REAL-TIME ULTRASONIC SENSOR FUSION FOR PRECISE ROBOTIC MEASUREMENT

INTRODUCTION

- The Real-time Ultrasonic Sensor Array is a project designed to provide accurate and precise distance measurements for applications such as Arduino-based robots.
- The sensor array consists of three ultrasonic distance sensors that work together to capture real-time distance data.
- The data is then processed and filtered using various techniques to ensure high accuracy and reliability.
- This project aims to improve the navigational capabilities and obstacle detection of Arduino-based robots, enabling them to perform tasks with increased precision and safety.

WHAT ARE THE USES OF ACCURATE ULTRASONIC MEASUREMENT

OBJECT DETECTION AND AVOIDANCE: ACCURATE ULTRASONIC SENSORS ARE ESSENTIAL FOR DETECTING OBJECTS AND OBSTACLES IN THE PATH OF AUTONOMOUS VEHICLES, DRONES, ROBOTS, AND AUTOMATED GUIDED VEHICLES (AGVS). RELIABLE DISTANCE MEASUREMENTS HELP THESE DEVICES AVOID COLLISIONS AND NAVIGATE SAFELY.

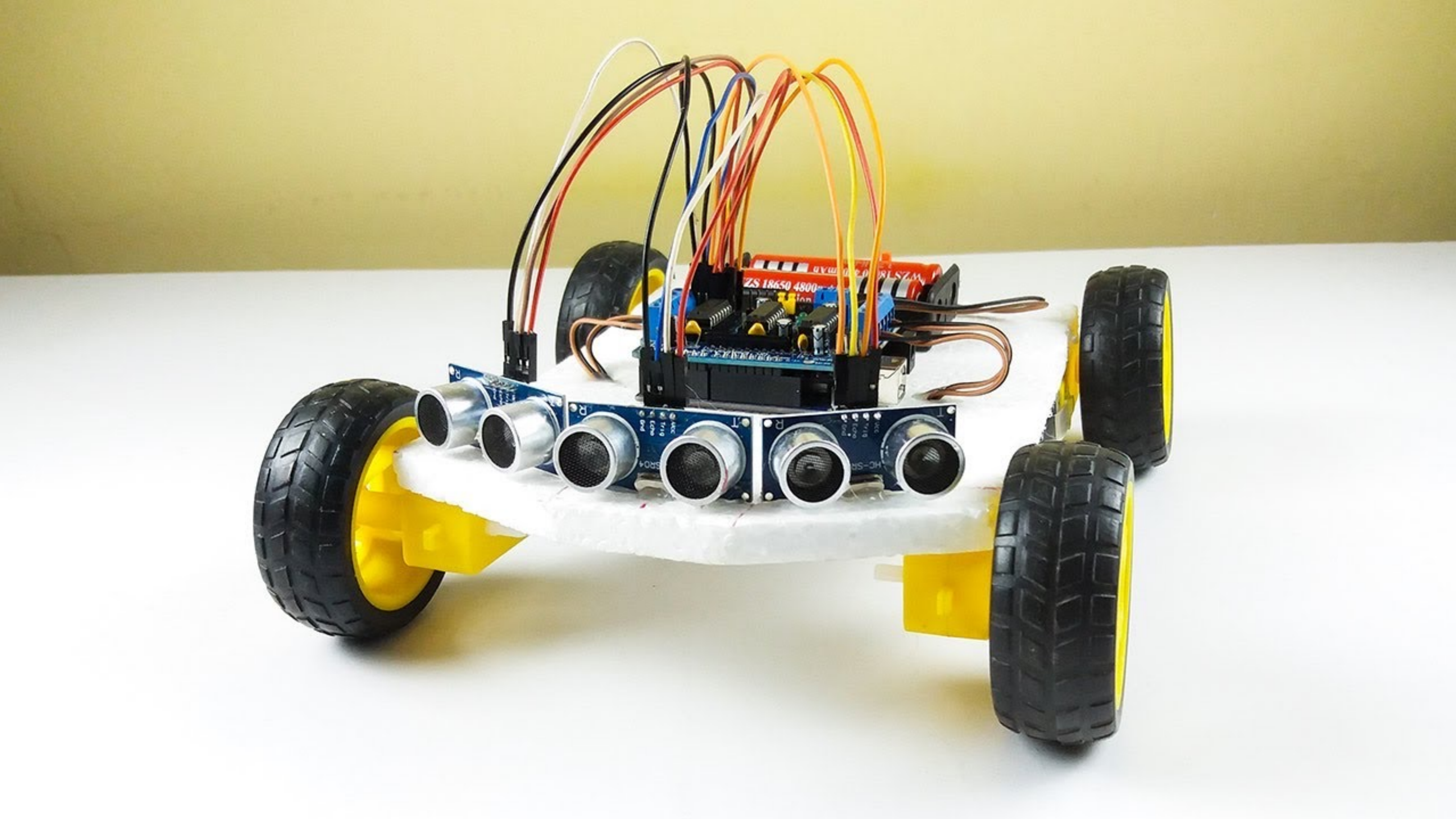
INDUSTRIAL AUTOMATION: IN MANUFACTURING AND INDUSTRIAL SETTINGS, PRECISE ULTRASONIC SENSORS ARE USED FOR MATERIAL HANDLING, POSITION MONITORING, AND PROCESS CONTROL. ACCURATE MEASUREMENTS ENSURE THE CORRECT POSITIONING AND MOVEMENT OF MACHINERY AND MATERIALS.

DISTANCE MEASUREMENT AND RANGING: ULTRASONIC SENSORS ARE COMMONLY USED FOR DISTANCE MEASUREMENT IN APPLICATIONS LIKE PARKING ASSIST SYSTEMS, LIQUID LEVEL MONITORING, AND OBJECT POSITIONING IN WAREHOUSING.

ENVIRONMENTAL MONITORING: IN ENVIRONMENTAL APPLICATIONS, ACCURATE ULTRASONIC SENSORS CAN BE USED FOR WEATHER MONITORING, FLOOD DETECTION, AND WATER LEVEL MEASUREMENTS IN RIVERS, LAKES, AND RESERVOIRS.
PRECISION AGRICULTURE: IN AGRICULTURE, PRECISE DISTANCE MEASUREMENTS PROVIDED BY ULTRASONIC SENSORS CAN BE UTILIZED FOR AUTOMATED TRACTOR STEERING, CROP HEIGHT MONITORING, AND IRRIGATION CONTROL.

STRUCTURAL HEALTH MONITORING: ACCURATE ULTRASONIC SENSORS ARE EMPLOYED IN STRUCTURAL HEALTH MONITORING OF BUILDINGS, BRIDGES, AND INFRASTRUCTURE TO DETECT DEFECTS, CRACKS, OR CHANGES IN MATERIAL PROPERTIES.

UNDERWATER APPLICATIONS: IN UNDERWATER ROBOTICS AND EXPLORATION, ACCURATE ULTRASONIC SENSORS ARE USED FOR DEPTH MEASUREMENTS, UNDERWATER MAPPING, AND MARINE RESEARCH.

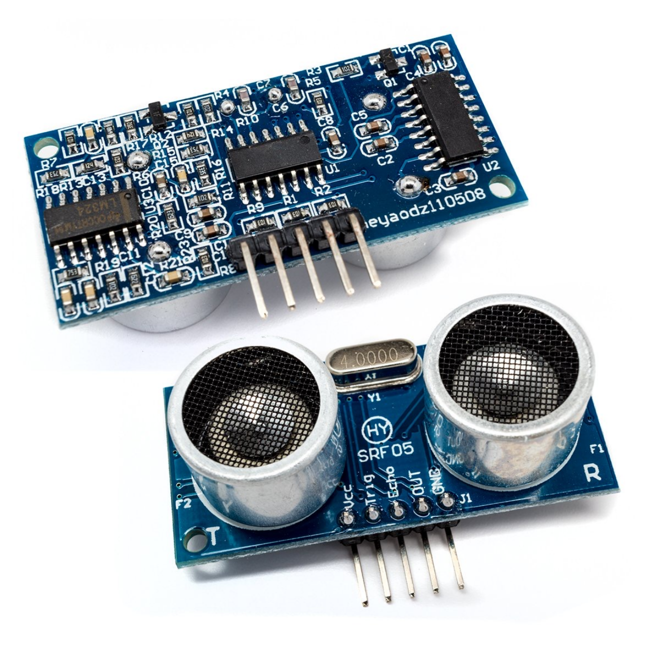

ZS 18650 4800

WHAT IS AN ULTRASONIC SENSOR?

An ultrasonic sensor has two parts:

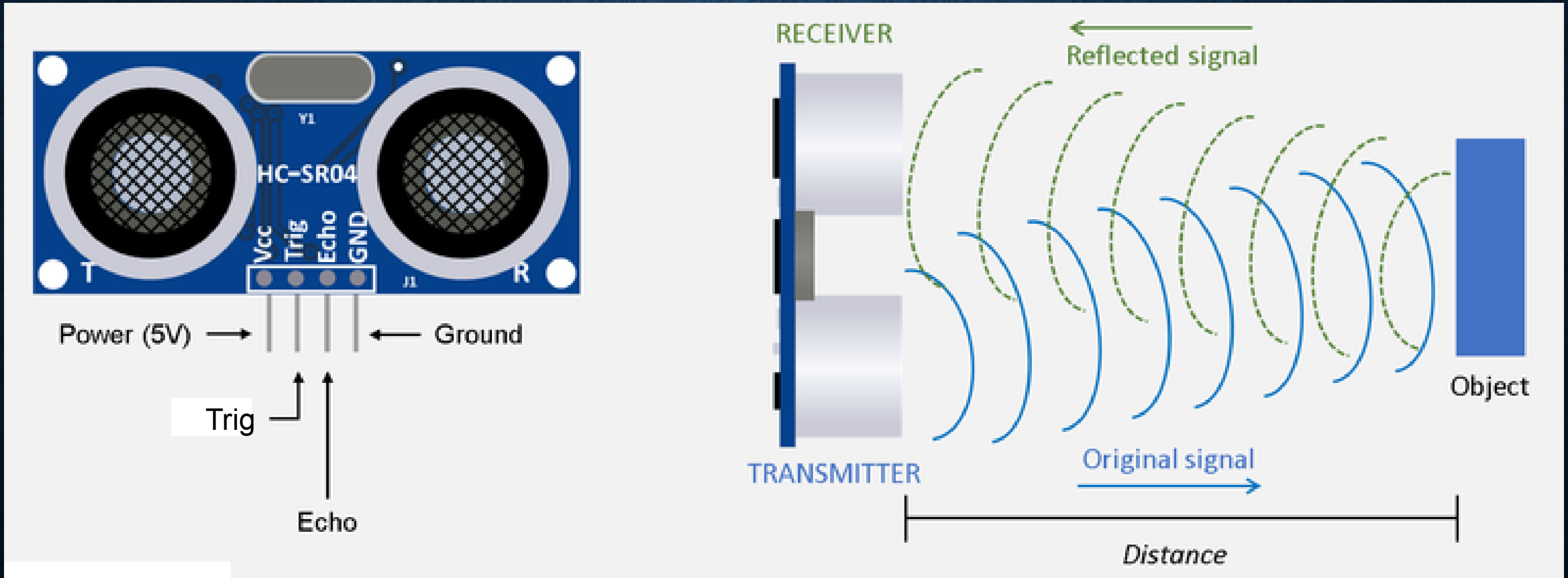
- A transmitter that sends out a signal that humans cannot hear.
- A receiver that receives the signal after it has bounced off nearby objects.

The sensor sends a message back to the computer telling it the time taken for the signal to return.



The sensor sends out its signal and determines how long the signal takes to come back.

- If the object is very close to the sensor, the signal comes back quickly.
- If the object is far away from the sensor, the signal takes longer to come back.
- If objects are too far away from the sensor, the signal takes so long to come back that is very weak when it comes back.



PROJECT OVERVIEW

Components of the sensor array

- Three ultrasonic distance sensors
- Arduino board

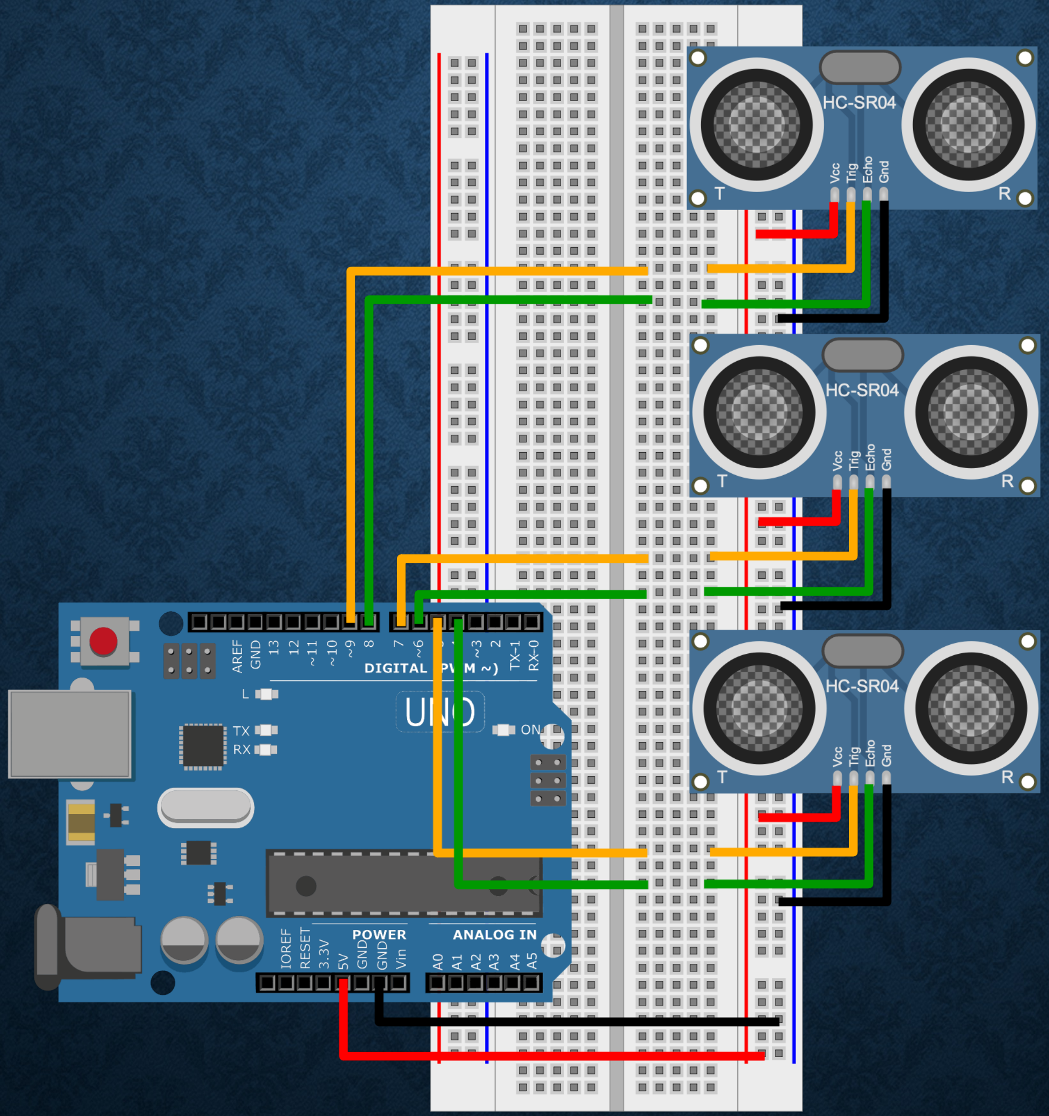
Filter Techniques

- Kalman filter
- Exponential moving average (EMA) filter

DATA ACQUISITION

The first function of the project involves acquiring data from the three ultrasonic distance sensors. Each sensor measures the distance between the sensor and an object, and the data is received in real time through a serial communication interface. The acquired data represents the raw distance measurements from each sensor, which will be further processed to obtain accurate distance values.

CIRCUIT DIAGRAM



KALMAN FILTER

To enhance the accuracy of distance measurements, a Kalman filter is employed for each sensor's data. The Kalman filter is a recursive algorithm that estimates the true state of a system based on noisy measurements. It effectively combines past information and current sensor readings to produce optimal estimates, making it ideal for real-time applications like robotics. The filtered data from each sensor is again visualized in separate plots to analyze the performance of the Kalman filtering technique.

The Kalman filter model assumes the true state at time k is evolved from the state at $(k-1)$ according to,

$$\mathbf{x}_k = \mathbf{F}_k \mathbf{x}_{k-1} + \mathbf{B}_k \mathbf{u}_k + \mathbf{w}_k$$

At time k an observation (or measurement) $\mathbf{z}_k$ of the true state $\mathbf{x}_k$ is made according to,

$$\mathbf{z}_k = \mathbf{H}_k \mathbf{x}_k + \mathbf{v}_k$$

x_k is called a state vector consisting of a state variable at time step k. A is the state matrix, and B is the control matrix. z_k is called the observation vector at time step k. It concerns data that is known through measurement.

- Prediction equations

Predicted (*a priori*) state estimate	$\hat{\mathbf{x}}_{k\|k-1} = \mathbf{F}_k \mathbf{x}_{k-1\|k-1} + \mathbf{B}_k \mathbf{u}_k$
Predicted (*a priori*) estimate covariance	$\hat{\mathbf{P}}_{k\|k-1} = \mathbf{F}_k \mathbf{P}_{k-1\|k-1} \mathbf{F}_k^{\mathsf{T}} + \mathbf{Q}_k$

➢ Measurement update equations

Innovation or measurement pre-fit residual	$\tilde{\mathbf{y}}_k = \mathbf{z}_k - \mathbf{H}_k \hat{\mathbf{x}}_{k\mid k-1}$
Innovation (or pre-fit residual) covariance	$\mathbf{S}_k = \mathbf{H}_k \hat{\mathbf{P}}_{k\mid k-1} \mathbf{H}_k^\mathsf{T} + \mathbf{R}_k$
Optimal Kalman gain	$\mathbf{K}_k = \hat{\mathbf{P}}_{k\mid k-1} \mathbf{H}_k^\mathsf{T} \mathbf{S}_k^{-1}$
Updated (*a posteriori*) state estimate	$\mathbf{x}_{k\mid k} = \hat{\mathbf{x}}_{k\mid k-1} + \mathbf{K}_k \tilde{\mathbf{y}}_k$
Updated (*a posteriori*) estimate covariance	$\mathbf{P}_{k\mid k} = (\mathbf{I} - \mathbf{K}_k \mathbf{H}_k) \hat{\mathbf{P}}_{k\mid k-1}$
Measurement post-fit residual	$\tilde{\mathbf{y}}_{k\mid k} = \mathbf{z}_k - \mathbf{H}_k \mathbf{x}_{k\mid k}$

•Kalman Filter: The Kalman filter is applied to each sensor's raw data to estimate the actual state of the system while accounting for noise and uncertainties in the sensor measurements. The Kalman filter helps improve the accuracy of distance measurements by combining predictions and measurements.

•The Kalman filter is applied first to estimate the true state of the system by considering the noisy sensor readings and the system dynamics (process variance Q and measurement variance R).
•Then, the EMA filter is applied to the output of the Kalman filter to further smoothen the data and reduce high-frequency noise.

1.Q (Process Variance): It represents the covariance of the process noise. Process noise refers to the uncertainty or randomness associated with the system's state transition. A higher value of Q allows the Kalman filter to adapt more quickly to changes in the underlying system dynamics, but it may also result in more noisy or jittery estimates.

1.R (Measurement Variance): It represents the covariance of the measurement noise. Measurement noise refers to the uncertainty or randomness associated with the sensor's measurements. A higher value of R allows the Kalman filter to trust the measurements more and rely less on the system's predictions, but it may also result in a slower adaptation to changes in the system.

EXPONENTIAL MOVING AVERAGE FILTER

The project also employs the Exponential Moving Average filter to further refine the distance data from each sensor. The EMA filter assigns exponentially decreasing weights to previous data points, emphasizing recent data and minimizing the impact of older measurements. This filter enhances the precision and responsiveness of the sensor array, leading to improved measurement accuracy. The filtered data from each sensor is presented in separate plots for detailed examination.

"EMA" STANDS FOR "EXPONENTIAL MOVING AVERAGE," AND IT IS A TYPE OF LOW-PASS FILTER USED TO SMOOTHEN DATA AND REDUCE NOISE. THE EMA FILTER GIVES MORE WEIGHT TO RECENT DATA POINTS WHILE GRADUALLY DECREASING THE INFLUENCE OF OLDER DATA POINTS. THE EMA FILTER IS DEFINED BY A TUNING PARAMETER CALLED ALPHA, WHICH CONTROLS THE SMOOTHING FACTOR. A HIGHER VALUE OF ALPHA GIVES MORE WEIGHT TO RECENT DATA, RESULTING IN A MORE RESPONSIVE FILTER BUT POTENTIALLY ALLOWING MORE NOISE. CONVERSELY, A LOWER VALUE OF ALPHA GIVES LESS WEIGHT TO RECENT DATA, RESULTING IN A SMOOTHER FILTER BUT WITH SLOWER RESPONSIVENESS.

ABNORMAL DATA HANDLING

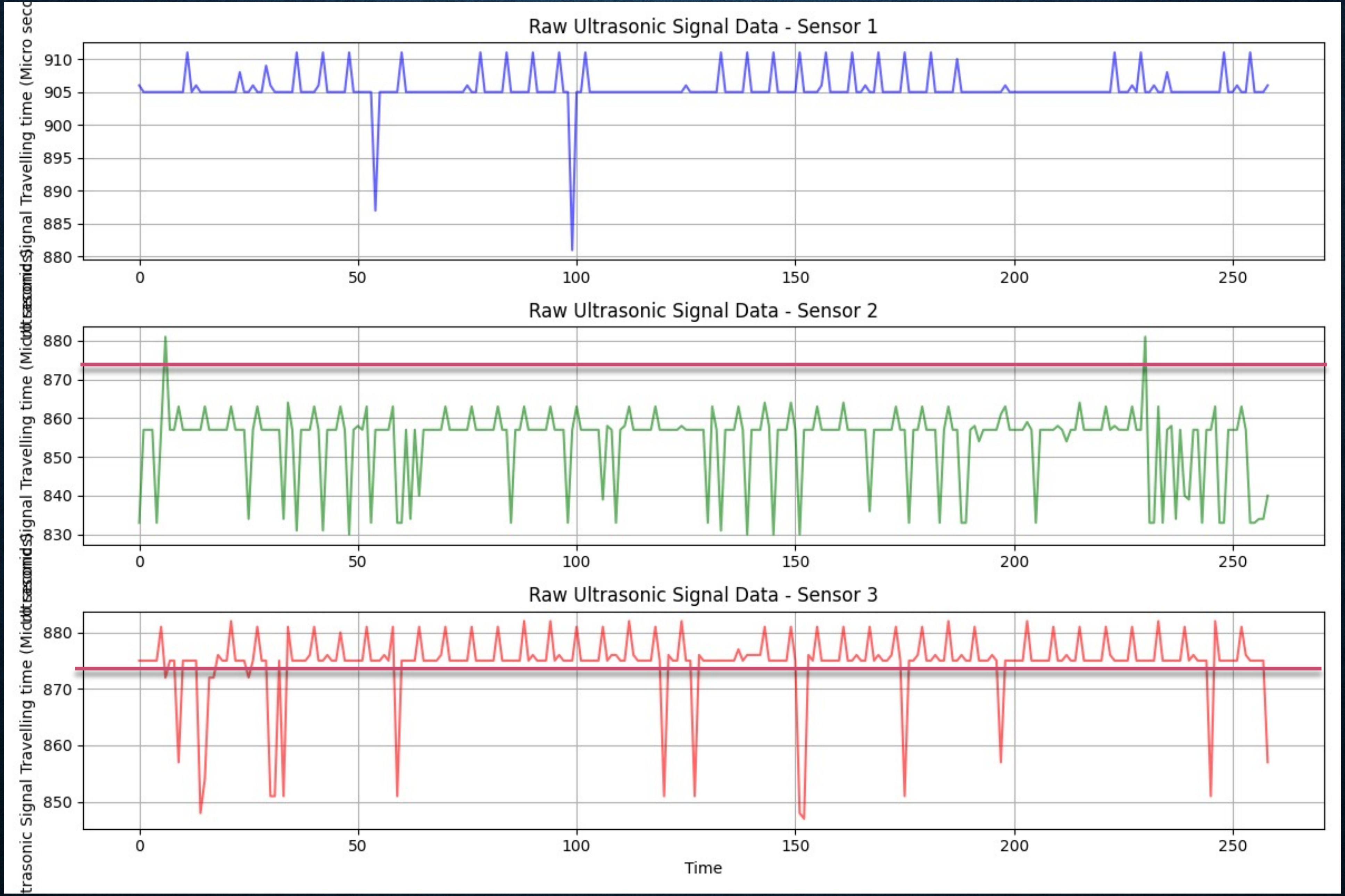
In real-world scenarios, sensors may occasionally produce abnormal or erroneous readings due to various factors. To mitigate the impact of such readings, the project incorporates a simple abnormal data handling mechanism. If the standard deviation of any sensor's filtered data exceeds a predefined threshold, it is considered as an abnormal sensor reading. In this case, the data from the abnormal sensor is excluded from the final combined data. If no abnormal sensor is detected, the final combined data is obtained by taking the average of the filtered data from all three sensors.

AFTER FILTERING, THE CODE CALCULATES THE STANDARD DEVIATION OF THE FILTERED DATA FOR EACH SENSOR. STANDARD DEVIATION IS A MEASURE OF HOW SPREAD OUT THE DATA POINTS ARE FROM THE MEAN. A HIGH STANDARD DEVIATION INDICATES THAT THE DATA POINTS HAVE SIGNIFICANT VARIATIONS OR NOISE.

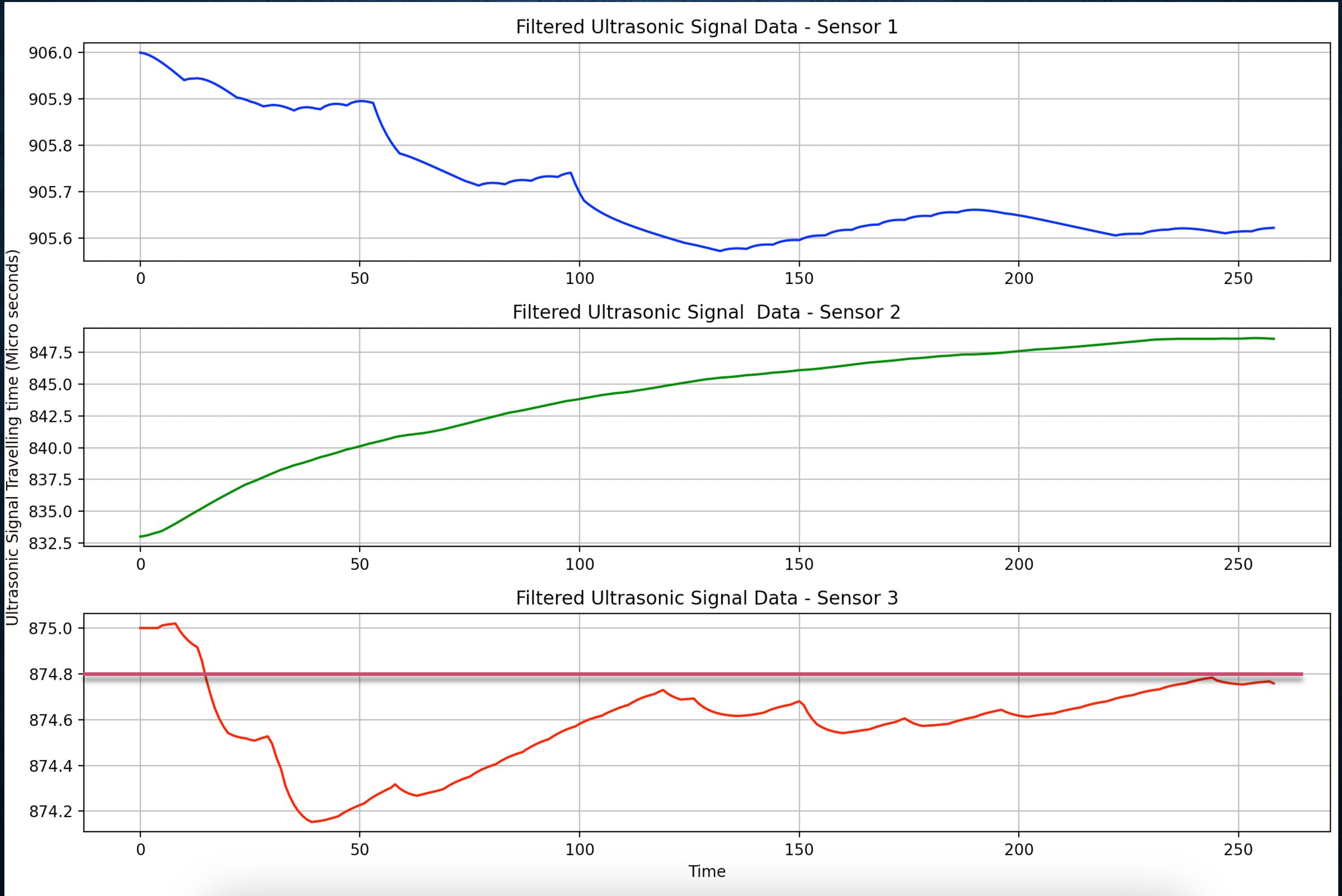
IF THE STANDARD DEVIATION OF THE FILTERED DATA FROM ANY SENSOR EXCEEDS A CERTAIN THRESHOLD (IN THIS CODE, IT IS SET TO 100), THAT SENSOR IS CONSIDERED TO BE PROVIDING ABNORMAL DATA.

IF AN ABNORMAL SENSOR IS DETECTED, THE CODE IGNORES THE DATA FROM THAT SENSOR AND COMBINES THE FILTERED DATA FROM THE OTHER TWO SENSORS. THE COMBINATION IS DONE BY TAKING THE AVERAGE OF THE FILTERED DATA FROM THE REMAINING TWO SENSORS.
IF NO ABNORMAL SENSOR IS DETECTED, THE CODE COMBINES THE FILTERED DATA FROM ALL THREE SENSORS BY TAKING THE AVERAGE OF THE FILTERED DATA FROM EACH SENSOR.

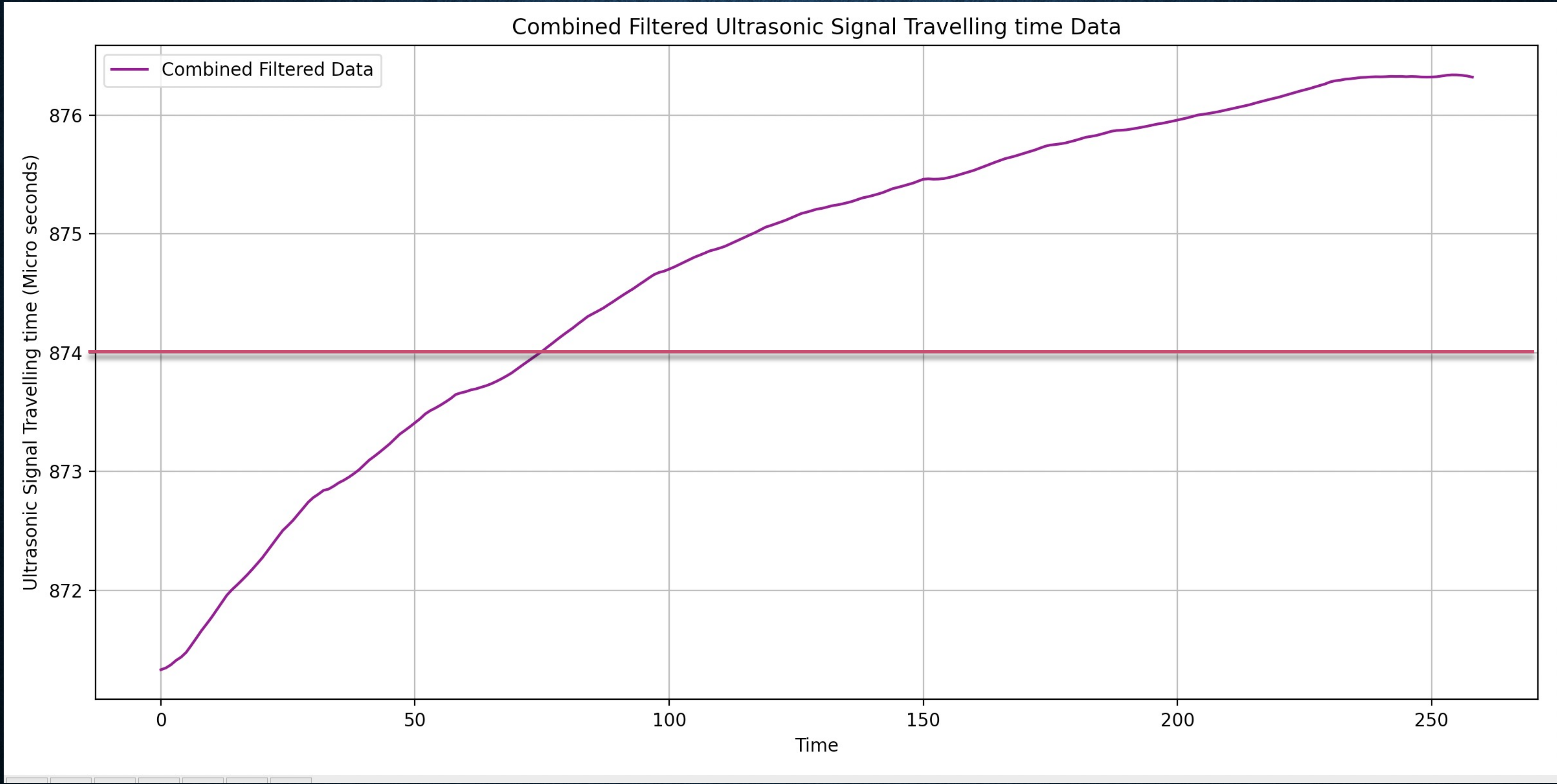
RAW ULTRASONIC SENSOR DATA (15 CM, 874 MICROSECONDS)



FILTERED ULTRASONIC SENSOR DATA (15 CM, 874 MICROSECONDS)



COMBINED FILTERED SENSOR DATA (15 CM, 874 MICROSECONDS)



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