# Working Principle and Operation of HC-SR04 Ultrasonic Sensor

## Working Principle of HC-SR04

The HC-SR04 operates on the time-of-flight (ToF) principle, measuring the time taken for an ultrasonic sound wave to travel to an object and return after reflection. The distance (D) to the object is calculated using:

D = (v × t) / 2

Where:  
- v: Speed of sound in air (343 m/s at 298 K, or 20°C).  
- t: Time for the echo to return (s).  
Division by 2 accounts for the round-trip distance.

## Operational Mechanism

### Trigger Signal:

A microcontroller (e.g., ESP32-WROOM) sends a 10 µs high pulse to the TRIG pin. This activates the sensor’s ultrasonic transmitter, which emits a burst of eight 40 kHz sound pulses.

### Ultrasonic Transmission:

The transmitter converts electrical energy into ultrasonic waves using a piezoelectric transducer. These waves travel at v = 343 m/s in air.

### Echo Reception:

When the waves hit an object, they reflect back toward the sensor. The receiver, another piezoelectric transducer, detects the returning waves and converts them into an electrical signal.

### Echo Signal Output:

The ECHO pin goes high upon sending the pulse and remains high until the echo is received. The duration of the high state (t) is proportional to the distance.

### Distance Calculation:

The microcontroller measures (t) using a function like pulseIn(). For example, if t = 1.744 ms:  
D = (343 × 1.744 × 10⁻³) / 2 = 0.299 m = 29.9 cm

## Construction of HC-SR04

The HC-SR04 is compact, typically measuring 45 mm × 20 mm, and consists of the following components:  
- Ultrasonic Transmitter: A piezoelectric transducer vibrating at 40 kHz.  
- Ultrasonic Receiver: Detects reflected waves and converts to electrical signals.  
- Control Circuit: An onboard IC (e.g., MAX232) manages timing, signal amplification, and pulse generation.  
- Pins:  
 \* VCC: 5V power supply  
 \* TRIG: Input for the trigger pulse  
 \* ECHO: Output for the echo duration  
 \* GND: Ground  
- Housing: Plastic casing with two cylindrical openings for the transmitter and receiver.

## How It Works

### Initialization:

The sensor is powered at 5V, consuming 15 mA. The TRIG pin is set low to prepare for the next pulse.

### Pulse Triggering:

A 10 µs pulse on TRIG prompts the control circuit to emit a 40 kHz burst.

### Wave Propagation:

The ultrasonic waves travel through air, with a wavelength:  
λ = v / f = 343 / 40000 = 8.575 mm  
The waves reflect off objects within 2 cm to 4 m range.

### Echo Processing:

The receiver detects the reflected waves and the control circuit measures the time difference. The ECHO pin outputs a high pulse with duration (t), typically 100 µs to 23.3 ms.

### Microcontroller Interface:

The microcontroller reads (t) via the ECHO pin and computes (D). In the smart dustbin, if D < 30 cm, the lid servo is activated.

## Key Parameters

- Frequency: 40 kHz  
- Range: 2 cm to 4 m  
- Accuracy: ±3 mm  
- Beam Angle: ≈15°  
- Response Time: <10 ms

## Factors Affecting Performance

- Temperature: Affects speed of sound (e.g., v ≈ 331 m/s at 0°C). Calibration may be needed.  
- Surface Properties: Soft/irregular surfaces may reduce echo strength.  
- Interference: Nearby objects or ultrasonic noise can cause false readings.  
- Air Conditions: Humidity and pressure have minimal impact at short range.

## References

HC-SR04 Datasheet. Available at: https://www.electronics.com  
Serway, R. A., & Jewett, J. W. (2018). Physics for Scientists and Engineers. Cengage Learning.