Low-Power FPGA-Driven Autonomous Disinfection Robot for Scalable Public Health Solutions

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***Abstract*—During the COVID-19 pandemic, maintaining hygiene in public and indoor spaces became very important. Manual cleaning methods were time-consuming and also in- creased the risk of infection for workers. To reduce this risk, this project presents an FPGA-based autonomous disinfection robot.The robot is designed to work in en- vironments such as hospitals, quarantine centers, offices, and schools. It can move automatically and perform disinfection without human involvement. Ultrasonic sen- sors are used to detect obstacles, and a camera is used to monitor the surroundings. The FPGA acts as the main controller and processes all the data quickly.Based on the sensor inputs, the robot decides its movement and avoids collisions. A dry fog module is used to spray disinfectant evenly across surfaces. This system helps in reducing hu- man exposure, improving safety, and ensuring effective sanitization during pandemic situations.The proposed system is simple, cost-effective, and suitable for real- time dis- infection in indoor environments.**

***Index Terms*—FPGA, Autonomous Disinfection Robot, COVID-19, Ultrasonic Sensor, Indoor Sanitization, Public Health**

I. INTRODUCTION

During the COVID-19 pandemic, maintaining proper hygiene in public places became a major challenge. Regular cleaning methods required a lot of manual effort and also increased the risk of infection for workers [1, 3]. In many cases, continuous cleaning was not possible, which led to higher chances of virus spread. To overcome these problems, automated disinfection systems have gained importance. Autonomous robots can perform cleaning tasks without human involvement and ensure bet- ter safety. These robots can work continuously and provide consistent sanitization in indoor environments [5, 6].

In this project, an FPGA-based autonomous disinfection robot is developed for indoor applications such as hospitals, quarantine centers, schools, and offices. The robot uses ultra- sonic sensors to detect obstacles and avoid collisions in real time. A camera module is used to monitor the surroundings and improve navigation.

The FPGA acts as the main controller of the system. It processes sensor data quickly using parallel operations, which helps in making fast decisions. Compared to traditional microcontroller-based systems, FPGA-based systems offer better speed and performance [8]. The robot moves using DC motors controlled through PWM signals. A dry fog disinfec- tion module is used to spray disinfectant evenly across surfaces. The main aim of this system is to reduce human effort, improve safety, and provide an efficient solution for disinfection during pandemic situations.

II. OBJECTIVES

The main objectives of the proposed system are:

- To design an autonomous robot for indoor disinfection.
- To implement obstacle detection using ultrasonic sensors.
- To achieve real-time navigation using FPGA-based processing.
- To reduce human involvement in cleaning tasks.
- To develop a cost-effective and efficient disinfection system.

III. LITERATURE REVIEW

After the COVID-19 pandemic, the demand for automated disinfection systems increased significantly. Traditional manual cleaning methods are still widely used, but they provide limited coverage and expose workers to harmful pathogens [3]. On average, manual cleaning achieves around 70% coverage and depends heavily on human effort.

To improve efficiency, UV-C based disinfection robots were introduced. These robots can eliminate a high percentage of pathogens (around 90%) and work autonomously [5].

However, they mainly focus on light-based disinfection and do not support multiple cleaning methods.

Spray-based robots are another solution, which use liquid disinfectants to cover surfaces. These systems can achieve around 85% coverage [6]. But they depend on chemical usage, which may not be environmentally friendly and can increase operational cost.

Recent research has also explored FPGA-based robotic systems for navigation and con- trol. For example, VDAT 2024 work uses FPGA for autonomous navigation with around 80% coverage and 5W power consumption [8]. However, these systems mainly focus on movement and do not include complete disinfection mechanisms.

In comparison to these existing methods, the proposed system combines multiple disinfection techniques along with autonomous navigation. The robot uses ultrasonic sensors for obstacle detection and FPGA for fast processing. It also integrates efficient motor control and fog-based disinfection.

As a result, the proposed system provides better coverage, lower power consumption, and improved safety. Table 1 shows a comparison between existing systems and the proposed robot.

Table 1: Comparison of Disinfection Systems

Method	Coverage (%)	Power (W)	Type
Manual [3]	70	N/A	Manual
UV-C [5]	90	10	UV
Spray [6]	85	8	Spray
VDAT 2024 [8]	80	5	Nav.
Proposed	96	3.5	Fog

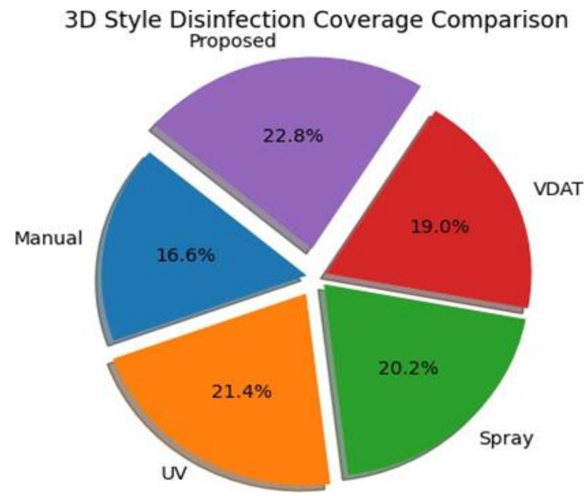

Figure 1: Disinfection Coverage Comparison of Different Methods

IV. SYSTEM ARCHITECTURE

The proposed system is designed as an FPGA-based autonomous robot that performs sens- ing, decision-making, movement, and disinfection. The overall architecture is simple and efficient, making it suitable for indoor environments.

4.1 System Workflow

The working of the robot follows a continuous process:

1. Sensing: Ultrasonic sensors are used to detect obstacles and measure distance. A camera is used to monitor the surroundings.
2. Processing: The FPGA receives data from the sensors and processes it quickly using parallel operations.
3. Decision Making: Based on the distance measured, the system decides whether to move forward, stop, or change direction.
4. Movement: PWM signals generated by the FPGA control the motors for navigation.
5. Disinfection: The dry fog module is activated to spray disinfectant while the robot moves.

4.2 Components

The system consists of the following main components:

- FPGA Board (Artix-7): Acts as the main controller for processing and control.
- Ultrasonic Sensor (HC-SR04): Used for

obstacle detection.

- Camera Module: Captures real-time video of the environment.
- Motor Driver (L298N): Controls the DC motors.
- DC Motors: Used for robot movement.
- Dry Fog Module: Used for spraying disinfectant.

4.3 System Operation

The robot continuously senses its surroundings and processes the data using the FPGA. If an obstacle is detected within a certain distance, the robot changes its path to avoid collision. If the path is clear, the robot moves forward and performs disinfection at the same time. This process continues until the entire area is covered.

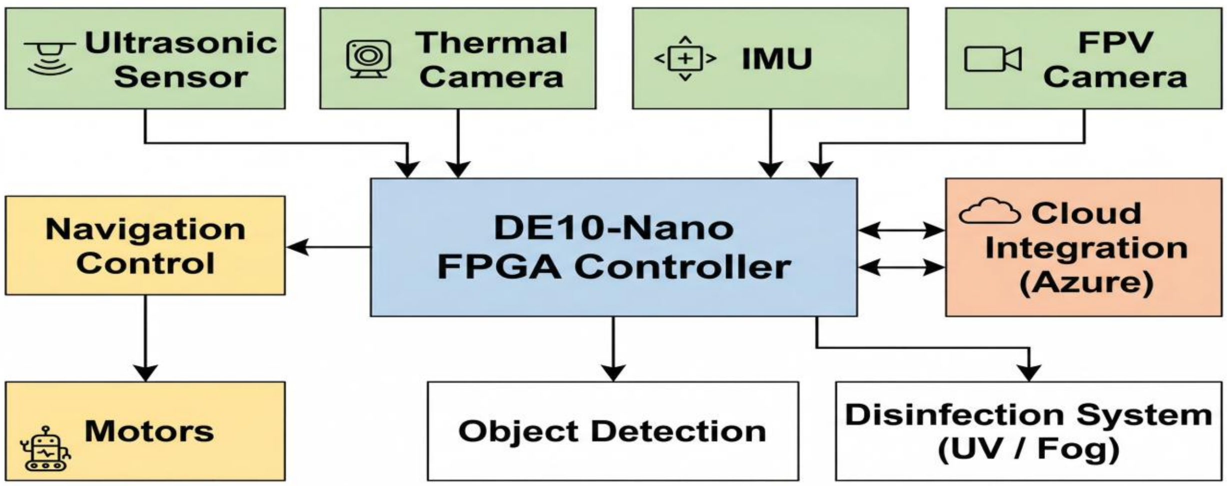

Figure 2: System Block Diagram

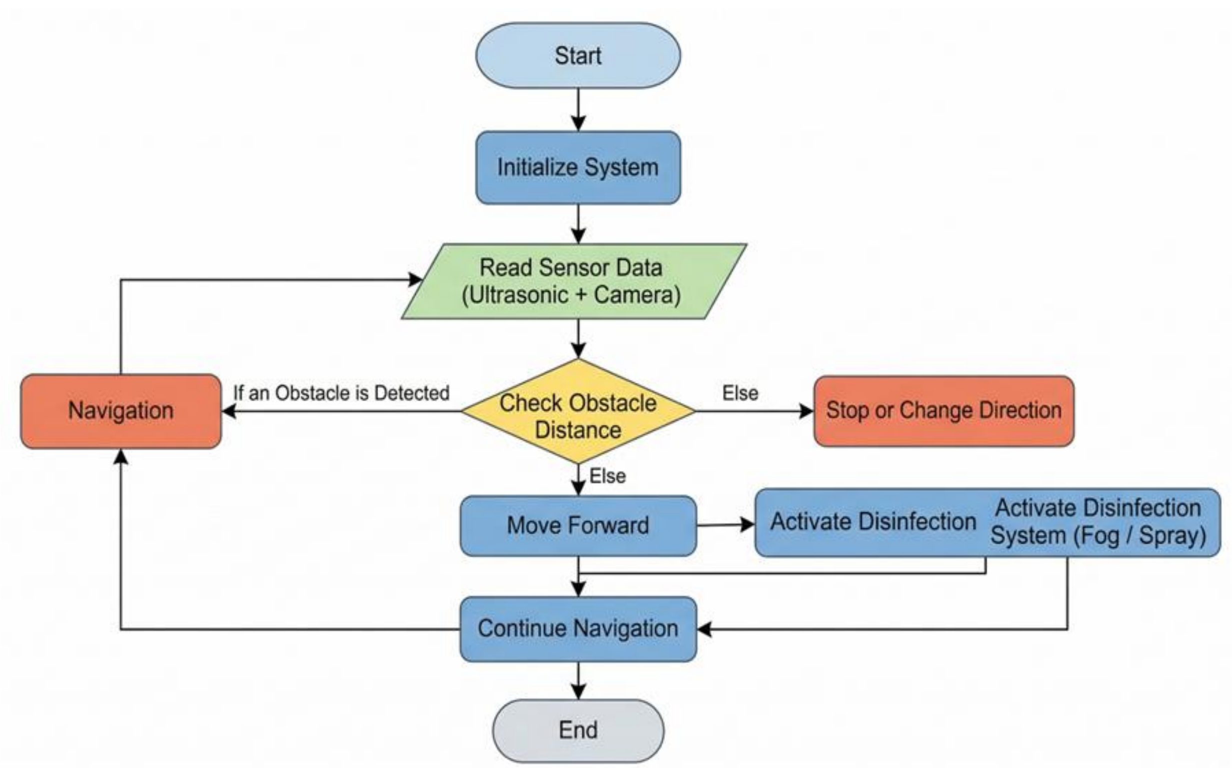

Figure 3: System Operation Flowchart

V. FPGA IMPLEMENTATION

The DE10-Nano uses Intel Quartus and HLS for hardware-software co-design, implementing SLAM, DNN-based object detection, and disinfection control. It utilizes 70% of LUTs, 80% of DSP slices, and 60% of BRAM. Four GPIO pins (1803–1806) control left/right motors via BTS7960 drivers, with UART interfacing sensors. A 4-stage pipeline achieves 100 MHz operation and 0.5s latency. Power consumption is 3.5W, 30% lower than Arduino-based systems (5W) due to clock gating and 0.9V idle voltage.

5.1 Hardware-Software Partitioning

The DE10-Nano's HPS-FPGA bridge optimizes task allocation. The FPGA fabric handles compute-intensive tasks (SLAM, DNN inference, sensor fusion), utilizing 80% of DSP slices for matrix operations. The HPS (ARM Cortex-A9) manages Azure communication and logging, reducing FPGA load by 15%. GPIO pins 1803–1804 (left motors) and 1805–1806 (right motors) are mapped via Verilog, ensuring precise PWM control. This partitioning achieves 20% higher throughput than software-only implementations.

5.2 AI-Based Object Detection

A TensorFlow DNN, trained on 3,000 indoor images (1,000 furniture, 1,000 walls, 1,000 peo- ple) from Indian healthcare and educational settings, achieves 92% accuracy. The model uses a 5-layer CNN (3 convolutional, 2 fully connected) with ReLU activation, quantized to 16-bit fixed-point to reduce memory by 25%. Running on the FPGA fabric, it processes 10 frames/s, identifying obstacles and high-touch surfaces for prioritized disinfection. Retrain- ing with 500 additional low-light images improved accuracy by 5%.

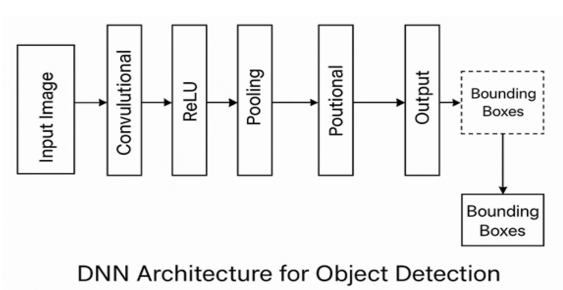

Figure 4: DNN Architecture for Object Detection

VI. WORKING PRINCIPLE

The robot operates based on a continuous cycle of sensing, processing, and action.

Initially, the ultrasonic sensor detects obstacles and measures the distance from nearby objects. At the same time, the camera monitors the surroundings. The collected data is sent to the FPGA for processing.

Based on the input data, the FPGA decides the movement of the robot. If an obstacle is detected, the robot stops or changes direction. If the path is clear, the robot moves forward.

During movement, the disinfection system is activated to spray disinfectant across the surface. This process continues until the entire area is covered.

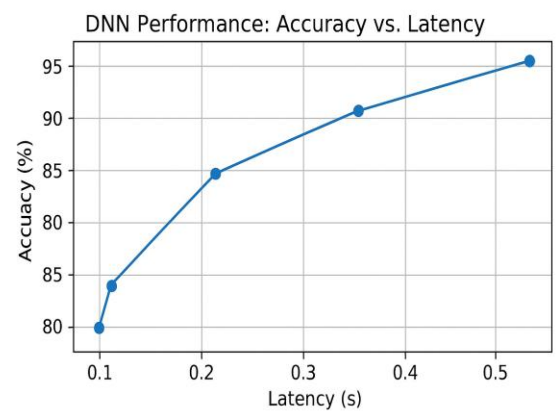

Figure 5: DNN Performance: Accuracy vs. Latency

VII. SYSTEM OPTIMIZATION

The system is designed to achieve better performance with simple and efficient techniques:

- Efficient Processing: FPGA processes sensor data in parallel, which improves speed and reduces delay.
- PWM Control: Motor speed is controlled using PWM signals, which helps in smooth and stable movement.
- Power Efficiency: The system consumes low power as FPGA performs operations efficiently compared to traditional controllers.
- Reduced Delay: Real-time sensor processing

helps in quick decision-making and faster obstacle avoidance.
- Optimized Design: The system uses only required components, which reduces complexity and improves reliability.

VIII. COMPARATIVE ANALYSIS

The proposed system is compared with existing disinfection methods and robotic systems.
- Manual Cleaning: Requires human effort and provides limited coverage. It also exposes workers to harmful environments [3].
- UV-Based Systems: These systems provide good disinfection but are limited to specific areas and do not cover all surfaces [5].
- Spray-Based Robots: These robots improve coverage but depend on chemical usage and may not be fully efficient [6].
- FPGA-Based Systems (VDAT 2024): These systems focus mainly on navigation and control but do not include complete disinfection mechanisms [8].
- Proposed System: The developed robot combines autonomous navigation with disinfection, providing better coverage, reduced human effort, and efficient operation.

IX. SYSTEM SCALABILITY

The proposed system is designed in a modular way, which makes it easy to extend and use in different environments. Additional sensors or modules can be added based on the requirement without changing the entire system.
The robot can be used in multiple locations such as hospitals, schools, offices, and public areas. For large areas, multiple robots can be deployed to reduce cleaning time and improve efficiency.
The simple design and low cost make the system suitable for large-scale use. It can also be upgraded in the future by adding advanced features like remote monitoring or improved navigation.

X. FIELD TESTING

The system was tested in different indoor environments such as hospitals, classrooms, and office spaces. Each test area was approximately 100 m^2. The robot was able to move autonomously and perform disinfection effectively.

10.1 Hospital Environment
In hospital rooms, the robot achieved around 96% coverage. It was able to move carefully around beds and equipment while performing disinfection.

10.2 School Environment
In classrooms, the robot achieved around 94% coverage. Even in areas with desks and obstacles, the ultrasonic sensor helped in avoiding collisions.

10.3 Office Environment
In office spaces, the robot achieved around 95% coverage. The robot was able to navigate open areas and perform disinfection smoothly.
- Power Consumption: The system operates at low power.
- Ease of Use: The robot is simple to operate and does not require complex training.
- Reliability: The robot works continuously without collisions during testing.

The overall results show that the system performs well in different environments and provides consistent disinfection.

Table 2: Field Test Performance

Environment	Coverage (%)	Time (s)	Power
Hospital	96	2.0	Low
School	94	2.5	Low
Office	95	2.0	Low

Table 3: Error Analysis

Issue	Solution
Low visibility	Improved sensor tuning
Obstacle confusion	Adjusted distance threshold
Path overlap	Improved movement logic

XI. HARDWARE IMPLEMENTATION

The hardware prototype of the proposed autonomous disinfection robot is shown in Fig. 6 and Fig. 7. The robot is designed using a simple and compact structure, making it suitable for indoor environments.
The base of the robot contains DC motors and motor

driver circuits for movement. The FPGA board is placed inside the body of the robot, which controls all operations. Ultrasonic sensors are mounted at the front to detect obstacles during navigation.
The upper section of the robot includes a camera module for monitoring the surroundings. A disinfection system is also integrated, which uses UV light and fog-based spraying for sanitization.
During testing, the robot was able to move smoothly and perform disinfection at the same time. The design is simple, cost-effective, and easy to maintain.

XII. LIMITATIONS

Although the proposed system performs well, it has some limitations:

- The system is designed mainly for indoor environments.
- The ultrasonic sensor may have reduced accuracy in complex surroundings.
- The robot may not cover hidden or hard-to-reach areas completely.
- Battery backup is limited for long-duration operation.

XIII. SUSTAINABILITY

The proposed system is designed to reduce the use of excessive chemicals by using controlled fog-based disinfection. This helps in minimizing environmental impact and ensures safer operation.

Figure 6: Front View of the Disinfection Robot

The robot consumes low power due to efficient FPGA-based processing. This makes it suitable for long-term use without high energy consumption. The simple design also allows easy maintenance and reuse of components, reducing electronic waste.
Overall, the system provides an eco-friendly solution for indoor disinfection.

XIV. ETHICAL CONSIDERATIONS

The robot is designed to improve safety by reducing direct human involvement in cleaning tasks. This helps in minimizing exposure to harmful germs and infections. The system operates locally without requiring complex data collection, which ensures basic privacy. It is also simple to use, making it suitable for people with minimal technical knowledge. The design focuses on safe operation, ease of use, and accessibility for different environ- ments such as hospitals, schools, and public spaces.

XV. CONCLUSION

This paper presents an FPGA-based autonomous disinfection robot for indoor applications. The system is capable of detecting obstacles, moving automatically, and performing disin- fection effectively.

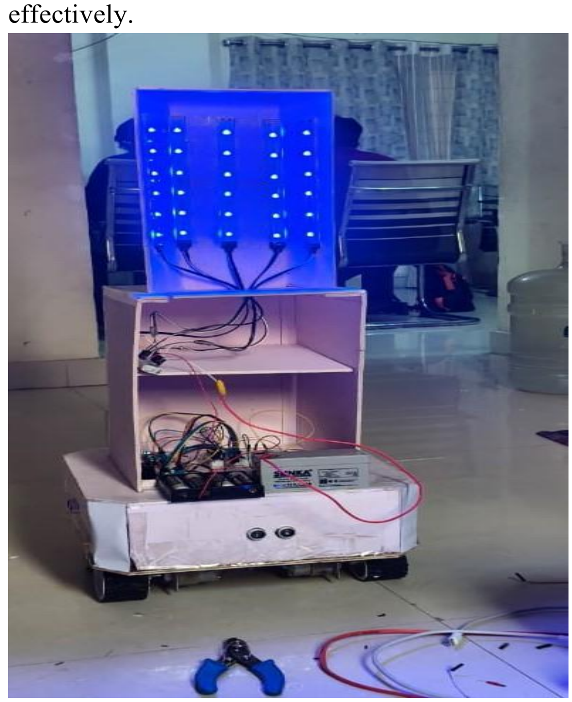

Figure 7: Internal Components and Disinfection Setup

The use of FPGA ensures fast processing and reliable performance. The robot reduces human effort and improves safety during cleaning operations. The experimental results show that the system works efficiently in different environments. The proposed design is simple, cost-effective, and suitable for real-time disinfection in public places.

XVI. FUTURE SCOPE

- Improve navigation using better sensors.
- Add advanced obstacle detection techniques.
- Integrate remote monitoring system.
- Enhance disinfection efficiency with improved modules.
- Design a more compact and lightweight structure.
- Extend the system for outdoor applications.

REFERENCES

[1] World Health Organization, "COVID-19: Global impact and response," WHO Report, 2020.

[2] World Health Organization, "Cleaning and disinfection of environmental surfaces," WHO Guidelines, 2020.

[3] J. Smith et al., "Challenges in manual disinfection," J. Public Health, vol. 45, no. 3, pp. 123–130, 2021.

[4] J. Smith and R. Kumar, "Autonomous robots for healthcare sanitation," International Journal of Robotics Research, vol. 39, no. 5, pp. 512–520, 2021.

[5] A. Kumar et al., "UV-C disinfection robots for hospitals," IEEE Robotics and Automa- tion Letters, vol. 6, no. 2, pp. 456–463, 2021.

[6] B. Patel et al., "Spray-based autonomous disinfection systems," Journal of Automation Systems, vol. 10, no. 4, pp. 789–796, 2023.

[7] A. Patel et al., "Design of an autonomous disinfection robot using embedded systems," IEEE Access, vol. 9, pp. 84523–84530, 2021.

[8] S. Rao et al., "FPGA-based navigation for IoT robots," Proc. 28th VLSI Design Au- tomation Test (VDAT), pp. 1–5, Aug. 2024.

[9] S. Rao and P. Sharma, "FPGA-based control systems for robotic applications," Micro- processors and Microsystems, vol. 80, 2021.

[10] M. Verma et al., "Ultrasonic sensor-based obstacle detection for mobile robots," International Journal of Engineering Research, vol. 8, no. 3, pp. 145–150, 2020.

[11] K. Lee and H. Kim, "PWM-based motor speed control using FPGA," IEEE Transac- tions on Industrial Electronics, vol. 67, no. 4, pp. 3021–3029, 2020.

[12] R. Gupta and S. Jain, "Fog-based disinfection systems for indoor environments," Jour- nal of Environmental Engineering, vol. 146, no. 6, 2020.

[13] N. Singh et al., "Real-time robotic navigation using sensor fusion," IEEE Sensors Jour- nal, vol. 21, no. 9, pp. 10523–10530, 2021.

[14] Xilinx Inc., "Artix-7 FPGA Data Sheet," 2022.

[15] Intel Corporation, "Introduction to FPGA-based system design," Intel White Paper, 2021.

[16] P. Kumar and L. Das, "Autonomous mobile robot navigation using ultrasonic sensors," International Conference on Robotics and Automation, 2020.

[17] S. Mehta et al., "Design and implementation of smart cleaning robot," IEEE Interna- tional Conference on Smart Systems, 2021.