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A

PROJECT REPORT

ON

SentriX - An Autonomous Border Surveillance System

SUBMITTED BY

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ABSTRACT

Border surveillance is a critical component of national security, yet traditional systems rely heavily on manual patrolling and static camera-based monitoring, leading to delayed responses, high manpower dependency, and reduced reliability in adverse environmental conditions. This paper presents **Sentrix**, an **autonomous border surveillance system** designed to provide intelligent, real-time threat detection with minimal human intervention.

Sentrix follows a **layered multi-sensor approach** to enhance detection accuracy and system reliability. A **mmWave radar sensor** acts as the primary detection unit, continuously monitoring long-range areas and detecting motion irrespective of lighting or weather conditions. Upon detection, short-range sensors including **ultrasonic, infrared (IR), and Time-of-Flight (ToF) sensors** are activated to confirm object presence and measure distance. Additional threat verification is achieved through a **sound sensing module** capable of detecting acoustic anomalies such as footsteps or gunshots, along with a **camera module** that captures visual evidence of the detected event.

The system is implemented using a **Real-Time Operating System (RTOS)** to enable parallel task execution and deterministic response. Sensor data is monitored locally and transmitted to an **IoT cloud platform** for real-time visualization. Future enhancements include the integration of **TinyML** for human–animal classification, improving autonomy and reducing false alerts.

ACKNOWLEDGEMENT

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CHAPTER 1

INTRODUCTION

1 INTRODUCTION

1.1 Introduction

Effective border surveillance is essential for ensuring national security and preventing unauthorized intrusions. Conventional surveillance methods, such as manual patrolling and camera-based monitoring, are often limited by environmental conditions, high operational costs, and delayed response times. Advances in embedded systems, sensor technology, and Internet of Things (IoT) platforms enable the development of autonomous and intelligent surveillance solutions. This project presents **Sentrix**, an autonomous border surveillance system that integrates multiple sensors, real-time processing, and cloud-based monitoring. By employing a layered detection approach and parallel task execution, Sentrix aims to improve detection accuracy, reduce false alarms, and provide reliable real-time situational awareness.

1.2 Need

- **Enhanced Border Security:**
  Continuous monitoring of sensitive border regions is critical to prevent unauthorized intrusions, infiltration, and hostile activities in real time.
- **Limitations of Manual Surveillance:**
  Human patrolling and camera-based systems are prone to fatigue, delayed response, and reduced effectiveness in low visibility and harsh environmental conditions.
- **Requirement for Real-Time Threat Detection:**
  Defence surveillance systems must detect, validate, and respond to threats instantly to minimize reaction time and potential damage.
- **Embedded and Autonomous Operation:**
  A low-power, embedded autonomous system is essential for deployment in remote border areas with minimal human intervention and maintenance.
- **Accurate Threat Identification:**
  Multi-sensor fusion enables reliable differentiation between genuine threats and non-threatening events, reducing false alarms and improving decision-making.

1.3 Targeted Community

The **SentriX Autonomous Border Surveillance System** is designed to address the operational requirements of the following sectors:

- **National Defense Organizations:**
  Providing a reliable and autonomous first line of surveillance for securing international borders and sensitive defense zones.
- **Border Security Forces:**
  Supporting patrol units by automating continuous monitoring in high-risk, inaccessible, or remote border terrains.
- **High-Security Infrastructure:**
  Enhancing protection of critical assets such as power plants, research facilities, ammunition depots, and strategic installations.
- **Autonomous and Smart Patrol Systems:**
  Acting as a foundational technology for integration with mobile patrol units and autonomous defense vehicles.

1.4 Scope

- **Perimeter Defense:**
  Deployment in permanent border installations to enable continuous, 24/7 autonomous monitoring and intrusion detection.
- **Tactical Surveillance:**
  Application in temporary military camps and forward operating bases where rapid sensor deployment and real-time threat awareness are critical.
- **Embedded Systems and RTOS Research:**
  Advancing real-time operating system implementation and multi-sensor fusion techniques on low-power ARM-based microcontrollers for mission-critical defense applications.

1.5 Objective

The primary objectives of the **SentriX Autonomous Border Surveillance System** are as follows:

- **Autonomous Intrusion Detection:**
  To enable real-time detection of unauthorized intrusions without continuous human supervision.

- **Multi-Sensor Integration:**
  To interface and process data from multiple heterogeneous sensors, including mmWave, ToF, sound, and camera modules, on a single STM32F407 microcontroller platform.

- **Real-Time Alert Generation:**
  To generate immediate local and remote alerts through visual and audible mechanisms upon confirmed threat detection.

- **Intelligent Activity Prediction:**
  To analyze sensor data patterns within an RTOS-based environment to identify and flag suspicious activity at an early stage.

CHAPTER 2

LITERATURE SURVEY

LITERATURE SURVEY

This literature survey explores the evolution of border security from simple manual monitoring to autonomous, multi-sensor systems, specifically focusing on technologies relevant to the **SentriX** architecture.

2.1 Literature Review

2.1.1 Evolution of Autonomous Surveillance Towers

Current research highlights a significant shift toward integrated autonomous towers that combine long-range thermal imaging, radar, and AI to identify threats before they reach critical zones. By 2025, the global border security market is projected to exceed US$60 billion, driven largely by advancements in "Ground Environment" systems that utilize unattended ground sensors and AI for real-time situational awareness. Recent studies emphasize that while radar provides initial wide-area detection, imaging and AI are required to provide positive visual identification (e.g., distinguishing a person from an animal).

2.1.2 Multi-Sensor Fusion Techniques (MMwave & ToF)

The integration of diverse sensing modalities—such as **MMwave radar** and **Time-of-Flight (ToF)** sensors—is a core trend in 2025 surveillance literature for overcoming the limitations of uni-modal systems.

- **MMwave Advantages:** Millimeter-wave radar is recognized for its ability to sense occluded objects and operate effectively in low-visibility conditions where standard RGB cameras fail.
- **Hybrid Ranging:** Recent research has successfully combined Doppler microwave sensors with 8x8 ToF infrared sensors to achieve near-perfect binary classification (99.88% accuracy) for object presence detection.
- **Point Cloud Processing:** Advanced systems now utilize point cloud generation and noise reduction stages to distinguish human cluster groups from static clutter, which is critical for high-accuracy tracking.

2.1.3 RTOS and Real-Time Intrusion Detection

Deterministic performance is essential in defense applications. Research indicates that a **Real-Time Operating System (RTOS)** is vital for managing latencies and supervising application software to ensure the system reacts to environmental changes without delay.

- **Task Scheduling:** RTOS-based architectures allow for "slew-to-cue" operations, where radar or ground sensors trigger high-priority camera tasks for visual confirmation.
- **Algorithm Efficiency:** Recent frameworks like Hybrid Ensemble Anomaly Detection (HEAD) have demonstrated the ability to maintain latencies as low as 180 ms while identifying both known and unknown threats.

2.1.4 Vision-Based Human Tracking

While vision remains a powerful tool, recent literature points to its heavy dependence on environmental lighting.

- **Deep Learning (YOLO):** Studies from June 2025 on YOLO-based systems show detection accuracy above 90% in favorable lighting, but performance degrades significantly in dark environments, necessitating the addition of thermal imaging or auxiliary sensors like the **OV7670** camera integrated with multi-modal sensor data.
- **Feature Extraction:** Intelligent intrusion systems for IoT now leverage Random Forest and CNN models to achieve detection accuracies of up to 99.5%, though these often require offloading complex tasks to edge computational platforms.

CHAPTER 3

DESIGN METHODOLOGY

DESIGN METHODOLOGY

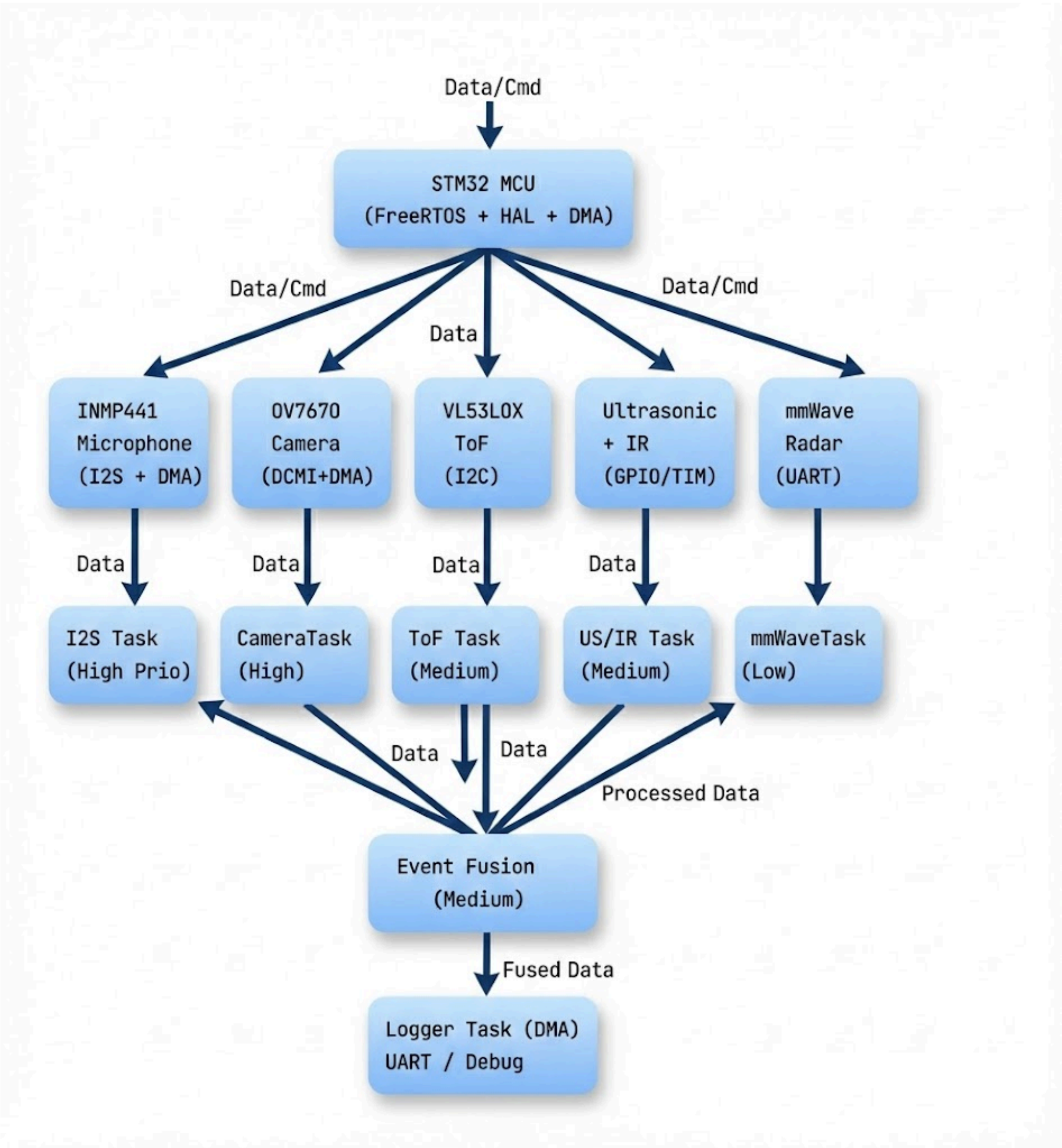


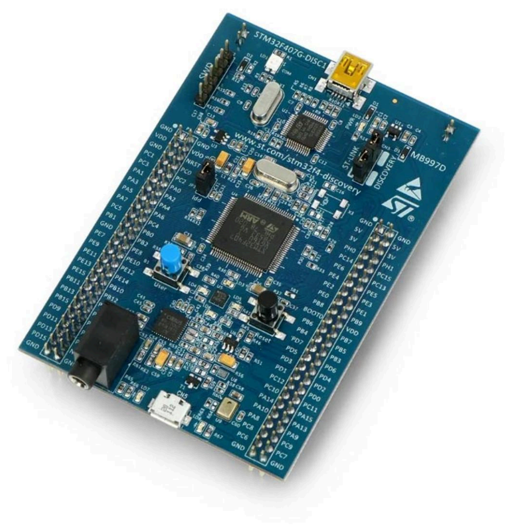
Figure 3.1.1:Block diagram

3.1 Block Diagram and Description

The system follows a star-topology hardware interface where the **STM32F407 Discovery-1 kit** acts as the central intelligence hub.

- **Central Processing Unit**: The **STM32F407** manages all peripheral communication using a mix of I2C, SPI, UART, and Parallel interfaces.
- **Primary Detection Layer**: The **MMwave (HLK-LD1115H)** and **ToF (VL53L0X)** sensors are continuously polled via UART and I2C respectively to detect human movement and precise distance.
- **Visual Confirmation**: The **OV7670 camera sensor** is interfaced via the DCMI (Digital Camera Interface) or parallel pins to capture image frames upon high-priority triggers.
- **Acoustic Intelligence**: The **INMP441 Sound Module** provides digital I2S audio data, allowing the system to "hear" intrusions that may be out of the visual line-of-sight.
- **Redundancy Suite**: **Ultrasonic (HC-SR04)** and **IR (HW-201)** sensors provide low-latency proximity data to confirm near-field breaches.

3.2.1 Core Controller: STM32F407 Discovery-1 Kit



The heart of the system is the **STM32F407VGT6**, an ARM® Cortex®-M4 32-bit MCU with a Floating Point Unit (FPU).

- **Performance:**
  Operates at clock frequencies up to **168 MHz**, delivering approximately **210 DMIPS**, enabling real-time multi-sensor processing and RTOS task scheduling.

- **Memory Resources:**
  Equipped with **1 MB Flash** and **192 KB + 4 KB SRAM**, sufficient for FreeRTOS kernel, peripheral drivers, and sensor fusion logic.

- **Operating Voltage:**
  Core operates at **1.2 V**, while I/O peripherals support **3.3 V**, making it compatible with most embedded sensors.

- **Communication Interfaces:**
  Provides **3 × I2C, 3 × SPI, and up to 6 × UART/USART interfaces**, facilitating seamless integration of heterogeneous sensors.

- **Imaging Support:**
  Features an **8- to 14-bit parallel Digital Camera Interface (DCMI)** supporting data rates up to **54 MB/s**, used for interfacing the OV7670 camera module.

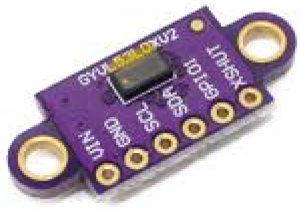
3.2.2 Primary Detection Hub: High-Sensitivity Sensors

The system uses a combination of radar and laser technology to ensure high-fidelity detection.

- **MMwave Sensor (HLK-LD1115H):**

  - **Application & Purpose:**
    Deployed as the **first-line long-range motion detector**, suitable for border areas where visibility is low or camouflaging is common.
  - **Role in System:**
    Detects micro-movements of human intruders using millimeter-wave radar and triggers secondary sensors only upon confirmed motion.
  - **Operating Voltage:**
    Typically operates at **5 V DC**, making it suitable for direct integration with embedded power rails.
  - **Pin Configuration:**
    Uses **4–6 pins** including VCC, GND, UART TX/RX, and configuration pins.
  - **Output Type:**
    Provides **digital output** via UART communication and logic-level presence detection signals.
  - **Added Advantage:**
    Capable of detecting presence through thin obstacles such as cloth, foliage, or camouflage nets, unlike optical sensors.

- ○
- **ToF Sensor (VL53L0X):**



  - **Application & Purpose:**
    Used at **specific perimeter crossing points** where accurate distance measurement is required.
  - **Role in System:**
    Provides precise ranging data to validate object proximity after mmWave detection.
  - **Operating Voltage:**
    Operates at **2.6 V to 3.5 V**, compatible with STM32 I/O levels.
  - **Pin Configuration:**
    Uses **4 pins** – VCC, GND, SDA, and SCL (I2C interface).
  - **Output Type:**
    Digital output via I2C communication.
  - **Added Advantage:**
    Distance measurement is independent of target color, reflectivity, or ambient lighting.

3.2.3 Audio-Visual Modules

Visual and acoustic data provide the necessary evidence for threat verification.

- **Camera Sensor (OV7670):**

- **Application & Purpose:**
  Deployed for **visual threat verification** once motion and proximity are confirmed.

- **Role in System:**
  Captures VGA/QVGA images of detected intruders for evidence and classification.

- **Operating Voltage:**
  Core operates at **1.8 V**, with I/O logic at **3.3 V**.

- **Pin Configuration:**
  Requires **20+ pins**, including data lines (D0–D7), clock, sync signals, and SCCB control pins.

- **Output Type:**
  Digital parallel output, interfaced through STM32 DCMI.

- **Added Advantage:**
  Lightweight and low-cost camera suitable for embedded edge systems.

- **Sound Module (INMP441):**

- **Application & Purpose:**
  Used for **acoustic threat detection**, such as footsteps, gunshots, or vehicle movement.

- **Role in System:**
  Enhances threat confidence by validating sound signatures in parallel with other sensors.

- **Operating Voltage:**
  Operates at **1.8 V to 3.3 V**.

- **Pin Configuration:**
  Uses **5 pins** – VDD, GND, WS, SCK, and SD (I2S interface).

- **Output Type:**
  Digital audio output (24-bit I2S).

- **Added Advantage:**
  High signal-to-noise ratio enables accurate sound event detection in outdoor environments.

3.2.4 Secondary Proximity & Alert Suite

Redundant sensors ensure that "blind spots" are minimized and alerts are triggered locally.

- **Ultrasonic Sensor (HC-SR04):**

  - **Application & Purpose:**
    Used for **short-range obstacle and intruder detection** near the protected perimeter.

  - **Role in System:**
    Confirms presence within close range before triggering alerts.

  - **Operating Voltage:**
    Operates at **5 V DC**.

  - **Pin Configuration:**
    Uses **4 pins** – VCC, Trig, Echo, and GND.

  - **Output Type:**
    Digital pulse output, where distance is calculated from echo time.

  - **Added Advantage:**
    Simple, reliable, and effective for near-field detection.

- **IR Sensor (HW-201):**

  - **Application & Purpose:**
    Used for **rapid close-range intrusion detection** where exact distance is not critical.

  - **Role in System:**
    Acts as a fast proximity switch to trigger immediate alerts.

  - **Operating Voltage:**
    Typically operates at **3.3 V to 5 V**.

  - **Pin Configuration:**
    Uses **3 pins** – VCC, GND, and OUT.

  - **Output Type:**
    Digital output (HIGH/LOW).

  - **Added Advantage:**
    Low power consumption and fast response time make it suitable for continuous monitoring

3.3 Software Requirements and Description

The software stack is built using the **HAL (Hardware Abstraction Layer)** for stability and **FreeRTOS** for task-based execution.

- **Task 1: Primary Intrusion Detection (Medium Priority):**
 Continuously monitors data from the mmWave radar (HLK-LD1115H) and Time-of-Flight (ToF) sensor. Upon detecting motion and significant distance variation beyond predefined thresholds, the task generates an event signal to activate higher-priority verification tasks.

- **Task 2: Visual Evidence Capture (High Priority):**
 Triggered by the intrusion detection task, this task interfaces with the OV7670 camera module to capture image frames using the DCMI and DMA. High priority ensures immediate visual confirmation during intrusion events.

- **Task 3: Acoustic Event Monitoring (Medium Priority):**
 Continuously samples audio data from the INMP441 digital microphone using the I2S interface. The task analyzes sound amplitude and frequency characteristics to detect suspicious acoustic patterns such as footsteps or impacts.

1.6 Methodology

1.**Sensor Fusion**: Instead of relying on a single sensor, **SentriX** uses a "voting" logic. A threat is only confirmed if both the MMwave detects motion and the ToF sensor detects a change in distance.

2.**Predictive Alerts**: By analyzing the rate of approach using **Ultrasonic** and **ToF** data, the RTOS-driven algorithm predicts if a breach is imminent, triggering a "Pre-Alert" before the intruder crosses the final perimeter.

Real-Time Execution: Use of **FreeRTOS** ensures that the system never misses a sensor pulse, as high-priority interrupts take precedence over secondary logging tasks.

CHAPTER 4

TEST PROCEDURES AND RESULTS

Test Procedure and Results:

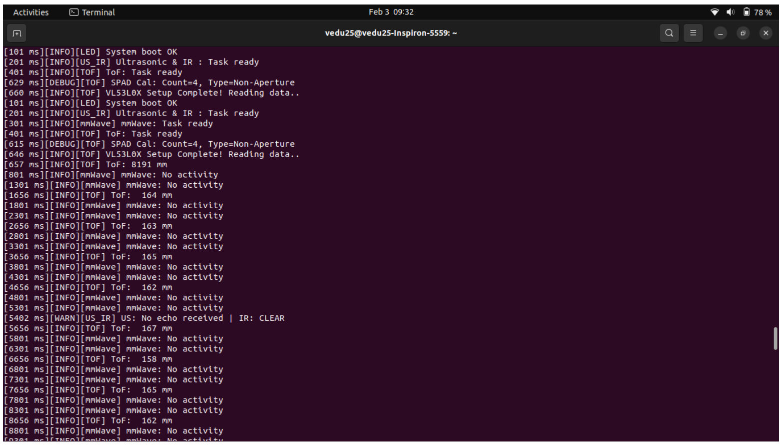
Before system integration, each sensor was tested individually to ensure hardware integrity and driver accuracy.

4.1.1 mmWave Sensor (HLK-LD1115H) Verification

Setup:
The mmWave module was interfaced with the STM32F407 via UART at a standard baud rate.

Procedure:
Movement was introduced at varying distances from 1 m to 4 m while monitoring serial output.

Result:
The sensor reliably detected micro-movements, including through thin obstacles, with a response latency of less than 100 ms.



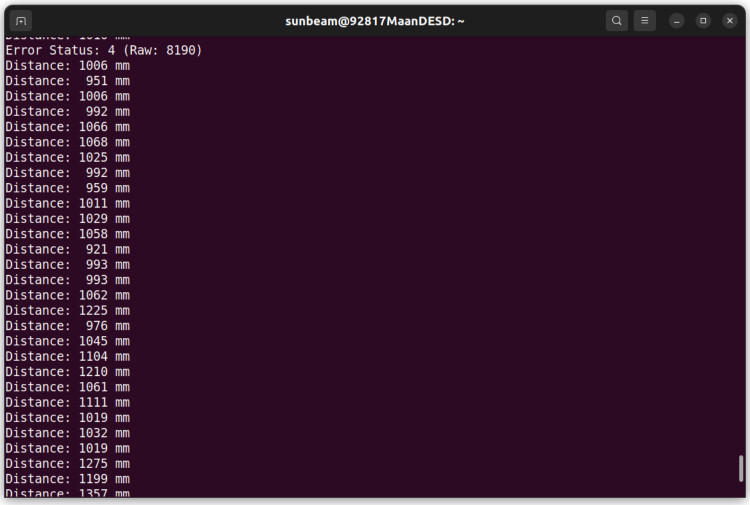
4.1.2 ToF Sensor (VL53L0X) Ranging Accuracy

Setup:
The ToF sensor was configured using the I2C interface through STM32CubeIDE.

Procedure:
Distance measurements were taken at fixed ranges of 50 cm, 100 cm, and 200 cm using targets of varying reflectance.

Result:
The sensor reported accurate distance measurements with an error margin of ±3% up

to 2 meters and effectively rejected ambient light interference.

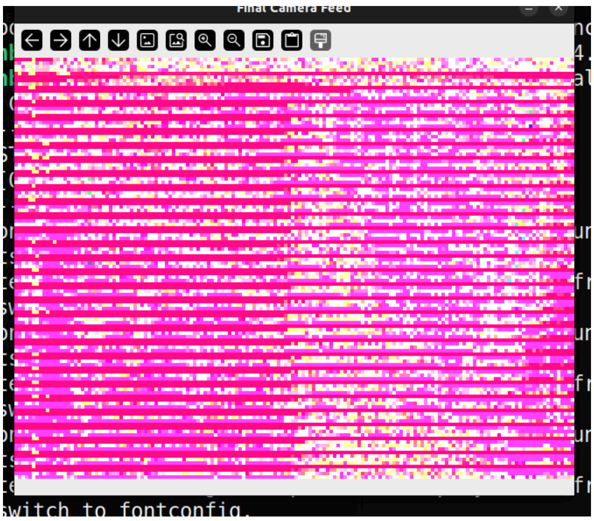


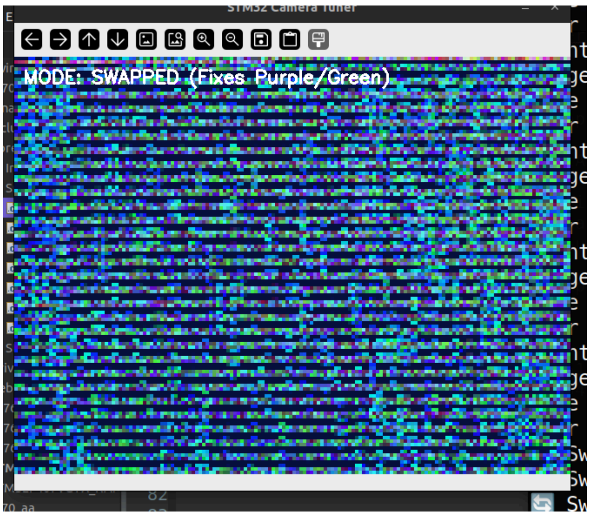
4.1.3 OV7670 Camera and DCMI Interface

Setup:
The OV7670 camera was connected to the STM32F407 using the Digital Camera Interface (DCMI).

Procedure:
Test images were captured and transferred to a memory buffer using DMA to reduce CPU load.

Result:
The system achieved a frame rate of approximately 20 FPS at QVGA resolution, enabling smooth visual verification during intrusion events.





4.1.4 Sound Sensor (INMP441) Verification

Setup:
The INMP441 microphone was interfaced with the STM32F407 using the I2S peripheral with DMA enabled for continuous audio sampling.

Procedure:
Acoustic events such as footsteps and impact sounds were generated at distances between 1 m and 5 m while monitoring audio data.

Result:
The sensor successfully captured sound events with low noise and consistent amplitude variation, enabling reliable detection of acoustic activity with minimal latency.

4.1.5 Ultrasonic Sensor (HC-SR04) Distance Measurement

Setup:
The ultrasonic sensor was connected to the STM32F407 using GPIO pins configured for trigger and echo, with timer-based pulse width measurement.

Procedure:
Objects were placed at distances ranging from 20 cm to 300 cm, and multiple readings were recorded for consistency.

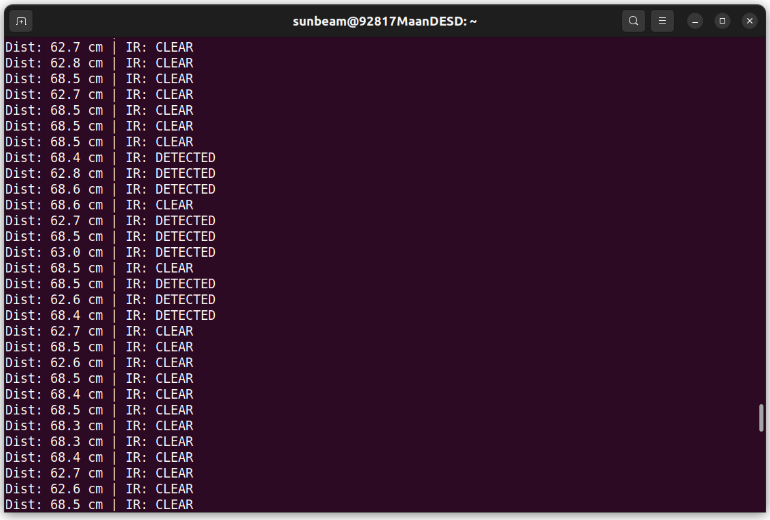
Result:
The sensor accurately measured distances within its operating range, showing stable and repeatable readings suitable for short-range intrusion detection.

4.1.6 IR Sensor (HW-201) Proximity Detection

Setup:
The IR sensor module was interfaced with the STM32F407 via a digital GPIO input pin, and the detection threshold was calibrated using the onboard potentiometer.

Procedure:
Objects were introduced within a range of 5 cm to 40 cm under different lighting conditions.

Result:
The sensor provided fast and reliable digital output for close-range detection, making it effective as a rapid proximity trigger.



4.2 System Integration and RTOS Task Scheduling

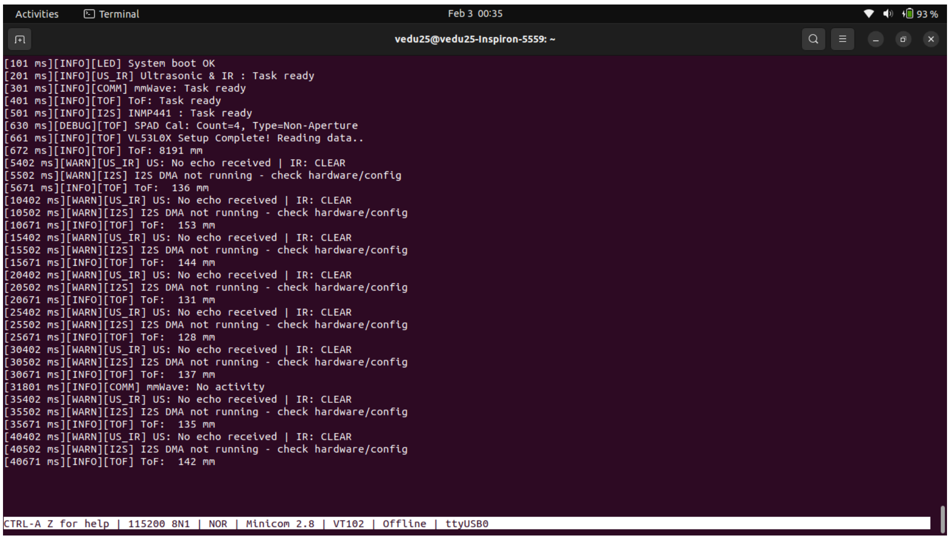
System-level testing focused on validating concurrent sensor operation, RTOS scheduling reliability, and intelligent decision logic under real-time conditions.

4.2.1 RTOS Task Prioritization Test

Test:
A high-priority *Intrusion Detection Task* (mmWave and ToF) was executed alongside a low-priority *Data Logging Task*.

Observation:
During simulated intrusion events, FreeRTOS preempted the logging task within microsecond-level latency to activate alert routines.

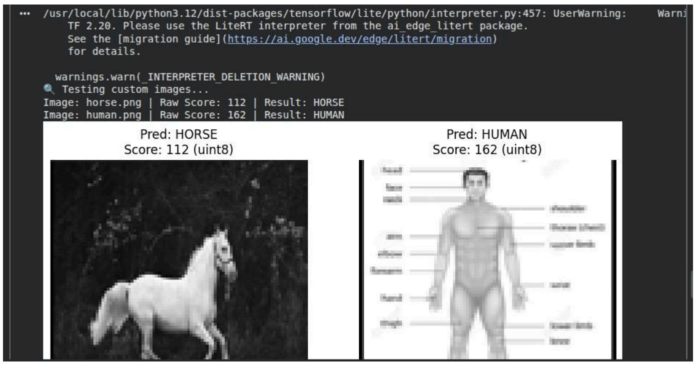
Verification:
Task states were monitored using vTaskList(), confirming stable execution with no tasks remaining indefinitely in a blocked state.



4.2.2 Multi-Sensor Fusion and ML-Based Decision Logic

Test:
A fusion logic combined mmWave motion detection and ToF distance variation, followed by lightweight ML-based pattern validation for intrusion confidence.

Result:
The combined fusion and ML logic successfully suppressed false alerts caused by environmental disturbances such as moving vegetation, improving detection reliability.


/usr/local/lib/python3.12/dist-packages/tensorflow/lite/python/interpreter.py:457: UserWarning: Warni
TF 2.20. Please use the LiteRT interpreter from the ai_edge_litert package.
See the [migration guide](https://ai.google.dev/edge/litert/migration)
for details.
warnings.warn(_INTERPRETER_DELETION_WARNING)
🔍 Testing custom images...
Image: horse.png | Raw Score: 112 | Result: HORSE
Image: human.png | Raw Score: 162 | Result: HUMAN
Pred: HORSE
Score: 112 (uint8)
Pred: HUMAN
Score: 162 (uint8)

CHAPTER 5

CONCLUSION AND FUTURE SCOPE

CHAPTER 5: CONCLUSION AND FUTURE SCOPE

5.1 Conclusion

The development of **SentriX** demonstrates the successful implementation of an autonomous, multi-modal border surveillance system using the **STM32F407** Discovery platform. By transitioning from a simple sequential logic to a high-concurrency architecture powered by **FreeRTOS**, the system effectively manages complex tasks like real-time sensor fusion and visual capture without deterministic lag. The integration of diverse sensing technologies—specifically **MMwave (HLK-LD1115H)** for motion, **ToF (VL53L0X)** for ranging, and **INMP441** for acoustics—creates a robust "smart fence" that significantly reduces false positives while maintaining a high sensitivity to unauthorized human intrusions. Ultimately, **SentriX** provides a low-power, scalable, and intelligent solution for perimeter security in critical defense and civilian applications.

5.2 Future Scope

The scalable and modular architecture of the **SentriX Autonomous Border Surveillance System** enables multiple avenues for future enhancement and technological expansion:

- **TinyML-Based Edge Intelligence:**
  Integration of lightweight TinyML models on the STM32F407 Cortex-M4 core to perform on-device classification, enabling reliable differentiation between human intruders and animals without cloud dependency.

- **Distributed Surveillance Networking:**
  Expansion from a standalone unit to a networked surveillance system using low-power communication technologies such as LoRa or V2X, allowing multiple SentriX nodes to share intrusion data and enhance regional situational awareness.

- **Energy-Efficient and Off-Grid Operation:**
  Incorporation of solar energy harvesting, intelligent power scheduling, and deep sleep modes to support long-term deployment in remote and inaccessible border regions.

- **Mobile and Adaptive Surveillance Platforms:**
  Deployment of SentriX algorithms on autonomous ground vehicles or aerial

drones to enable dynamic patrolling and adaptive response to evolving threat scenarios.

- **Predictive Threat Analysis:**
  Application of machine learning techniques on long-term sensor data to identify movement patterns and predict potential intrusion hotspots, enabling proactive border security measures.

CHAPTER 6
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