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FPGA based Real Time Obstacle Detection and Alert System for Drones and Small Aircrafts

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***Abstract*— This paper introduces a real-time obstacle detection and alerting system for drones and small aircraft that is implemented on an FPGA and ultrasonic sensor. The purpose of the proposed system is to enhance the safety of flight by ensuring low latency and high reliability for obstacle detection in the vicinity. The ultrasonic sensor constantly sends an ultrasonic wave, measures the echo time of objects in the vicinity, and measures the distance using the trigger–echo principle. The FPGA continuously processes the echo time, calculates the distance, compares with the threshold, and generates alerts. The FPGA's parallel processing capability makes it quicker to respond and more capable in real time than traditional microcontroller-based systems. The system alerts the operator by giving visual and audible alarms (using LEDs and buzzers) when an obstacle is detected within a set distance. Experimental results show the successful measurement of the short-range distances, the speed of response, and the reliable detection of the obstacles with a minimum error. The proposed design can be used in UAV safety applications and real-time embedded systems in a cost-efficient, energy-efficient, scalable way.**

***Index Terms*— FPGA, UAV, Obstacle Detection, Ultrasonic Sensor, Tang Nano, Real-Time Processing, Drone Safety, Embedded System.**

I. Introduction

Unmanned Aerial Vehicles (UAVs) and small aircraft are used in areas like surveillance, disaster management, agriculture, infrastructure inspection, and delivery services are growing in use. Safe navigation, collision avoidance, is one of the key challenges in an expanding drone operation in complex and dynamic environments. Sometimes power lines, trees, and buildings may be potential hazards if not identified during operation. Common obstacle detection systems using microcontrollers have sequential processing delays which are problematic in air-borne applications where they move quickly.

To overcome these drawbacks, the obstacle detection and warning system with an ultrasonic sensor and Tang Nano FPGA board has been proposed in this work. The FPGA is used for high-speed parallel processing to detect obstacles and generate alerts, while the ultrasonic sensor is used to measure the distance from objects. The FPGA technology provides low latency, deterministic performance and high speed response compared to the traditional processing systems, which is well suited to real-time UAV applications.

The developed system is able to permanently monitor the environment, and as soon as an obstacle is detected within a certain distance from the system, both visual and audible alarms are triggered. The experimental results demonstrate the good accuracy and stability of the system in short-range obstacle detection.

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II. Related Work

In recent years, UAV technology has gained significant improvements and extensive research has been carried out on the problems of obstacle detection, autonomous navigation, fault diagnosis and disaster management. A number of sensing and processing methods have been proposed to enhance the safety, reliability and efficiency of drone operation.

To enhance UAV operation reliability, a vibration-based UAV fault detection system is proposed in the paper titled "LiDAR-Based Obstacle Avoidance With Autonomous Vehicles: A Comprehensive Review," [1] by P. Y. Leong and N. S. Ahmad. The system utilized cheap vibration sensors, fuzzy logic and neural network methods to detect fault conditions in the arms of an UAV under a variety of operational conditions. The study showed that the use of artificial intelligence (AI) techniques to identify faults can enhance UAV safety and system monitoring.

In the paper titled "RF Drone Detection System Based on a Distributed Sensor Network," [2] by P. Flak and R. Czyba, a distributed system for detection of drones using RF technology and Software Defined Radio (SDR) and FPGA processing was presented. The system was able to continuously monitor the RF spectrum and use FPGA acceleration to enhance both bandwidth handling and signal processing. The proposed design showed good drone detection capabilities in real-time and low computational load.

A lightweight deep learning approach for obstacle avoidance and navigation of a nano-UAV was suggested in the titled "Tiny Neural Networks for Real-Time Obstacle Avoidance in Nano-UAVs," [3] by A. Loquercio, A. Pullin, and D. Scaramuzza, and named Tiny-PULP-Dronet. The system used compact neural networks optimized to low power UAV platforms and showed real-time navigation in indoor environments. The method was effective in autonomous navigation, but needed to be processed with artificial intelligence and was sensitive to changes in lighting and textures in the environment.

The use of UAVs for search and rescue after a disaster was studied in the paper titled "Tiny Neural Networks for Real-Time Obstacle Avoidance in Nano-UAVs," [4] by A. Loquercio, A. Pullin, and D. Scaramuzza. This study centered on maximizing the efficiency of the UAV path planning, communication coverage, and energy-aware deployment strategies to maximize the efficiency of victim detection and rescue operations in disaster areas. The proposed framework highlighted the importance of real-time sensing and efficient mission planning in UAV applications.

In the paper titled "Obstacle Detection and Avoidance for UAVs: A Survey," [5] by S. Hrabar, a detailed survey of indoor UAV obstacle avoiders was provided. Various obstacle detection approaches such as vision based, LiDAR based, ultrasonic sensor based and hybrid sensor fusion were discussed in the study. The survey found that both vision-based and LiDAR-based systems are capable of obtaining accurate environmental mapping, but require more computational power and higher cost of the system. In contrast, ultrasonic sensors are also another simple and affordable technology for short range obstacle detection and have lower processing demands.

For airport obstacle detection and aviation safety applications, dense image matching technique are proposed utilizing UAVs in the paper titled "Airport Obstacle Detection Using UAV-Based Dense Image Matching," [6] by Y. Chen, J. Li, and X. Wang. Aerial image processing techniques were used in the study for the purpose of locating buildings, towers and other obstacles in airports. The proposed approach was able to perform accurate environmental mapping but its performance was largely restricted by lighting and weather.

In the paper titled, "Wireless Communications With Unmanned Aerial Vehicles: Opportunities and Challenges," [7] by Y. Zeng, R. Zhang, and T. J. Lim, secure UAV communication and obstacle-aware deployment strategies were explored. The study introduced three dimensional positioning methods for UAV to enhance the reliability of communication and reduce security threats like eavesdropping in wireless network. The research has shown the significance of smart positioning of UAV and awareness of the environment in the modern communication system.

The concept of UAV system for powerline inspection and monitoring was discussed in the paper titled "A Survey of Mobile Robots for Distribution Power Line Inspection," [8] by A. Katrasnik, F. Pernus, and B. Likar. This study was aimed at enhancing the UAV trajectory tracking and inspection accuracy in the vicinity of a power transmission line by adapting the Iterative Learning Control (ILC) techniques. The proposed system improved the safety of the operation and lowered the risks of manual inspection methods.

In the paper titled "A Novel Multi-Robot System for Wildlife Monitoring," [9] by M. S. Couceiro, R. P. Rocha, and N. M. Ferreira, UAVs integrated with wireless sensor networks and object detection models with artificial intelligence were presented for wildlife monitoring and surveillance. The system used sensors like PIR sensors, ultrasonic sensors, stereo cameras, and LiDAR, for navigation and environmental monitoring tasks. YOLO,

artificial intelligence techniques, were used to identify wildlife and poachers. While good detection accuracy was obtained, flight duration and environmental conditions remained a challenge.
In the paper titled “On the Security of the Automatic Dependent Surveillance-Broadcast Protocol,” [10] by M. Strohmeier, V. Lenders, and I. Martinovic, the authors studied cooperative mid-air collision avoidance systems for UAVs. The Detect and Avoid Cooperative Management (DACM) system allowed for the exchange of UAV flight information in real time via Electronic Conspicuity Devices. The system enhanced the safety of airspace by mitigating the risk of collision between UAVs in the same airspace. But the strategy was primarily based on a cooperation between the UAVs and it was limited in detection of Uncooperative aerial objects.
In the paper titled “Survey on UAV Cellular Communications: Practical Aspects, Standardization Advancements, Regulation, and Security Challenges,” [11] by A. Fotouhi, H. Qiang, M. Ding, M. Hassan, L. G. Giordano, A. Garcia-Rodriguez, and J. Yuan, UAV swarm integration in the context of smart city was suggested for applications like surveillance, traffic monitoring, delivery services etc. The paper discussed wireless charging, energy harvesting and swarm intelligence methods to enhance coordinate and efficient operation of UAVs in urban areas. The framework showed potential to use UAVs in the future smart cities infrastructure.
In the paper titled “Vision-Based Monitoring of Locally Linear Structures Using an Unmanned Aerial Vehicle,” [12] S. Rathinam, Z. Kim, and R. Sengupta, energy-aware mission planning and optimized path management of the UAV were studied. The study modeled the UAV mission planning as an optimization problem with battery constraints and charging. The efficient route planning strategies were suggested to reduce energy consumption and increase the operational time of the UAV. The work highlighted the significance of the design of energy efficient systems in long duration UAV missions.
Approaches to avoid obstacles based on monocular vision and optical flow were proposed for quadrotor navigation in the paper titled, “Collision Avoidance Strategies for Unmanned Aerial Vehicles in Formation Flight,” [13] by J. Seo, Y. Kim, S. Kim, and A. Tsourdos. The system assessed the time until the collision by calculating the optical flow divergence, and executed reactive collision avoidance maneuvers to avoid obstacles nearby. In this way, a real-time obstacle detection method was realized with light-weight vision processing techniques, which was applicable for resource-limited UAV platforms. The performance, however, was very much dependent on environmental texture and lighting conditions.
In the paper titled “Survey of Advances in Guidance, Navigation, and Control of Unmanned Rotorcraft Systems,” [14] by A. Kendoul, a comprehensive survey of UAV collision avoidance strategies was presented. Various autonomous UAV navigation algorithms to avoid obstacles were studied for obstacle avoidance, including rule-based, optimization-driven and AI-based algorithms. Also discussed were the multi-UAV coordination, scalability and inter-UAV communication challenges. The survey indicated that the future use of UAVs will utilize intelligent collision avoidance systems, which will increase in significance.
In the paper titled “Pedestrian Protection Systems: Issues, Survey, and Challenges,” [15] by T. Gandhi and M. M. Trivedi, indoor UAV navigation and autonomous flight control techniques were discussed. The study highlighted the significance of employing artificial intelligence and reinforcement learning techniques to enhance navigation in complex and unfamiliar indoor settings. AI Navigators performed better in adaptability and decision making, but needed more computation resources and more power consumption.
A thorough survey of the LiDAR based obstacle avoidance systems for AVs and UAVs was provided in the paper titled, “LiDAR-Based Obstacle Avoidance With Autonomous Vehicles: A Comprehensive Review,” [16] by P. Y. Leong and N. S. Ahmad. The paper presented the applications of LiDAR sensors for accurate environmental mapping, object detection, and collision avoidance. While LiDAR systems were able to deliver high resolution distance measurement and robust obstacle detection, this study revealed their high cost, power consumption and computational complexity as significant issues for lightweight UAV platforms.
In the paper titled “RF Drone Detection System Based on a Distributed Sensor Grid With Remote Hardware-Accelerated Signal Processing,” [17] by P. Flak and R. Czyba, distributed RF based drone detection systems using sensor networks were explored. The system proposed used the techniques of RF signal analysis for detection and identification of UAV in real-time. Distributed sensing architectures in large environments provided monitoring coverage and detection reliability. The study highlighted the need to use efficient signal processing and communication methods in UAV surveillance applications.
In the paper titled “Real-Time Local Obstacle Avoidance and Trajectory Tracking Control of Quadrotor UAVs With Suspended Payload in Complex Environments,” [18] by Z. Zhang et al., lightweight neural network architectures for real time navigation and obstacle avoidance of UAV were further explored. The research was targeted at compact deep learning models specifically tailored to embedded deep learning systems on UAVs with constrained computational capabilities. The suggested models were able to enhance the autonomous navigation

and obstacle recognition performance, and reduce memory and energy consumption. But, the environment and equipment constraints remained to be a factor in the detection accuracy and system reliability.

The discussion of the aviation monitoring and infrastructure inspection systems based on UAVs can be found in the paper titled "Obstacle Avoidance of a UAV Using Fast Monocular Depth Estimation for a Wide Stereo Camera," [19] by Cho et al. The study examined the use of UAVs for safety-critical tasks like security surveillance at airports, infrastructure inspections, and environmental monitoring. Advanced sensing systems and image processing techniques were used to enhance detection accuracy and safety of operation. The research work emphasized the use of UAVs for automated inspection and monitoring applications.

In the paper titled "UAV Dynamic Path Planning Based on Obstacle Position Prediction in an Unknown Environment," [20] by J. Feng et al., energy-efficient UAV mission planning and optimization techniques were presented. The research was primarily aimed at minimizing energy consumption and optimizing the efficiency of UAVs in flying and resource utilization. The factors of battery constraints, mission duration and computational efficiency were found to be of importance in the enhancement of UAV performance and sustainability.

As reported in the reviewed studies, the advanced sensing capabilities, intelligent processing methods, and optimized mission planning strategies are becoming essential to the modern UAV system to enhance navigation and safety. While these are beneficial methods to improve the capabilities of a system, many of them are energy intensive, require high computing power and are costly in terms of hardware. The proposed FPGA-based ultrasonic obstacle detection system, on the contrary, offers a low-complexity, low-cost, low-latency and energy-efficient solution, which is appropriate for real-time obstacle detection for UAV safety applications.

III. Proposed Methodology

This proposed obstacle detection and alert system based on FPGA will ensure reliable and low latency obstacle detection for drones and small aircraft. The system is based on HC-SR04 ultrasonic sensor and Tang Nano FPGA board to continuously check the surrounding environment and alert when it detects an obstacle within a certain distance.

The proposed system is a whole working principle is shown in the Figure 1. The trigger signal is sent by the FPGA to the ultrasonic sensor which emits ultrasonic sound waves into the environment. When these waves hit an obstacle, the wave is reflected back to the sensor as an echo signal. The FPGA measures an echo's duration and computes the distance to an obstacle by applying the speed of sound principle. The distance calculated is then compared to a set threshold value. When the measured distance is below the threshold, the FPGA turns on visual and audio alarms (LEDs and buzzer).

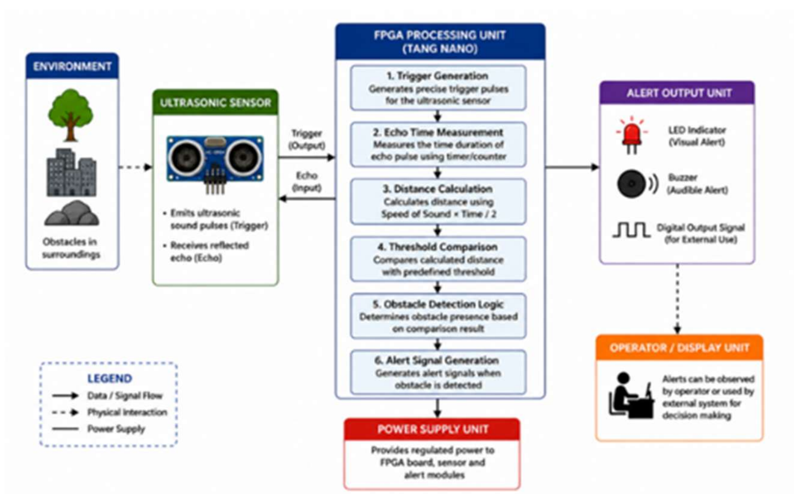

Figure 1. Working Principle of the Proposed Obstacle Detection System

The FPGA is used as the central processing unit of the system and processes all functions including signal measurement of echoes, generation of trigger pulses, calculation of distance, comparison of thresholds, and generation of alerts. The FPGA operates in parallel processing to minimize latency and enhance the real-time performance as compared with the conventional microcontroller based systems that are sequential processing systems.

The schematic of the practical hardware implementation of the obstacle detection module is presented in Figure 2. The whole system is composed of Tang Nano FPGA board, ultrasonic sensor, buzzer, LEDs and related circuits, which is embedded on the drone platform. The ultrasonic sensor always sends out signals to measure the distance to nearby obstacles, which are then processed in real-time by the FPGA and sent as alerts when obstacles are detected.

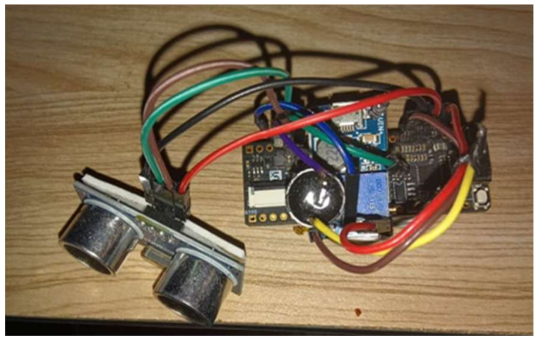

Figure 2. Hardware implementation of an Obstacle Detection Module

The above mentioned system works recyclably and continuously which allows the drone surroundings to be monitored in real-time. The obstacle detection module is not connected to the drone flight control and the operator can intervene manually via the ESP Drone mobile application to respond to alerts. The modular concept offers more flexibility, ease of implementation and easy integration into UAV platforms.

IV. Hardware And Software Requirements

A. Hardware Components

The system to be proposed should include the following hardware:

- Tang Nano FPGA Board: Tang Nano FPGA board is used as the central processing unit of the proposed system. It carries out all of the major functions of trigger signal generation, echo pulse measurement, distance calculation, threshold comparison, and alert generation. The FPGA has the ability to process sensor data in parallel, which has a tremendous amount of time and speed advantage over any conventional microcontroller-based system. It also communicates with the ultrasonic sensor, LEDs and buzzer to synchronize the entire obstacle detection process.
- HC-SR04 Ultrasonic Sensor: The ultrasonic sensor HC-SR04 can be used to detect obstacles nearby and measure the distance between the drone and nearby objects. The sensor is based on the trigger–echo principle, which involves sending ultrasonic sound waves into the environment and receiving them back when they bounce off an object. The time taken for the echo signal to return is measured by the FPGA to calculate the distance. The sensor will detect obstacles with accuracy within a close range and can be used in a variety of lighting conditions.
- Quadcopter Drone Platform: The quadcopter is used to physically implement and test the obstacle detection system. During operation it transports the FPGA board, ultrasonic sensor and alert devices. The drone is controlled by the ESP Drone mobile application, and while the FPGA system is autonomous, it communicates with the drone and triggers alerts based on its findings. The platform provides a means to test the design in real time and how it can be used.
- LED Indicators: The LED indicators will give visual warning if any obstacle is detected inside the set threshold distance. If the FPGA detects an obstacle in the vicinity, the LEDs become active right away, alerting the operator. The LEDs provide an effective and easy to see way to indicate obstacle presence during drone operation.
- Buzzer: Buzzer is used as an alarm device in the proposed system. The FPGA will activate it when the distance of the obstacle is less than the threshold value. The buzzer provides audible alerts to the operator, enhancing safety when operating the drone in crowded environments.
- Power Supply Unit: The power supply unit supplies a stable power to the FPGA board, ultrasonic sensor, LEDs and buzzer. A well regulated power supply helps maintain the proper operation of this system and help prevent any voltage fluctuations that may impact on the operation in real-time obstacle detection scenarios.

The Tang Nano FPGA board is responsible for trigger generation, echo measurement, distance calculation and alert control.
The HC-SR04 ultrasonic sensor is capable of measuring the distance to an obstacle at a short range with a high level of accuracy, through the use of trigger and echo signals. LEDs and buzzers flash and beep to alert you if there's an obstacle in the way.

B. Software Components

The FPGA logic is implemented using Verilog Hardware Description Language (HDL) and developed using Gowin IDE.
The software environment enables HDL coding, synthesis, bitstream generation and FPGA programming. It is controlled by hand with the help of an application on the smartphone, called ESP Drone.

V. RESULTS

The project was successfully implemented on the Tang Nano 1K FPGA board using the HC-SR04 Ultrasonic Sensor.
The system works reliably and meets all the defined objectives.

TABLE I. KEY PERFORMANCE RESULTS

Parameter	Result	Remarks
Measurement Range	2 cm – 400 cm	Reliable up to 3.5–4 meters
Accuracy	± 3–5 cm	Good for most applications
Update Rate	~20 measurements per second	Smooth real-time response
Red LED	Distance < 30 cm	Correctly triggered
Green LED	Distance 30 – 60 cm	Correctly triggered
Blue LED	Distance > 60 cm	Correctly triggered
Buzzer	Activated when < 100 cm	Reliable audio alert
Measurement Range	2 cm – 400 cm	Reliable up to 3.5–4 meters
Invalid Reading Handling	LED OFF when sensor error	Good robustness

A. System Behavior Summary

- The RGB LED clearly indicates three distance zones with distinct colors.
- Buzzer provides immediate audio feedback for close objects.
- The system is stable with minimal jitter after basic calibration.
- Response time is fast enough for real-time applications (obstacle detection, robotics, safety systems).
- The implementation demonstrates the capability of the Gowin Tang Nano 1K FPGA to handle real-time sensor interfacing using pure hardware description (Verilog). Unlike microcontroller-based solutions, the FPGA approach offers parallel processing and deterministic timing, resulting in very consistent trigger generation and echo pulse measurement.
- The distance calculation formula (echo_cnt / 158) was calibrated empirically for the 27 MHz system clock and showed good agreement with actual distances measured using a ruler.

The use of active-low logic for the onboard RGB LED matched the Tang Nano 1K hardware design perfectly. The system proved robust against occasional noisy readings by implementing timeout protection and invalid data filtering.

TABLE II. KEY PERFORMANCE RESULTS

Challenge	Cause	Solution Implemented
VL53L0X I²C not working	Missing init sequence, no ACKs, complex FSM	Switched to Ultrasonic Sensor (HC-SR04)
LED completely OFF	FSM stuck / no reach to update block	Added forced debug colors in states
Wrong distance calculation	Clock frequency mismatch	Calibrated divider (/158)
Unstable readings	Sensor noise & echo jitter	Added timeout protection + range limiting
Gowin IDE syntax & declaration errors	Missing signals (byte_idx, etc.)	Careful signal declaration & clean project
Timing issues in I²C bit-banging	Fast clock + poor pull-ups	Abandoned I²C for PWM/Ultrasonic

Figure 3 shows the software simulation of the proposed obstacle detection module. It can be observed that the alert signals like the three different LEDs and the buzzer and responding in real-time for the detected obstacle. This response time using the Tang Nano FPGA is comparitively faster to the traditional microcontroller based systems.

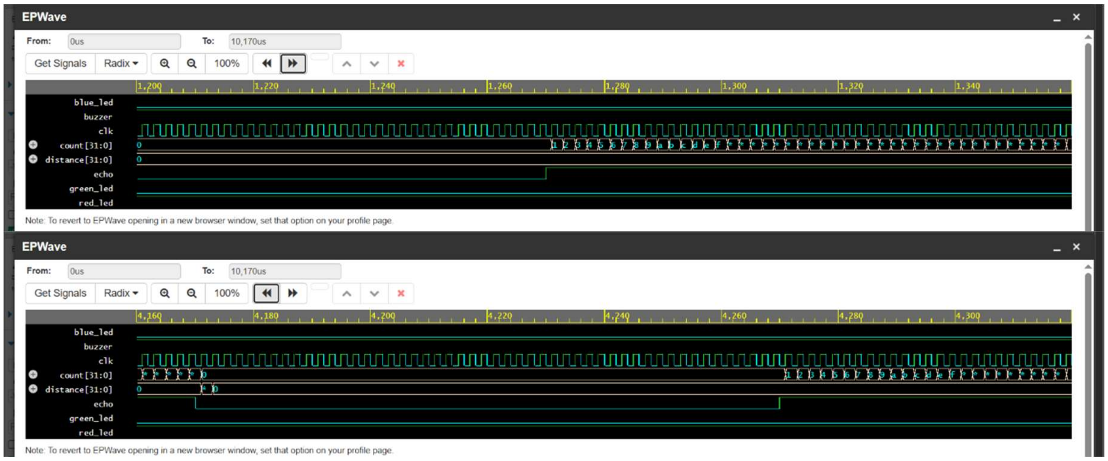

Figure 3. Waveforms obtained at software simulation

VI. Future Scope

The proposed FPGA-based real-time obstacle detection and alert system is effective for short-range obstacle detection but there are several improvements that can be considered in future to improve the capability, accuracy, and automation of the system. The one significant improvement is using several ultrasonic sensors to provide multi-directional obstacle detection. This is the current system which is only capable of detecting obstacles in the direction the sensor is looking in. Multiple sensors on the drone can be used to provide all-round coverage and better collision avoidance. The system can also be upgraded with advanced sensors like LiDAR sensors, infrared sensors, or cameras, in addition to ultrasonic sensors. They can be used for sensor fusion techniques to increase the accuracy of obstacle detection and improve performance in complex environments and long-range applications.

Automatic drone control and autonomous obstacle avoidance could also be areas for future research. The FPGA system does not just alert the drone, but can directly communicate with the flight controller to automatically alter the drone path if it comes across an obstacle. This would add to the UAV's autonomy and decrease the dependence on the operator. Further enhancements can be made using Artificial Intelligence (AI) and Machine Learning (ML) techniques for better object recognition, intelligent path planning and adaptive navigation. In dynamic environments, AI systems can be used to detect various obstacle types and make intelligent decisions for the drones. The design proposed can also be further optimized for outdoor real-time applications, with the consideration of possible external environmental changes like temperature fluctuation, wind disturbance, etc., signal noises, etc. Further low-power hardware and FPGA optimization techniques can also be applied to make UAVs even more energy efficient and to extend their flight time. The system can be expanded for future applications like autonomous surveillance drones, smart transportation systems, inspection for industries, disaster management, defense monitoring, etc. High-speed FPGA processing coupled with intelligent sensing technologies offer good potential for the development of advanced UAV safety and navigation systems in real-time.

VII. Conclusion

In this paper, a real-time obstacle detection and alert system has been designed and implemented on an FPGA board (Tang Nano) and ultrasonic sensor (HC-SR04) for drones and small aircraft. The system was able to detect obstacles successfully with low latency and good performance. High-speed parallel processing at hardware level was efficiently implemented by the FPGA, which carries out operations like echo measurement, distance computation, threshold comparison and alert determination.

Experimental results showed that the distance could be measured accurately, the response time was short, the experimental operation was stable and the measurement reliability was high. The proposed system is safe and energy efficient at an economical cost to the UAV safety systems. Possible future enhancements are multi-directional sensing, integration with automatic drone control and more sophisticated sensor fusion for improved obstacle detection capabilities.

REFERENCES

[1] P. Y. Leong and N. S. Ahmad, “LiDAR-Based Obstacle Avoidance With Autonomous Vehicles: A Comprehensive Review,” IEEE Access, vol. 12, pp. 164248–164261, Nov. 2024.

[2] P. Flak and R. Czyba, “RF Drone Detection System Based on a Distributed Sensor Network,” Sensors, vol. 24, no. 3, pp. 1–18, 2024.

[3] A. Loquercio, A. Pullin, and D. Scaramuzza, “Tiny Neural Networks for Real-Time Obstacle Avoidance in Nano-UAVs,” IEEE Robotics and Automation Letters, vol. 6, no. 2, pp. 1–8, 2021.

[4] M. Erdelj and E. Natalizio, “UAV-Assisted Disaster Management: Applications and Open Issues,” International Conference on Computing, Networking and Communications, pp. 1–5, 2016.

[5] S. Hrabar, “Obstacle Detection and Avoidance for UAVs: A Survey,” Journal of Intelligent and Robotic Systems, vol. 84, no. 1–4, pp. 629–646, 2016.

[6] Y. Chen, J. Li, and X. Wang, “Airport Obstacle Detection Using UAV-Based Dense Image Matching,” Remote Sensing, vol. 13, no. 9, pp. 1–15, 2021.

[7] Y. Zeng, R. Zhang, and T. J. Lim, “Wireless Communications With Unmanned Aerial Vehicles: Opportunities and Challenges,” IEEE Communications Magazine, vol. 54, no. 5, pp. 36–42, May 2016.

[8] A. Katrasnik, F. Pernus, and B. Likar, “A Survey of Mobile Robots for Distribution Power Line Inspection,” IEEE Transactions on Power Delivery, vol. 25, no. 1, pp. 485–493, Jan. 2010.

[9] M. S. Couceiro, R. P. Rocha, and N. M. Ferreira, “A Novel Multi-Robot System for Wildlife Monitoring,” International Conference on Autonomous Robot Systems and Competitions, pp. 1–6, 2015.

[10] M. Strohmeier, V. Lenders, and I. Martinovic, “On the Security of the Automatic Dependent Surveillance-Broadcast Protocol,” IEEE Communications Surveys & Tutorials, vol. 17, no. 2, pp. 1066–1087, 2015.

[11] A. Fotouhi, H. Qiang, M. Ding, M. Hassan, L. G. Giordano, A. Garcia-Rodriguez, and J. Yuan, “Survey on UAV Cellular Communications: Practical Aspects, Standardization Advancements, Regulation, and Security Challenges,” IEEE Communications Surveys & Tutorials, vol. 21, no. 4, pp. 3417–3442, 2019.

[12] S. Rathinam, Z. Kim, and R. Sengupta, “Vision-Based Monitoring of Locally Linear Structures Using an Unmanned Aerial Vehicle,” Journal of Infrastructure Systems, vol. 14, no. 1, pp. 52–63, Mar. 2008.

[13] J. Seo, Y. Kim, S. Kim, and A. Tsourdos, “Collision Avoidance Strategies for Unmanned Aerial Vehicles in Formation Flight,” IEEE Transactions on Aerospace and Electronic Systems, vol. 53, no. 6, pp. 2718–2734, Dec. 2017.

[14] A. Kendoul, “Survey of Advances in Guidance, Navigation, and Control of Unmanned Rotorcraft Systems,” Journal of Field Robotics, vol. 29, no. 2, pp. 315–378, 2012.

[15] T. Gandhi and M. M. Trivedi, “Pedestrian Protection Systems: Issues, Survey, and Challenges,” IEEE Transactions on Intelligent Transportation Systems, vol. 8, no. 3, pp. 413–430, Sept. 2007.2

[16] P. Y. Leong and N. S. Ahmad, “LiDAR-Based Obstacle Avoidance With Autonomous Vehicles: A Comprehensive Review,” IEEE Access, vol. 12, pp. 164248–164261, Nov. 2024, doi: 10.1109/ACCESS.2024.3493238.

[17] P. Flak and R. Czyba, “RF Drone Detection System Based on a Distributed Sensor Grid With Remote Hardware-Accelerated Signal Processing,” IEEE Access, vol. 11, pp. 138759–138772, Dec. 2023, doi: 10.1109/ACCESS.2023.3340133.

[18] Z. Zhang et al., “Real-Time Local Obstacle Avoidance and Trajectory Tracking Control of Quadrotor UAVs With Suspended Payload in Complex Environments,” IEEE Access, vol. 11, pp. 144017–144029, Dec. 2023, doi: 10.1109/ACCESS.2023.3344578.

[19] Cho et al., “Obstacle Avoidance of a UAV Using Fast Monocular Depth Estimation for a Wide Stereo Camera,” IEEE Transactions on Industrial Electronics, vol. 72, no. 2, pp. 1763–1773, Feb. 2025.

[20] J. Feng et al., “UAV Dynamic Path Planning Based on Obstacle Position Prediction in an Unknown Environment,” IEEE Access, vol. 9, pp. 154679–154691, Nov. 2021, doi: 10.1109/ACCESS.2021.3128295.