ITM Web of Conferences **82**, 01001 (2026) https://doi.org/10.1051/itmconf/20268201001
ICNEXTS'25

Intelligent IoT-based Runway incursion detection for Aircraft system

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Abstract. Runway incursions pose a serious threat to the safety of aviation and, as such, necessitate proactive and intelligent mitigation measures. Traditional surveillance systems are usually inefficient and far from automated when it comes to real-time risk assessment. Recent developments in AI, IoT, and computer vision have made it possible to create cutting-edge systems for prevention systems. The cloud-enabled monitoring interface uses simple communication with air traffic control for timely action. By utilizing deep learning-based object detection, along with edge computing, the system offers fast and efficient detection of a potential threat. The proposed solution, is designed to work in changing environmental conditions and is highly reliable and scalable. Computer vision enhances situational awareness and reduces human dependency. Tests show that the system can detect, classify, and sort obstacles with a high level of accuracy. This approach allows for improved operational dependability and will be kept current with contemporary aviation safety regulations. We expect a lot of coverage and accuracy from the detecting algorithms through possible enhancements. The following study emphasizes how AI-based automation can be used to improve airport security protocols.

1 Introduction

The most intractable and unsafe aviation safety issues of our time are runway incursions. According to the International Civil Aviation Organization, runway incursions are any unauthorized presence of a vehicle or a person. The likelihood and seriousness of such incursions have increased due to increased air traffic. The severity can vary from huge collisions. The real-time monitoring and prompt reaction thus become an essential requirement for both non-commercial and commercial airports.

Against this menace, busy airports generally depend on radar-based surveillance systems like the Airport Surface Detection Equipment – Model X (ASDE-X) and the Advanced Surface Movement Guidance and Control System (ASMGCS). Such expedients are great at generating robust situational awareness: they allow us to monitor aircraft and their vehicle positions throughout the airfield. However, these technologies also have a number of severe drawbacks that are costly to set up and keep running.

Transponder signals are the only source of information for those devices, and moreover, their low-resolution rejections of small or non-tagged entities such as humans or animals. Additionally, such systems will depend on centralized processing, which would invariably delay responses and detection in critical operating windows. Smaller, un-towered airports that comprise a majority of airstrips around the world lack access to such sophisticated infrastructure because of limited finances and logistics. Under such circumstances, surveillance is mostly human, subject to man-made mistakes, and unable to provide real-time incursion neutralization. Moreover, available solutions do not use cloud-based technologies or edge-based AI appropriately, which could give quicker, decentralized decision-making and system design scalability. This operational shortfall enhances the potential of these airports for safety violations and reduces their capacity for conform to the contemporary aviation safety standards.

The Cognitive Aero-Surveillance and Runway Incursion Detection System is presented in this paper as a solution to these constraints. It is a smart monitoring system that uses AI to merges low-cost hardware with alerting based on the cloud, detection of objects in real-time, and sensor fusion. To alert the actions instantly, CAS-RIMS consists of a microcontroller alert system and, at the same time, ultrasonic and infrared sensors for the detection of people and a vision module together with YOLO and OpenCV for the classification of objects that uses YOLO and OpenCV for object classification. ThingSpeak is used to push data logging and alerts for air traffic personnel to monitor remotely. CAS-RIMS is a solution that can be scaled, is accurate, has low latency, and can be deployed in a modular manner for changing airfield conditions, particularly in places with limited resources.

2 Related works

Over the years, multiple research works have explored various strategies to detect and prevent runway incursions, ranging from radar-based monitoring and simulation tools to low-cost embedded systems. Despite addressing specific problems to a better extent, they posed few limitations related to cost, scalability, and environmental adaptability.

In the "Study on Airport Runway Incursion Monitoring Based on Computer Vision,", [1] a proposal was made to recognize runway incursions by visual means through the use of equipping airports with optical systems and their floors. The precise positioning of objects resulted from the transformations of the camera axes and the calibration, while the accuracy was also improved by the merge with the data of the runway status light. The method had demonstrated itself to be effective in high-traffic airports but was hampered by the condition of lighting, occlusions, and large camera coverage requirements.

“A Runway Incursion Detection Approach Based on Multi-ple Protected Area and Flight Status Machine for A-SMGCS” [2] developed an enhanced detection model within the ICAO-defined A-SMGCS framework. The method had improved accuracy and minimized the complexity of detection through the introduction of several (protected) areas and a Flight Status Machine (FSM) to model the transitions between the operational states of aircraft. It has been validated using a custom Human Machine Interface (HMI) and was shown to advantage early detection, but had been deployed only at airports that already had A-SMGCS infrastructures.

“Incorporating Controller Intent into a Runway Incursion Prevention System” [3] analyzed the human, procedural, and systemic factors influencing runway incursions. Using the SHELL model, along with DEMATEL and Interpretative Structural Modeling (ISM), the researchers had identified 15 contributing factors and had developed a multi-layered causal structure. The research had established that poor safety prioritization by leadership of the airport was the root cause, while inefficient training, supervision, and human errors were immediate causes. Although a new framework for decision-making was presented in the work, it remained conceptual and lacked a hardware implementation.

“An Affordable Approach to Runway Incursion Prevention” A solution that is inexpensive and scalable, suggested by [4] to enhance safety in non-towered airports involves the application of ADS-B information to provide wireless activation of Simple, Affordable, Flexible, and Expandable Runways Status Lights (SAFE-RWSL). The system had availed real time visual alerts to airplanes, vehicles and pedestrians to supplement see and avoid without having to use ground radar. The research had established the barriers of smaller airports as cost, complexity, and hesitancy to adopt the system and had demonstrated the system to have a benefit-cost ratio of 2.37 within a period of ten years.

“Advanced Surveillance System for Public Safety” [5] describes an advanced vision-based surveillance system with the ability to analyze, detect and alert the object of interest of various classes. This also implements behavior analysis, a feature that helps in analyzing the behavior of persons in the field of view.

“Design and Implementation of Runway Incursion Automatic Warning Simulation System” [6] described a simulation-based platform aimed at training air traffic controllers. It had employed full-duplex asynchronous serial communication between a microcontroller and a PC to collect runway simulation data and process multiple signals for automatic incursion recognition. The simulation had provided alerts for both pseudo controllers and intruders, which appeared in real time on a PC interface. Although it is good in training, the system did not undergo testing in live airport operations. “Low-cost Runway Incursion Detection System for General Aviation Airports” [7] documented a freshman engineering project in which multidisciplinary teams had developed con-ceptual detection systems for small airports. The focus had been on affordability, scalability, and practical design with leadership and collaboration being key educational goals. The resulting prototypes had shown some basic detection capability for low infrastructure airfields, but this focus had been more educational than technical, and no system-level testing had been done.

“Fusion of Airborne Radar and FLIR Sensors for Runway Incursion Detection” [8] investigated a sensor fusion method of using Forward-Looking Infrared (FLIR) cameras with Doppler weather radar for onboard detection from approaching aircraft. A fusion algorithm was applied in a manner that it successfully lowered the number of false positives and facilitated tracking by merging radar data simulated with infrared data collected in both long-wave and short-wave spectra during NASA flight tests. The method had been very successful under low-visibility night conditions but its validation was on a laboratory.

“Real-Time Runway Incursion Cockpit Advisory” [9] introduced a system that sent manual radio warnings by sending automated incursion alerts straight to pilots via Mode S uplinks. The developed system, resulting from a joint venture between Honeywell Aerospace and Sensis Corporation, incorporated KSDE-X data for the purpose of conflict detection, thereby enabling communication from the cockpit during taxi, short final and departure. The validity of the system was proven through field trials at Syracuse Hancock International Airport, though due to its dependence on ASDE-X, its use was restricted to airport with high-end technology.

“Runway Incursion Prevention System Simulation Evaluation” [10] It is a NASA Langley model of the RIPS system, which managed to increase pilot situational awareness by merging both the ground and air sensors. The outcome is less clear, owing to sample generalizations, but a study on the values of the DT system-parameter was conducted with 46 examples. However, the system had not yet reached the operational stage, it had only been validated through simulations.

“Runway safety Program Annual Report” [11] modified the RIPS concept for airports that are smaller and have fewer instruments. The adaptation was tested in a simulated environment and had an altered interface and alerting logic for general aviation use. Although these results had indicated safety improvements were likely for light aircraft, further testing in live conditions had been required to confirm how well the equipment was performing operationally.

3 Proposed System

The proposed system is a scalable, reasonably priced method of preventing runway incursions that is mainly intended for airports with limited resources or no towers. The system, as opposed to traditional radar-based techniques like ASDE-X which rely on a massive central arrangement.

A vision-based detection module, infrared and ultrasonic proximity sensors, and microcontrollers that can identify obstruction or unwanted access on operational runways are all intended to be integrated. Using pair-wise combinations and performing sensor fusion at this stage needs to come to a temporary rest very local processing is effective through either an Arduino UNO or an ESP8266 based NodeMCU. These fast decentralized decisions are made possible through this processing, hence there is no need to depend on expensive surface radar networks.

The camera or webcam-based vision detection unit is the system's most important component that runs YOLOv8 object detection models and OpenCV to classify detected objects in the live stream as humans, vehicles, or animals. Object localization and labelling are done on a companion processor that processes this video stream. Ultrasonic sensors output depth or distance metrics whereas infrared sensors provide near-field detection, which is useful during night time or in situations of low visibility. In order to reduce false positives and guarantee accurate detection of possible incursion threats, those heterogeneous inputs are cross-validated. The system exhibits real-time information on an LCD module and triggers visual (LED) and audio (buzzer) alerts instantly if it detects any.

Additionally, it supports wireless telemetry with microcontrollers that are Wi-Fi enabled. In case of any incursion, data will be sent to the cloud dashboard, such as ThingSpeak or Firebase, where remote operators or connected ATC personnel may read incident logs and find real-time alerts. The modular architecture is made up of multiple sensor nodes that are situated on the runway, and every node is capable of independent operation or interconnection in a mesh configuration with other nodes. The architecture, therefore, offers a number of benefits including low latency, high fault tolerance, and easy deployment in various airport environments. The object detection framework YOLOv8 was selected for the vision-based detection module because of its high precision and low inference time, which are critical in situations where aircraft incursions happen very fast. On the other hand, the traditional two-stage detectors working in different stages provide an output which can be processed in real-time by both live camera feeds and cloud-based systems. YOLO, however, takes detection as a single step and hence provides an output which is real-time applicable. Moreover, regardless of the lighting and weather conditions, YOLOv8's deployment can distinguish small and moving objects like people, cars, and animals. The models allow easy customization, training on airport-specific datasets in order to improve contextual accuracy.

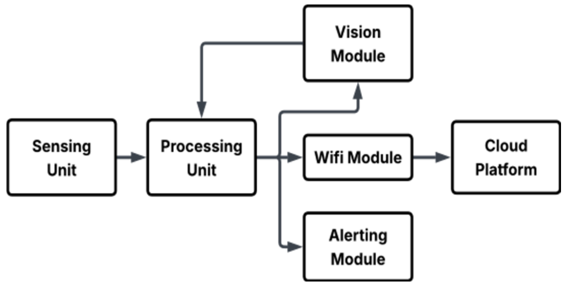

Fig. 1. System Architecture

The architecture of the proposed runway incursion prevention system has a modular, decentralized design that can operate reliably in the low-infrastructure environment of non-towered airports. Through small embedded systems, it combines sensing, processing, alerting and cloud-based logging. The sensing unit, processing unit, Vision-based detection, alerting interface, and cloud telemetry are the main parts of this architecture.

A. Sensing Unit

The sensing unit forms the core of the intrusion detection mechanism. It is made up of ultrasonic sensors to measure the range and proximity of entities and infrared sensors for short range obstacle detection When there has been any movement, these are placed in key runway entry points and edge zones for pointing out the risk. Each sensor continuously sends analog or digital signals to the microcontroller in order to interpret the presence, distance and motion characteristics of an entity nearby. The adjustment of the ultrasonic sensors is done in such a way that it not only helps background noise to be removed but also helps differentiate between still and moving objects. Infrared sensors enhance detection in low light or at night to guarantee accurate detection in the range of conflicting data. This way, the technique uses the majority strategy for detection when multiple sources of input potentially conflict with each other.

B. Processing Unit

Arduino UNO and NodeMCU ESP8266 microcontrollers would be the processor's driving force. The reason why these boards were selected is their power efficiency, low price, and the number of GPIO interfaces that is enough to accommodate several sensor inputs. The microcontrollers go on a programmed loop continually looking for sensor input, doing logic threshold application, and making instant decisions based on the data arriving. This is how, in the event of any anomaly, such as the detection of a moving object within a protected runway zone, the activation of an alerting system is done through the microcontroller and data transmission is triggered to the cloud platform. The NodeMCU is responsible for the Wi-Fi communication, but at the same time, it enables the whole system to be powered by wireless and to not have physical monitoring stations.

C. Vision-Based Behavior Analysis Module

This system involves the use of a real-time vision intelligence-based behavior analysis detection module to enhance situational awareness and reduce false alerts. The utilization of OpenCV and the YOLOv8 motion-tracking framework together could provide the analysis is of runway entities such as cars and humans in terms of their pattern's recognition. Unauthorized entry and irregular movement are examples of normal and abnormal actions that a behavioural classifier profiles. The output further gets cross-verified with IR and ultrasonic sensors for confirming genuine incursions. In poor weather, the camera is supported by IR and ultrasonic sensors. Thermal or IR cameras can improve the camera performance.

D. Alerting and Notification Interface

After the confirmation of a runway incursion, this system activates an integrated alerting interface, including a buzzer, LED warning signal, and 16x2 LCD display. These notifications of risk observation, which will be near entryways and ground attendants, will take steps to immediately alert them to any inadvertent harm they might be inflicted. A high-frequency tone is emitted through a buzzer, while the nature and zone of incursion are depicted through a message on the LCD. This will guarantee that the alert mechanism linked to ground crew and other nearby stakeholders will be truly informed about real-time threats despite connectivity to the cloud. The microcontroller is the one supplying the power to the system's visual and audio parts, and the latency of its response is aimed to be no more than 1.5 seconds to ensure great interactivity. The system integrating with ATC through the WebSocket/MQTT leads to the sending of real-time alerts in a format that is standard across ATC systems. By complying with ICAO guidelines for runway incursion alerts, it becomes possible to display and integrate with current ATC software without any issues.

E. Cloud Telemetry and Monitoring

Using the ThingSpeak IoT platform, a telemetry module is sued to increase system visibility for distant controllers or airport authorities. One of the features of the ESP8266 is that it sends crucial data like intrusion incidents, time-stamped information, zone identification numbers, and classifications to a live dashboard that can be viewed on any computer or mobile device. It is possible to identify recurring threats, peak incursion times or the efficiency of mitigation efforts by analyzing the historical logs kept in the cloud. With this feature, long-term reporting, risk assessment, and monitoring are greatly improved, and no manual logging or physical logging is required.

4 Implementation and Experimental Setup

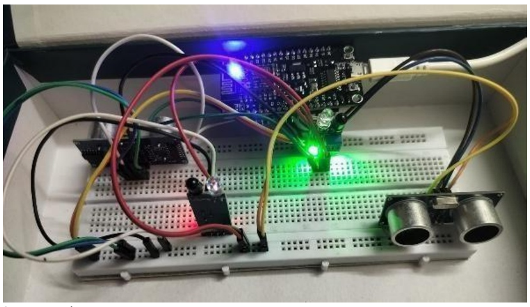

Fig 2. Hardware setup

The implementation of the proposed system was done by assembling and integrating both hardware and software components for real-time runway incursion detection. Two ultrasonic sensors (HC-SR04) and two infrared (IR) proximity sensors positioned at crucial runway model at entry points of a made up the hardware configuration. The utilization of these sensors was done through an interfacing with Arduino UNO and ESP8266 NodeMCU for Wi-Fi communication. The Arduino UNO was busy with reading the sensor and logic application in actual time, whereas the NodeMCU was made to transmit the data onto the cloud dashboard. A standard USB webcam was used for vision-based detection for on-board processing. Software-wise, the Arduino IDE C/C++ programming was used to implement the sensor logic. While the IR sensors provided information, the ultrasonic sensors measured the distance to approaching objects.

Using OpenCV and a pre-trained model, the vision module was created in Python to identify people, animals and automobiles. The ThingSpeak IoT platform, which was able to show real-time telemetry including the type of object, timestamp, and location zone ID, was utilized to log and visualize sensor data and detection events. This system can be deployed using multiple sensors across the runway with the help of wireless mesh networks. In order to replicate the detection of intrusions brought on by the movement of objects such as carts, people, or static obstacles, sensors were calibrated in range of 0.2 to 4 meters. This system achieved an average detection latency of 1.2 over 90% seconds. Alert are locally generated within 1.5 seconds with respect to a network tolerance range of ± 0.5 seconds.

5 Results and Discussions

A wide range of quantitative performance metrics, such as detection accuracy, classification accuracy, false positive rate, response latency, and cloud transmission delay were used to assess the efficacy of the suggested runway incursion detection system. Experimentation took place in a lab-designed runway simulator comprising actual flight operating conditions that included various types of light conditions. Fig 3 and 4 shows the graph readings of Ultrasonic and IR Sensor.

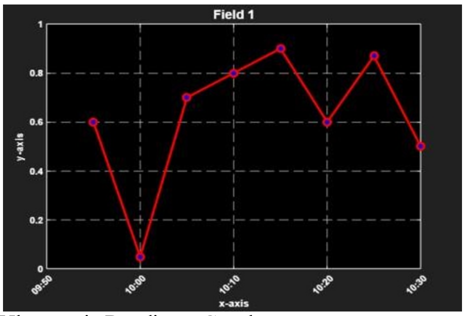

Fig 3. Ultrasonic Readings Graph

The evaluation of the sensor fusion capability consisted in a comparison of detection logs obtained from ultrasonic and infrared (IR) sensors with a ground truth dataset which was constructed from annotated video recordings and manual annotation. Ultrasonic sensors sense moving objects in an average of 92% cases within the measured distance of 0.2 - 4m and IR sensors managed to do it with a percentage of 95%.

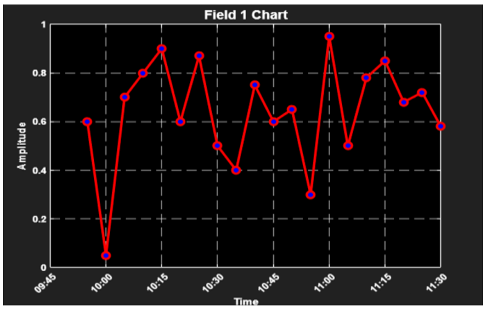

Fig 4. IR Sensor Readings Graph 2

1,200 marked image frames of people, animals, and cars in daylight, dim light, and total darkness (IR-aided) were used to test the YOLOv8 vision-based detection system. Even in the absence of infrared light, the accuracy of the classification process was still 84.5% in low light and 90.7% in high light. Latency testing revealed that the total time for the system response, that included the detection by the sensor, the processing by the microcontroller, and so on, was between 1.2 and 1.5 seconds. The Wi-Fi data transfer to the ThingSpeak IoT platform by the cloud, which indicated a delay variance of ±0.5 seconds, met the real-time operational requirements of runway safety systems.

Table 5.1 Performance comparison

Feature/Metric	Radar-based, centralized	Multimodal (Ultrasonic, IR, vision based)
Deployment cost	High (Expensive infrastructure)	Low (Affordable sensors, open-source)
Latency	High (Centralized processing delays)	Low (1.2 - 1.5 seconds, decentralized)
Scalability	Limited (Requires large infrastructure)	High (Modular, IoT-based, easy deployment)

Using both the sensors and camera, the accuracy can be improved by 20-30% and can eliminate the false alarm through enhanced detection and cross verification. In order to replicate actual runway entry points and high-risk intrusion areas, the ultrasonic HC-SR04 sensors and IR proximity sensors were placed in the best possible locations In order to simulate both static and moving intrusions, such as stationary obstacles, human movement and the motion of small vehicles, test cases were created. The experiments mainly aimed at ascertaining the accuracy of detection, system responsiveness, and reliability under different environmental conditions. There were 25 controlled experiments in total where the lighting variations in the light levels ranged from daylight to low-light and complete darkness, the latter accommodated by IR sensors to ensure it is visible. The raw detection results from each sensor were also compared against a manually annotated ground truth dataset in order to quantify true positives, false positives and false negatives as the basis for computing accuracy.

The ultrasound sensors could attain a range of detection accuracy between 92% and 96% over ranges from 0.2 meters up to 4 meters. Moreover, by measuring the distance through time-of-flight computations, the sensors were able to distinguish the approaching and retreating target which made them very useful for dynamic targets. This was enhanced by infrared sensors, which have a 95% detection rate in low-speed, stationary, and short-range intrusions, particularly in low or no light. However, the software-based threshold compensation of the microcontroller firmware decreased the infrared's sensors sensitivity to variations in ambient light. Compared to using the sensors separately, combining the two types of sensors in a fusion logic algorithm significantly decreased false positives by more than 40%.

The vision-based detection module was majorly required for very high classification accuracy and for avoiding mistakes in identifying objects. This is a device using a USB camera that switches to YOLOv8-tiny object detection for processing the real-time video streams to identify vehicles, people, and animals More than 1200 frames were used in training, and the real-time classification accuracy under natural lighting has been cited as 90.7%. The algorithm's resistance to unfavorable visibility conditions was proved by the low-light tests without infrared lighting in which the accuracy dropped only by 6%. The real-time processing of image frames was done at 15 to 18 frames per second to ensure the detection flow had low latency. The data obtained from the vision module was combined with the sensor readings. Hence, every visual detection was supported by one more sensor measurement, thereby eliminating alerts due to false alarms and also increasing the overall accuracy of the decision-making process.

Latency of the whole end-to-end system was always maintained between 1.2 and 1.5 seconds, which represented the total time from the attack to the issuance of local alerts and the updates to cloud telemetry. This period included the various operations of gathering the signals from the sensors, processing the logic with the microcontroller, acknowledging visually, activating the buzzer and LED for alert, updating the message display on the LCD, and sending the wireless data updates to the ThingSpeak cloud platform. Cloud updates showed a network delay tolerance of ±0.5 seconds to ensure that remote monitoring officers or air traffic controllers received almost instantaneous updates. The findings support the assertion that the system's open-source framework, inexpensive hardware parts, and modular design not only provided the expected performance but also ensured scalability and flexibility as well. The present tests proved the system's capability in a runway simulation; however, it is suggested that more testing in outdoor airport environments should be conducted in order to have a better operational readiness, particularly in the case of fast-moving targets and weather-related conditions.

6 Conclusion

In order to increase safety at non-towered and under-resourced airports, this research project presented the design and assessment of a low-cost, modular runway incursion prevention system. Ultrasonic and IR sensors coupled with the visual detection based on YOLO not only reduce the number of false positives but also keep ground staff and monitoring systems installed at a distance informed. The object detection performance of the system was validated by the experimental outcomes which reported more than 90% accuracy, and the controlled setting where the average response time was under 1.5 seconds. The employing of standard components and open-source platforms increases its cost-effectiveness and allows for its customization to different airport infrastructures. In the future, this system can be further improved by working with complex runway layouts and adding other sensor types like thermal/LiDAR sensors to improve visibility in low-visibility areas and under adverse weather conditions. The evaluation of the proposed innovations regarding the throughput, robustness, and integration with the existing air traffic control (ATC) systems will necessarily involve trials at actual airport sites in order to gauge the performance level of the innovations. Among the future innovations are GSM or LoRa discharges for communication over longer distances, deep learning, and autonomous solar-powered devices.

In conclusion, the recommendation systems now in place should henceforth be of further help in both training and testing the software configurations. With these improvements, the system will develop into an intelligent, fully autonomous safety layer for airside operations at all types of airports.

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