# Design and Development of Electronic Systems – Drone


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Date: July 21, 2025

# Student Declaration

We hereby declare that the work presented in the report entitled **”Design and Development of Electronic Systems – Drone”** submitted by us for the partial fulfilment of the requirements for the degree of *Electronics and VLSI Engineering* at Indraprastha Institute of Information Technology, Delhi, is an authentic record of our work carried out under the guidance of **Dr. Anuj Grover**. Due acknowledgements have been given in the report for all material used. This work has not been submitted elsewhere for the reward of any other degree.

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**Place & Date:** July 21, 2025

# Certificate

This is to certify that the above declaration made by the students is correct to the best of my knowledge. The work presented in this report has been carried out under my supervision and guidance

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# Abstract

This report details the design, development, and implementation of an FMCW (Frequency-Modulated Continuous-Wave) ultrasonic radar system. The project's primary objective was to create a robust and reliable sensor capable of accurate distance and, eventually, velocity measurement. The development process involved a synergistic co-design of hardware and software, navigating significant challenges in signal integrity and noise. Key breakthroughs include the development of a high-power transmitter using a repurposed MAX232A driver, which dramatically improved the signal-to-noise ratio (SNR), and the implementation of a sophisticated, adaptive ”sliding window” detection algorithm on an STM32 microcontroller. This algorithm dynamically calculates a local noise floor to reliably distinguish faint echoes, achieving a final detection range of 2.2 meters. A preliminary velocity estimation module using differentiation of distance over time has also been implemented. The final integrated system demonstrates robust object detection, overcoming initial issues of signal attenuation and environmental noise through iterative design and strategic pivots in both hardware architecture and software methodology.

# Contents

# Chapter 1

# Introduction

The goal of this project was to design and build a functional Frequency-Modulated Continuous-Wave (FMCW) ultrasonic radar system. Unlike simple pulsed Time-of-Flight (ToF) sensors, an FMCW system offers the potential to measure both the range and velocity of a target with high precision. This report chronicles the semester-long effort, from initial theoretical simulations in MATLAB to the development of a fully integrated hardware and software system built around an STM32 microcontroller. The initial simulations were crucial for understanding fundamental concepts like the Doppler effect and mitigating issues such as aliasing in a controlled environment before tackling hardware complexities.

The project followed a concurrent development strategy, with efforts divided between analog hardware design, digital control implementation, and signal processing algorithm development. The core challenge revolved around reliably detecting a weak ultrasonic echo in the presence of significant electrical and environmental noise. This report documents the journey of diagnosing these issues and the engineering solutions devised to overcome them.

# Chapter 2

# System Architecture and Methodology

The system architecture evolved significantly over the course of the project. The final design consists of three main subsystems:

1. **Transmitter Subsystem:** A high-voltage driver circuit responsible for exciting the ultrasonic transducer to generate a powerful acoustic wave.

2. **Receiver Subsystem:** An analog front-end (AFE) designed to amplify and condition the weak echo signal captured by the receiving transducer.

3. **Digital Processing Subsystem:** An STM32 microcontroller that controls signal transmission, acquires the received echo via ADC, and runs real-time digital signal processing (DSP) algorithms to detect objects and calculate their range.

## 2.1 System Workflow

The complete system workflow for the FMCW ultrasonic radar is illustrated below:

**Row 1: Signal Generation & Transmission**

| **STM32** | → | **MAX232A Driver** | → | **TX Transducer** |
|---|---|---|---|---|
| *PWM 40kHz* | | *±10V swing* | | *Acoustic wave* |

↓ *Acoustic propagation to target and reflection back*

**Row 2: Signal Reception & Analog Processing**

| **RX Transducer** | → | **LM324 Amplifier** | → | **Band-Pass Filter** | → | **ADC + DMA** |
|---|---|---|---|---|---|---|
| *Echo signal (mV)* | | *2-stage amp + bias* | | *35-45 kHz* | | *100 kSPS* |

↓ *Digital signal processing pipeline*

**Row 3: Digital Processing & Output**

| | | | | | | |
|---|---|---|---|---|---|---|
| **Digital Rectifier** | $\rightarrow$ | **IIR Filter** | $\rightarrow$ | **Sliding Window** | $\rightarrow$ | **ToF & Velocity** |
| *Envelope detection* | | *Low-pass* | | *SNR validation* | | *Range: 2.2m max* |

A critical design decision was the choice of data acquisition method. An initial plan, conceived in Week 4, was to use the STM32's internal hardware comparator for low-overhead ToF measurement. This approach is computationally efficient and can provide a clean digital edge for timing a direct echo. However, it was ultimately discarded because a comparator-based approach discards the analog waveform's essential characteristics (shape, frequency content). To preserve the data needed for future implementation of Doppler velocity measurement—a key goal of the FMCW methodology—the team pivoted back to a strategy of capturing the full, raw waveform using the ADC with DMA. This decision, made in Week 5, was crucial for the project's ability to pursue advanced signal processing.

# Chapter 3

# Hardware Design and Implementation

The hardware development was an iterative process of design, prototyping, and testing. The primary focus was on maximizing the transmitted signal power and ensuring the integrity of the received signal.

## 3.1 Transmitter Design

The transmitter design underwent the most significant revision. Initial drivers based on simple transistor stages struggled with the heavy capacitive load of the transducer, leading to signal degradation. A more robust two-stage driver using a TC4420 MOSFET driver IC was designed and simulated, but the breakthrough solution was the implementation of a high-power transmitter using a MAX232A IC in the final development phase.

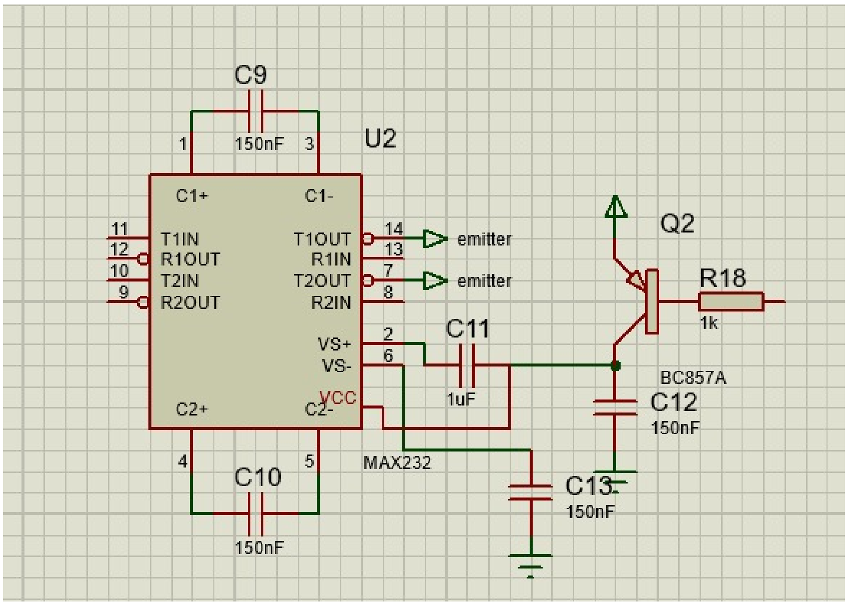


Figure 3.1: Transmitter Circuit using MAX232A IC for High-Voltage Drive

- **Innovation:** The MAX232A, an RS-232 driver IC, was ingeniously repurposed to generate a ±10V bipolar swing (20V peak-to-peak) across the transducer.
- **Impact:** This high-voltage drive dramatically increased the transmitted acoustic power, resulting in a much stronger echo signal that was easily distinguishable from the noise floor. This hardware upgrade was the single most important factor in solving the project's core signal-to-noise ratio (SNR) problem.

## 3.2 Receiver Analog Front-End (AFE)

The receiver circuit's role was to amplify the millivolt-level echo signal without introducing significant noise or distortion.

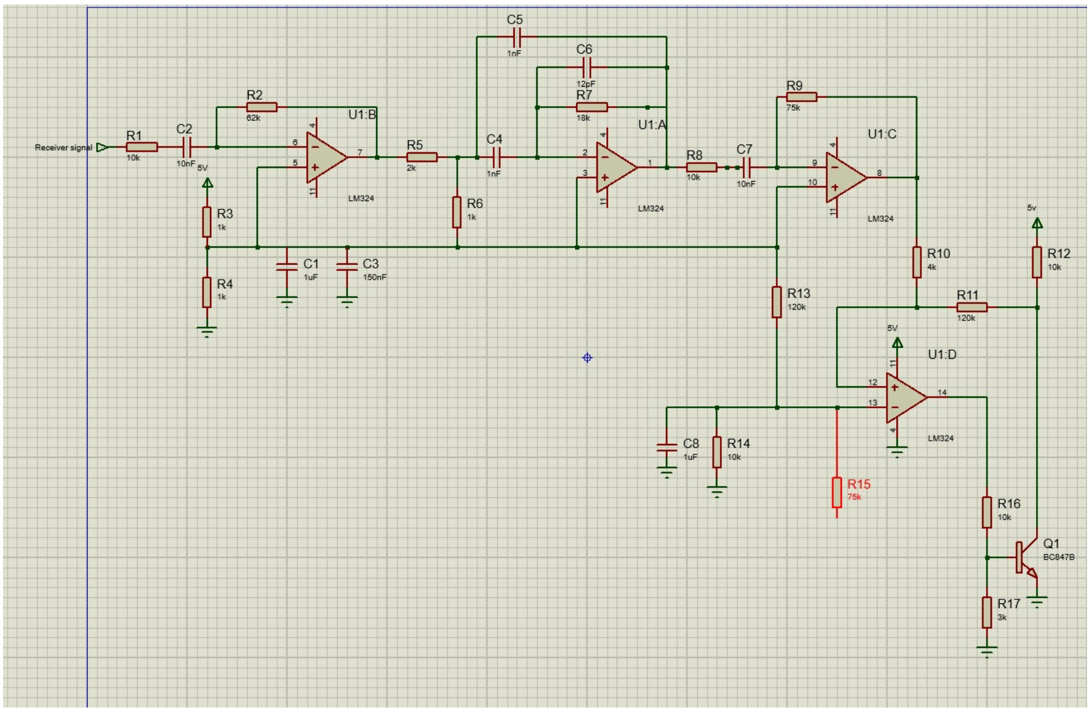


Figure 3.2: Multi-Stage Receiver Circuit with LM324-based Amplification and Filtering

- **Initial Design:** A two-stage op-amp (LM324) based amplifier was designed and tuned with a band-pass filter centered at 40kHz.
- **Integration Challenge:** A critical step, discovered during debugging in Week 5, was conditioning the AFE output for the STM32's ADC. The amplifier's AC-coupled output failed to correctly trigger the MCU's logic, leading to software timeout errors. The solution was to add a DC biasing circuit to shift the bipolar analog signal to be centered at 1.6V, placing it squarely within the ADC's 0-3.3V input range and preventing signal clipping.

## 3.3 Crosstalk and Noise Mitigation

Early in testing, the dominant challenge was identified not as random noise, but as a large, predictable artifact caused by direct electrical crosstalk from the transmitter and mechanical ringing of the transducer.

- **Diagnosis:** Oscilloscope analysis confirmed that a high-energy pulse was coupling into the sensitive receiver circuit during transmission.
- **Attempted Solution:** A hardware ”gating” circuit using a BJT was prototyped to disconnect the receiver during the transmit pulse. While the concept was sound, the implementation introduced its own switching noise and provided incomplete isolation.
- **Final Strategy:** The problem was ultimately solved through a combination of the vastly improved SNR from the new transmitter and a software-based ”blanking” period (detailed in the DSP section).

## 3.4 Power Supply Considerations

System-level testing revealed that the new high-power MAX232A transmitter drew significant transient current. It was discovered that the on-board 5V regulator was insufficient to handle these current spikes, a critical finding for the system’s long-term stability and a key learning in robust electronic design.

# Chapter 4

# Digital Signal Processing

With a viable signal provided by the hardware, the focus shifted to implementing a robust detection pipeline on the STM32 microcontroller.

## 4.1 High-Speed Signal Acquisition

The foundation of the DSP pipeline is clean, high-fidelity data. The STM32's peripherals were configured for optimal performance:

- A timer was used to trigger the ADC at a precise sampling rate of **100 kSPS** (10µs per sample).
- DMA (Direct Memory Access) was used to transfer the ADC conversion results to a memory buffer without CPU intervention, allowing for continuous, high-speed data capture.

## 4.2 Real-Time Envelope Demodulation

To measure the strength of the echo, the 40kHz carrier frequency must be removed, a process known as demodulation. Instead of a hardware envelope detector, this was implemented efficiently in software:

1. **Digital Rectification:** The raw ADC data was processed to take its absolute value.
2. **IIR Low-Pass Filter:** A computationally efficient single-pole Infinite Impulse Response (IIR) filter was applied to the rectified signal to extract the signal's strength envelope in real-time.

## 4.3 Range Calculation: From Thresholding to Adaptive Windowing

The method for calculating range evolved from simple, unreliable techniques to a sophisticated and robust final algorithm. This evolution was central to the project's success.

### 4.3.1 Initial Approach: Simple Thresholding

The most straightforward method is to set a fixed voltage threshold. Any signal rising above this threshold is considered an echo. This proved fundamentally unreliable, as changes in distance, target reflectivity, and ambient noise would either cause missed detections or false positives.

### 4.3.2 Improvement: Dynamic SNR-Based Detection

The first major software breakthrough was an algorithm that dynamically calculated the ambient noise floor by averaging the signal level during quiet periods. A potential echo was then validated only if its amplitude was significantly higher than this noise floor (a set Signal-to-Noise Ratio). This was a significant improvement but could still be fooled by localized noise spikes.

### 4.3.3 Final Algorithm: The Adaptive Sliding Window

The final and most effective solution, implemented in the last stage of the project, was an adaptive "sliding window" system. This algorithm represents the culmination of the software effort:

1. **Software Blanking:** The algorithm first ignores all incoming ADC data for a brief, fixed period after transmission to eliminate predictable crosstalk and ringing artifacts.

2. **Local Noise Calculation:** As the algorithm searches for an echo through the data buffer, it uses a "sliding window" to calculate the noise floor in the samples *immediately preceding* a potential echo.

3. **Adaptive Validation:** A pulse is confirmed as a valid echo only if it rises significantly above this *local* noise floor.

This adaptive, localized approach is extremely effective at identifying faint signals at long distances, as it is insensitive to the overall noise level of the entire capture, and was the key to unlocking the system's maximum range.

## 4.4 Velocity Estimation

As a final step, a preliminary velocity estimation module was implemented.

- **Method:** The computationally efficient method of calculating the differentiation of distance over time ($\Delta d/\Delta t$) was used.
- **Status:** The implementation successfully identifies the direction of motion (positive for an approaching target, negative for a receding one). However, the velocity readings are currently unstable and exhibit significant jitter.
- **Analysis:** The instability is a direct result of the method's high sensitivity to small fluctuations and noise inherent in the raw distance measurements. Even minor variations in the detected range are amplified by the differentiation process.

# Chapter 5

# Results and Discussion

The project successfully culminated in a working ultrasonic radar prototype that demonstrated robust object detection. The key result was achieved in the final weeks, where the synergistic combination of the high-power MAX232A transmitter and the adaptive ”sliding window” detection algorithm solved the long-standing challenge of reliable echo detection.

The final calibrated system now reliably detects large, static objects at a distance of up to **2.2 meters**, a significant improvement achieved by increasing the transmitted pulse duration to 300µs and deploying the superior sliding window algorithm.

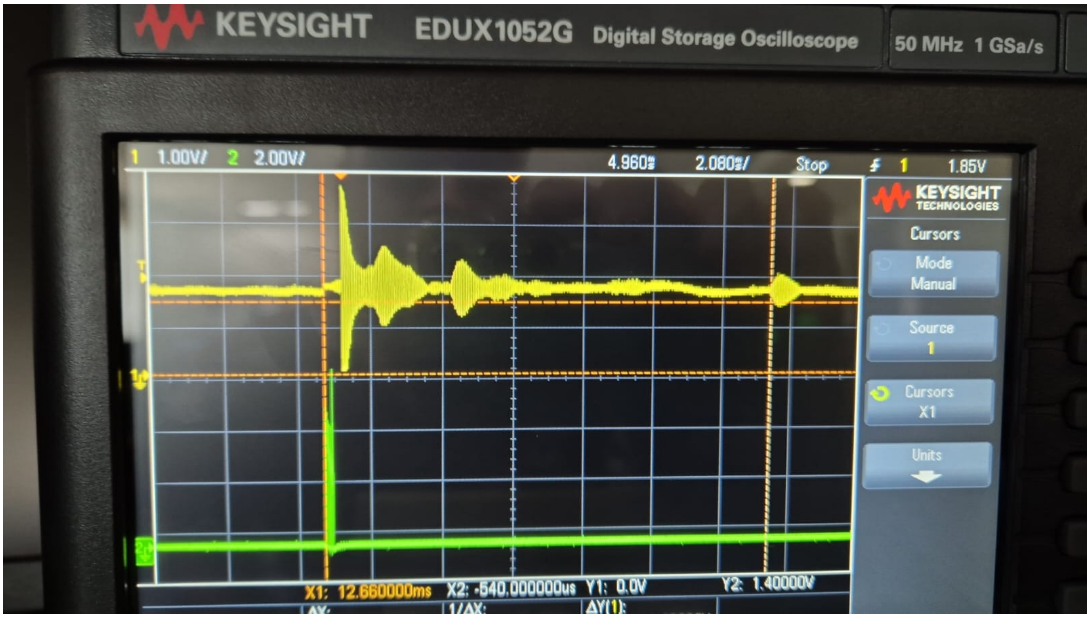


Figure 5.1: Digital Storage Oscilloscope (DSO) Output Showing Echo Signal with Improved SNR

The journey of overcoming hardware limitations like noise, crosstalk, and power instability with targeted software solutions represents the primary learning outcome of this project. The preliminary implementation of velocity estimation serves as a successful proof-of-concept, correctly identifying the direction of motion, while its current instability highlights the need for further signal processing, a common challenge in radar systems.

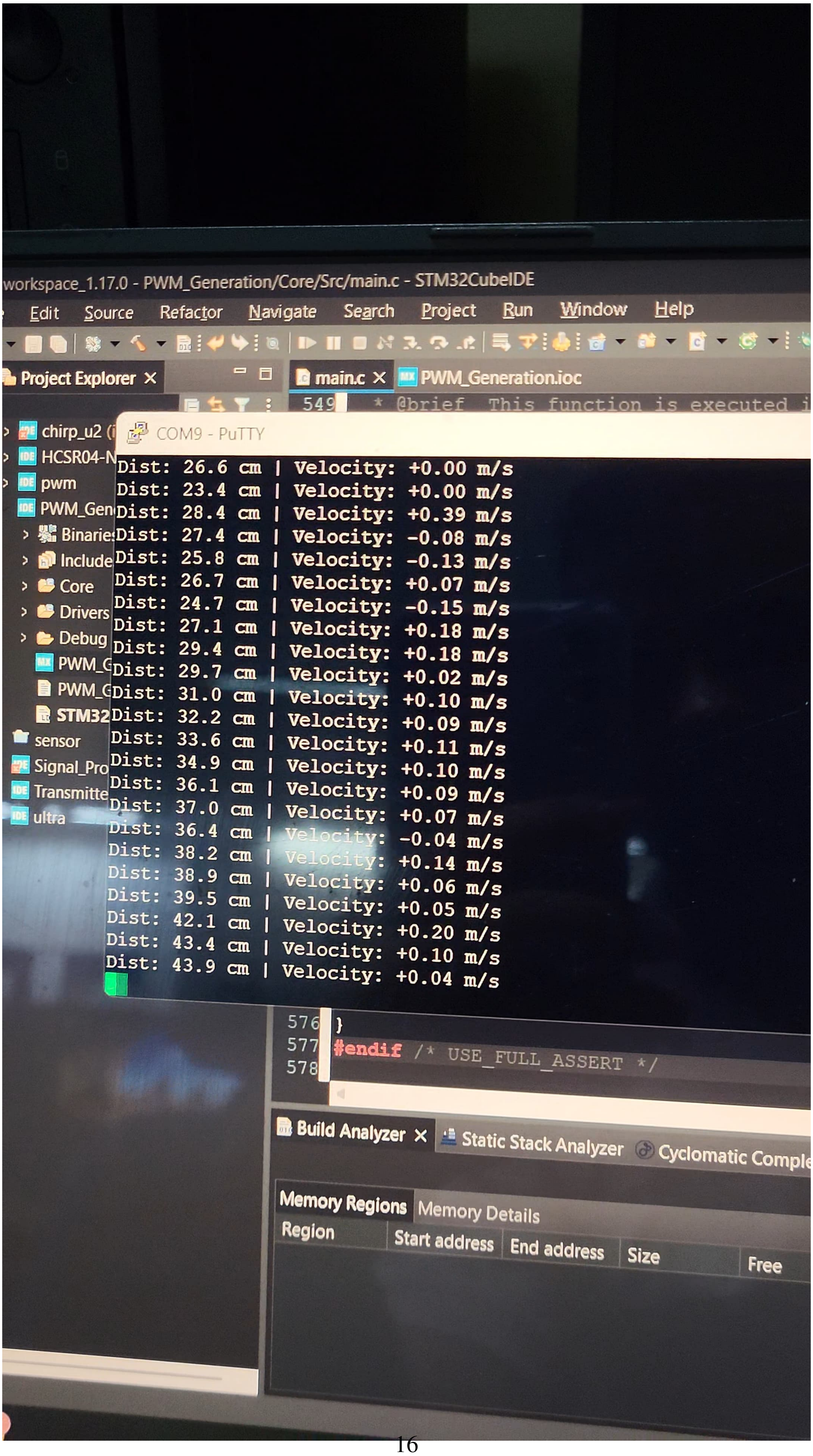




Figure 5.2: Demonstration Output of the System Showing Object Detection

# Chapter 6

# Conclusion and Future Work

This project successfully achieved its goal of designing and developing a robust ultrasonic sensor system. By systematically diagnosing issues and iteratively improving both hardware and software, the team engineered a solution that is far more reliable than a simple off-the-shelf sensor. The two key innovations—the repurposed high-voltage transmitter and the adaptive SNR-based detection algorithm—were critical to this success.

For future work, the following paths are recommended:

- **PCB Design:** Migrating the circuit from a breadboard to a custom-designed Printed Circuit Board (PCB) would significantly reduce noise and improve overall signal integrity.
- **Velocity Measurement Refinement:** With the raw waveform data now available, the next logical step is to implement more advanced DSP algorithms (e.g., FFT-based analysis) to perform true Doppler velocity estimation.
- **Velocity Output Filtering:** To improve the existing $\Delta d/\Delta t$ method, a digital filtering stage (such as a Kalman or moving average filter) should be implemented on the distance readings before differentiation to stabilize the velocity output.
- **Hardware Gating Refinement:** A more advanced hardware gating circuit, perhaps using a high-speed analog switch IC, could be explored to further improve receiver isolation.