user control layer utilizes Android-based control panels running the Virtuino application to provide real-time channel selection and communication control. The IoT control layer consists of a wireless access point, local network infrastructure, and a NodeMCU ESP8266 microcontroller that processes user commands into control signals. The voice communication layer employs relay-based switching circuitry and a SA828 UHF FM transceiver module to manage voice signal routing across four communication channels.

This layered architecture was designed to ensure modularity, ease of maintenance, and efficient communication control within the ATC simulator training environment. By separating control, processing, and communication functions into distinct layers, the system can be upgraded or maintained with minimal impact on overall operation.

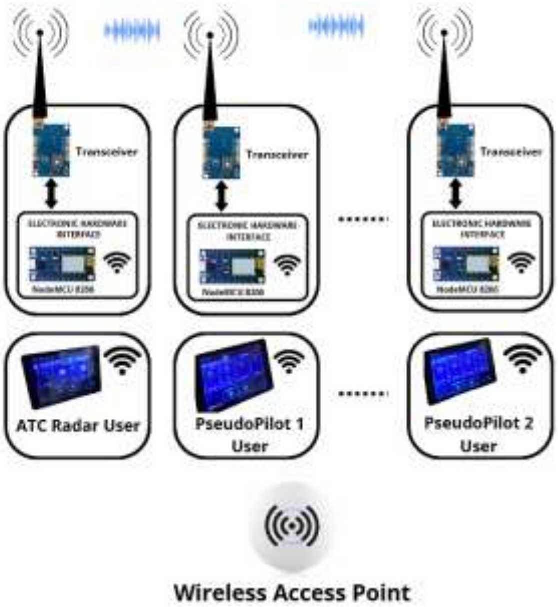

Figure 2. Proposed IoT-Based VCCS Architecture for ATC Simulator Support

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Figure 2 illustrates the overall architecture of the proposed IoT-based Voice Communication Control System (VCCS). The system operates alongside the Air Traffic Control (ATC) radar simulator as an independent supporting communication subsystem rather than being directly integrated into the simulator's core processing architecture. Its primary function is to facilitate realistic voice communication between ATC students acting as radar controllers and pseudo pilots during simulation-based training sessions. This separation allows the communication subsystem to be developed, maintained, and upgraded independently from the radar simulation platform.

The proposed architecture consists of three functional layers: the user control layer, the IoT control layer, and the voice communication layer. The user control layer comprises Android-based control panels running the Virtuino application, providing a graphical interface for channel selection, operational control, and system monitoring. Through this interface, users can select one of four communication channels, adjust audio settings, and activate communication functions in real time, thereby improving operator mobility compared to conventional wired control panels.

The IoT control layer consists of a wireless access point, local network infrastructure, a NodeMCU ESP8266 microcontroller, and a custom-designed PCB interface. Commands from the Android interface are transmitted through the local Wi-Fi network and received by the ESP8266 controller, which converts incoming instructions into control signals for switching operations. The ESP8266 was selected due to its low cost, integrated Wi-Fi capability, and sufficient computational performance for embedded control applications.

The voice communication layer consists of relay-based audio switching circuitry and a SA828 UHF FM transceiver module responsible for voice signal routing and channel transmission. This layer ensures stable audio communication between users within the simulation environment. Unlike operational ATC communication infrastructure, the proposed VCCS operates entirely within a controlled training environment and does not interface with live ATC radio systems. Overall, the architecture provides modular scalability, simplified maintenance, and significant cost efficiency while preserving the communication functionality required for ATC simulator training.

2.2 System Implementation

Following the conceptual architecture design, the proposed IoT-based VCCS was implemented as a functional prototype by integrating hardware, firmware, and software components into a unified communication control system. This stage focused on transforming the conceptual design into an operational prototype capable of supporting real-time communication control within the ATC radar simulator training environment. The implementation process consisted of four main stages: hardware implementation, firmware configuration, user interface development, and system integration. Each stage was carried out to ensure reliable communication control, stable wireless connectivity, and proper interaction between the embedded controller and user control interface.

2.2.1 Hardware Implementation

The hardware implementation stage translated the conceptual architecture into a functional VCCS prototype by integrating embedded control, communication, and interface modules into a custom-designed printed circuit board (PCB). The prototype consists of a NodeMCU ESP8266 microcontroller, a SA828 UHF FM transceiver module, channel selection circuitry, digital audio control circuitry, auxiliary relay modules, and supporting power regulation components. The system operates using a 5 VDC power supply to ensure stable operation of all embedded modules.

Two hardware variants were implemented to support different operational roles within the ATC radar simulator environment: the ATC control unit and the pseudo pilot control unit. Although both units share the same core communication architecture, the ATC unit includes additional auxiliary communication functions such as SP/IP mode selection and signaling controls, which are beyond the scope of this study. Therefore, this research focuses exclusively on hardware components associated with IoT-based communication switching, channel selection, push-to-talk (PTT) control, and digital audio adjustment.

Communication channel switching was implemented using a CD4053 multiplexer to generate the digital selection logic required by the SA828 transceiver for four-channel communication control. This approach enables efficient channel selection without requiring dedicated switching hardware for each communication channel. Relay modules were used only for auxiliary switching functions, primarily for PTT and signaling control. In addition, digital audio volume adjustment was implemented using an X9C103 digital potentiometer connected to the SA828 volume control pin, allowing remote audio level adjustment through the control interface. The ESP8266 acts as the main controller, converting wireless commands into digital control signals for channel selection, switching, and audio control. This hardware configuration provides a compact, modular, and low-cost implementation suitable for ATC simulator communication training.

2.2.2 Firmware Configuration

The firmware configuration stage focused on programming the NodeMCU ESP8266 microcontroller to enable wireless communication, command processing, and hardware control for the VCCS prototype. The firmware was developed using the Arduino IDE, which provides a flexible environment for implementing embedded control logic and GPIO-based device interaction.

The ESP8266 was configured as a client device connected to a local Wireless Access Point (WAP), enabling stable communication with the Android-based control interface. User commands generated through the Virtuino

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application installed on Android devices were transmitted over the local Wi-Fi network using Virtuino's internal communication protocol. The firmware continuously monitored incoming commands and interpreted them as control instructions for communication switching and device control.

After receiving a command, the ESP8266 converted the input into digital output signals used to control channel selection through the CD4053 multiplexer, auxiliary switching functions such as push-to-talk (PTT) activation, and digital audio volume adjustment through the X9C103 potentiometer. This firmware configuration enabled real-time communication control with low processing overhead and ensured reliable interaction between the wireless control interface and the hardware subsystem.

2.2.3 User Interface Development

The user interface was developed as a custom Android-based human-machine interface (HMI) panel to provide wireless communication control for both ATC operators and pseudo pilots. The interface was developed using the Virtuino application, which was selected due to its low-code development capability, rapid prototyping support, and seamless integration with ESP8266-based IoT systems over Wi-Fi. The developed interface enables simple, responsive, and real-time interaction with the VCCS prototype through the local wireless network.

The HMI panel provides real-time communication control through visual status indicators, active channel indicators, transmit indicators, and digital audio volume control. Volume adjustment is performed remotely through the Android interface, where volume commands are transmitted to the ESP8266 controller and converted into digital control signals for the X9C103 digital potentiometer connected to the SA828 transceiver volume control pin. This mechanism enables wireless audio level adjustment without requiring manual hardware tuning.

Two interface layouts were implemented to support different operational roles within the ATC radar simulator environment. The ATC interface was designed according to the operational workflow of the radar simulator, where each ATC console is permanently assigned to a single communication channel. Therefore, channel switching functionality is not required on the ATC interface. Instead, the interface provides Air-to-Ground (A/G) communication control and operational status monitoring. Additional SP/IP communication features are available but are beyond the scope of this study.

In contrast, the pseudo pilot interface includes channel switching capability because pseudo pilots must communicate with multiple ATC consoles during simulation sessions. The interface provides channel selection controls for Channel 1 to Channel 4, allowing pseudo pilots to dynamically select the intended communication target corresponding to Radar 1, Radar 2, Radar 3, or Radar 4. By adapting the interface to each operational role, the developed HMI improves usability, operational efficiency, and communication realism in ATC simulator training.

2.2.4 System Integration

The system integration stage combined the hardware, firmware, and user interface components into a unified IoT-based VCCS prototype capable of supporting real-time communication control within the ATC radar simulator environment. Integration was performed by establishing communication between the Android-based HMI, the local wireless access point (WAP), the ESP8266 controller, and the VCCS hardware subsystem.

In the integrated system, user commands generated from the Android interface were transmitted through the local Wi-Fi network to the ESP8266 microcontroller. The controller processed incoming commands and generated digital control signals to perform channel selection, push-to-talk (PTT) activation, and digital audio volume adjustment. These control signals interacted with the communication hardware subsystem, including the CD4053 multiplexer, relay modules, and X9C103 digital potentiometer, to execute the requested communication functions in real time.

After system integration, end-to-end functional verification was performed to ensure proper interaction among all subsystems. The verification process included testing wireless connectivity between the Android interface and ESP8266, validating channel switching functionality, confirming PTT operation, and verifying remote audio volume adjustment. Successful integration of these components produced a fully operational VCCS prototype ready for functional testing, reliability evaluation, and prototype validation.

2.3 Iterative Testing & Refinement

After system integration, the developed IoT-based VCCS prototype underwent testing and refinement to evaluate system functionality, operational stability, and performance. This stage aimed to ensure that all communication control functions operated according to design specifications before proceeding to prototype validation. The testing process consisted of functional testing, reliability testing, and performance evaluation. Any anomalies identified during testing were used as feedback for iterative refinement to improve overall system stability and operational reliability.

2.3.1 Functional Testing

Functional testing was conducted to verify that all major functions of the developed VCCS prototype operated according to the intended design. The testing focused on validating communication between the Android-based HMI and the ESP8266 controller, channel switching functionality, push-to-talk (PTT) activation, digital audio volume control, and voice communication through the SA828 transceiver module.

Each function was tested by executing corresponding control commands from the Android interface and observing the hardware response in real time. The testing procedure ensured that user commands were correctly transmitted, processed by the controller, and executed by the communication hardware subsystem. Functional testing served as the initial verification stage to confirm that the integrated system was ready for repeated operational testing.

2.3.2 Reliability Testing

Reliability testing was conducted to evaluate the operational stability of the developed VCCS prototype using a failure detection approach under repeated operating conditions. The test was performed through 100 operational cycles to simulate repetitive usage during ATC radar simulator training sessions. One operational cycle consisted of opening the Android-based VCCS application, establishing automatic connection to the local wireless network and ESP8266 controller, operating the communication system, performing communication testing using push-to-talk (PTT), executing channel switching for the pseudo pilot interface, and closing the application.

System reliability was assessed by detecting operational failures occurring during each cycle. Failure events were recorded using an operational observation sheet and manual response delay measurement using a stopwatch. The failure criteria used in this study are summarized in Table 1.

Table 1. Failure Detection Criteria for Reliability Testing

Failure Code	Failure Description
F1	Connection failure between VCCS application and ESP8266
F2	Channel switching failure
F3	System response time exceeds 2 seconds
F4	VCCS application crash or hang
F5	System unavailable for operation

The objective of reliability testing was to identify and minimize operational failures across repeated testing cycles. Any detected failure was recorded and analyzed to determine its cause and frequency of occurrence. The collected reliability data served as the basis for evaluating system robustness and guiding iterative refinement to reduce or eliminate failure events in subsequent prototype improvements.

2.3.3 Performance Evaluation

Performance evaluation was conducted by analyzing the reliability testing results to assess operational consistency and identify performance bottlenecks in the developed VCCS prototype. The evaluation focused on failure frequency, failure distribution across testing cycles, and response delay characteristics to determine subsystem weaknesses affecting overall system performance.

The recorded reliability data were analyzed based on five failure criteria: connection failure, channel switching failure, excessive response delay, application crash or hang, and system unavailability. Particular attention was given to response delay behavior, since delays exceeding 2 seconds were categorized as failure conditions. Failure occurrence patterns were examined to identify whether performance degradation originated from wireless communication instability, firmware processing delays, hardware switching latency, or application-related issues.

The evaluation results were used as feedback for iterative prototype refinement. Identified failure events and delay anomalies were analyzed to improve system timing synchronization, optimize firmware control logic, and enhance subsystem coordination. This iterative evaluation-refinement process ensured continuous improvement of system reliability and supported progressive reduction of operational failures throughout prototype development.

3. RESULTS AND DISCUSSION

This section presents the results obtained from the development and evaluation of the proposed IoT-based Voice Communication Control System (VCCS) prototype for ATC radar simulator applications. The discussion covers the implementation outcomes of the developed prototype, functional testing results, reliability and performance analysis, and cost efficiency evaluation compared to conventional proprietary VCCS systems. The presented results are analyzed to assess the technical feasibility, operational reliability, and economic advantages of the proposed architecture as a sustainable communication control solution for aviation training environments.

3.1 Prototype Implementation Results

The implementation process successfully produced a functional Internet of Things (IoT)-based Voice Communication Control System (VCCS) prototype designed to support communication operations within the ATC radar simulator environment. The developed prototype consists of two primary subsystems: the hardware communication control unit and the Android-based human-machine interface (HMI). These subsystems were integrated through a local wireless network to enable real-time communication control between ATC operators and pseudo pilots.

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Figure 3. Hardware Prototype

Figure 3 shows the hardware implementation of the developed VCCS prototype. Two hardware variants were constructed to support different operational roles, namely the ATC control unit and the pseudo pilot control unit. Both units share a similar core architecture consisting of the ESP8266 microcontroller, SA828 UHF transceiver module, channel switching circuitry, digital volume control, and supporting interface components. The ATC unit provides dedicated communication control for a fixed radar channel, while the pseudo pilot unit supports dynamic channel switching across four communication channels corresponding to Radar 1 through Radar 4.

Legacy Proprietary HMI *Developed Android-based HMI*

Figure 4. Comparison Between Legacy Proprietary HMI And The Developed Android-based HMI

Figure 4 compares the legacy proprietary HMI previously used in the ATC radar simulator laboratory with the proposed Android-based HMI developed in this study. The legacy system relied on a fixed hardware control panel with limited flexibility, making maintenance and system upgrades difficult due to dependency on proprietary components. In contrast, the proposed HMI introduces a wireless and modular control interface designed to improve maintainability and operational flexibility.

Separate interface layouts were implemented for ATC operators and pseudo pilots to match their respective operational workflows. The ATC interface provides Air-to-Ground (A/G) communication control and system status monitoring, while the pseudo pilot interface enables channel selection, transmit control, and communication monitoring across multiple radar channels. This implementation successfully replaced the legacy proprietary control interface with a more flexible, scalable, and maintainable communication control system.

The final prototype demonstrated successful end-to-end integration between hardware, firmware, and user interface components. Communication commands issued through the Android interface were successfully transmitted to the ESP8266 controller and executed by the hardware subsystem, enabling channel switching, Push-To-Talk (PTT) activation, and digital audio volume adjustment in real time. These results confirm that the proposed architecture was successfully implemented as a fully operational VCCS prototype.

3.2 Functional Testing Results

Functional testing was performed to verify whether all primary communication control functions of the developed VCCS prototype operated according to the intended design. The evaluation focused on validating wireless connectivity, channel switching functionality, push-to-talk (PTT) activation, digital audio volume control, and voice communication performance between ATC operators and pseudo pilots.

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Table 2. Functional Testing Results.

Test Parameter	Expected Result	Actual Result	Status
Wireless Connectivity	Android successfully connects to ESP8266	Successful	Pass
Channel Switching	Selected channel activates correctly	Successful	Pass
Push-to-Talk (PTT)	Transmission activates properly	Successful	Pass
Digital Volume Control	Audio level changes according to command	Successful	Pass
Voice Communication	Clear two-way communication	Successful	Pass

Table 2 summarizes the functional testing results of the developed system. All tested functions operated successfully without major functional errors. Wireless communication between the Android-based HMI and the ESP8266 controller was established successfully, enabling reliable command transmission through the local wireless network.

Channel switching functionality on the pseudo pilot interface successfully activated the intended communication channels corresponding to Radar 1 through Radar 4. Push-to-talk (PTT) activation also functioned correctly, allowing controlled transmission during communication sessions. In addition, digital volume control successfully adjusted audio output through the X9C103 digital potentiometer without requiring manual hardware adjustment.

Voice communication testing confirmed clear two-way communication between ATC operators and pseudo pilots across all tested channels. These results indicate that the developed prototype successfully fulfilled all primary functional requirements and was ready for extended reliability testing under repeated operational conditions.

3.3 Reliability and Performance Analysis

Reliability and performance analysis was conducted based on 100 operational cycles to evaluate the stability of the developed VCCS prototype under repeated usage conditions. Each cycle simulated a complete operational sequence consisting of application startup, automatic connection establishment, communication operation, push-to-talk transmission, channel switching, and application closure. The reliability test produced 96 successful cycles and 4 failure events, resulting in an overall operational reliability of 96%.

Table 3. Reliability Testing Failure Summary

Failure Code	Description	Occurrence
F1	Connection failure	0
F2	Channel switching failure	1
F3	Response delay > 2 sec	2
F4	Application crash/hang	0
F5	System unavailable	1

Table 3 summarizes the detected failure events based on the predefined failure criteria. Among the five evaluated failure modes, no connection failures (F1) and no application crashes or hangs (F4) were observed during testing. This indicates that both the wireless communication architecture and the Android-based HMI remained stable throughout repeated operation.

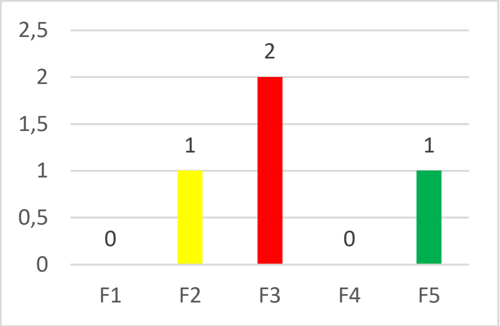

Figure 5. Failure Distribution

Figure 5 illustrates the distribution of detected failure events during the 100-cycle reliability test. The distribution shows that most failure events were associated with response delay anomalies (F3), while connection-related failures (F1) and application instability (F4) were not observed throughout testing.

A single channel switching failure (F2) was recorded, indicating occasional control synchronization issues during communication channel selection. Two failures were associated with excessive response delay (F3), where system initialization time exceeded the defined threshold of 2 seconds. In addition, one system unavailability event (F5) was observed, indicating a rare initialization anomaly during startup.

The performance evaluation identified response delay as the primary performance bottleneck of the developed prototype. Delay anomalies occurred intermittently rather than continuously, suggesting that performance degradation

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was not caused by permanent hardware failure but more likely related to temporary firmware timing inconsistencies or command processing latency. Despite these anomalies, the low number of failure events indicates that the prototype maintained stable operation across repeated testing cycles.

The reliability and performance analysis results were used as feedback for iterative refinement of the prototype. Detected failure events were analyzed to improve firmware timing synchronization, optimize command handling, and enhance startup stability. This iterative evaluation provided a basis for further refinement of the proposed IoT-based VCCS architecture.

3.4 Cost Efficiency Analysis

Cost efficiency analysis was conducted to evaluate the economic feasibility of the proposed IoT-based VCCS prototype as a replacement for conventional proprietary VCCS systems used in ATC radar simulator environments. The analysis focused not only on initial system acquisition efficiency but also on long-term maintenance sustainability, which is a critical factor in communication infrastructure lifecycle management.

The evaluation showed that the proposed system achieved approximately 91.05% cost efficiency compared to proprietary VCCS alternatives. This result indicates that the developed prototype can significantly reduce initial acquisition and replacement costs while maintaining the communication control functionality required for ATC simulator operations.

Beyond acquisition cost reduction, the proposed architecture also offers substantial advantages in maintenance sustainability. The use of commercially available embedded hardware, modular subsystem design, and open development platforms reduces dependency on proprietary vendor-specific components. Previous studies have shown that IoT-based architectures improve system maintainability by enabling real-time monitoring, modular hardware replacement, and predictive maintenance strategies that reduce long-term operational costs and downtime (Hamasha et al., 2025; Lisboa et al., 2025; Palomeque-Gonzalez, 2025).

The modular design of the developed prototype enables subsystem-level maintenance, allowing faulty components such as microcontrollers, transceiver modules, or interface circuits to be replaced individually without requiring complete system replacement. This architecture significantly reduces maintenance complexity and contributes to lower lifecycle costs. These findings suggest that the proposed IoT-based VCCS architecture provides not only reliable technical performance but also strong long-term economic sustainability, making it a practical solution for aviation training institutions operating under budget and maintenance constraints.

3.5 Discussion

The results of this study demonstrate that the proposed IoT-based VCCS architecture provides a practical alternative to conventional proprietary communication control systems used in ATC radar simulator environments. From an architectural perspective, the developed system introduces a modular and open communication control framework that operates independently from the radar simulator core system. This separation improves maintainability, simplifies subsystem replacement, and enables future scalability without requiring major modifications to the simulator infrastructure. Similar architectural advantages have been reported in recent IoT-based voice-interactive control systems, where modular communication layers improve flexibility, scalability, and integration efficiency (Xu et al., 2025).

From a reliability perspective, the prototype demonstrated stable operational performance during repeated testing cycles, with only a small number of detected failure events. The failure analysis showed that most anomalies were associated with temporary response delay rather than critical communication failure or application instability. This indicates that the proposed architecture provides sufficient operational stability for training applications, where communication continuity and rapid system responsiveness are essential for realistic ATC simulation scenarios. Similar findings in embedded IoT systems show that response latency, timing synchronization, and fault detection are among the dominant factors affecting system reliability under repeated operational conditions (Cogo et al., 2024; Misaros et al., 2025).

From an economic perspective, the proposed system offers substantial advantages over proprietary alternatives. The achieved cost efficiency of 91.05% indicates that IoT-based communication control can significantly reduce financial barriers associated with communication infrastructure modernization. In addition to reducing initial acquisition costs, the modular design also supports lower long-term maintenance burden through easier component replacement and reduced dependency on proprietary hardware ecosystems. Previous studies have shown that lifecycle reliability and maintainability are strongly influenced by system architecture, where modular subsystem replacement and open technology adoption contribute to reduced maintenance complexity and improved long-term sustainability (Breznická et al., 2023; Delinchant & Ferrari, 2021).

Despite these promising results, several limitations should be acknowledged. The reliability evaluation was limited to 100 operational cycles within a controlled laboratory environment and therefore may not fully represent long-term operational behavior under extended usage conditions. In addition, broader user acceptance evaluation involving technicians, instructors, and ATC cadets has not yet been conducted. Future research may focus on long-term reliability analysis, predictive maintenance modeling, and structured user acceptance assessment to further evaluate the practical deployment potential of the proposed VCCS architecture.

4. CONCLUSION

This study successfully developed and evaluated an Internet of Things (IoT)-based Voice Communication Control System (VCCS) prototype as an alternative to conventional proprietary communication control systems used in Air Traffic Control (ATC) radar simulator environments. The proposed system was developed using a prototype-based approach integrating embedded wireless control, an Android-based human-machine interface, and modular communication hardware to support real-time communication between ATC operators and pseudo pilots. The experimental results confirmed that the prototype fulfilled all primary functional requirements, including wireless connectivity, channel switching, push-to-talk control, digital volume adjustment, and voice communication. Reliability testing conducted over 100 operational cycles resulted in 96 successful cycles, corresponding to an operational reliability of 96%. The proposed architecture also achieved a cost efficiency of 91.05% compared with conventional proprietary VCCS alternatives while providing greater maintenance sustainability through modular subsystem replacement and reduced dependency on proprietary hardware. These results demonstrate that the developed IoT-based VCCS can address key limitations of legacy communication control systems while maintaining the communication functions required for ATC simulator training. Therefore, the proposed architecture provides a practical, reliable, and economically sustainable approach to communication system modernization in aviation training environments. Future research should extend the evaluation through longer operational testing, predictive maintenance modeling, and structured user acceptance assessment to further examine long-term deployment readiness.

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