

Sound source localization

Tutorial

Daniel Pizarro Pérez (University of Alcala)



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Objectives

This tutorial is focused on

- Understanding the basic concepts of audio propagation.
- Sound source direction estimation with a pair of microphones.
- Example code in Arduino platform.

This tutorial is not focused on

- General multi-source localization
- Propagation in close-field conditions and reverberant scenarios

Basic concepts (I)

What is Sound?

Definition: Sound is a mechanical wave that results from the back-and-forth vibration of particles in a medium (such as air).

Sound Waves:

Type: Longitudinal waves where particle displacement is parallel to the direction of wave propagation.

Medium: Air molecules transmit these pressure variations by colliding with neighboring molecules, transferring energy through the medium.

Speed of Sound:

Factors: Depends on the medium's properties, such as temperature, pressure, and density.

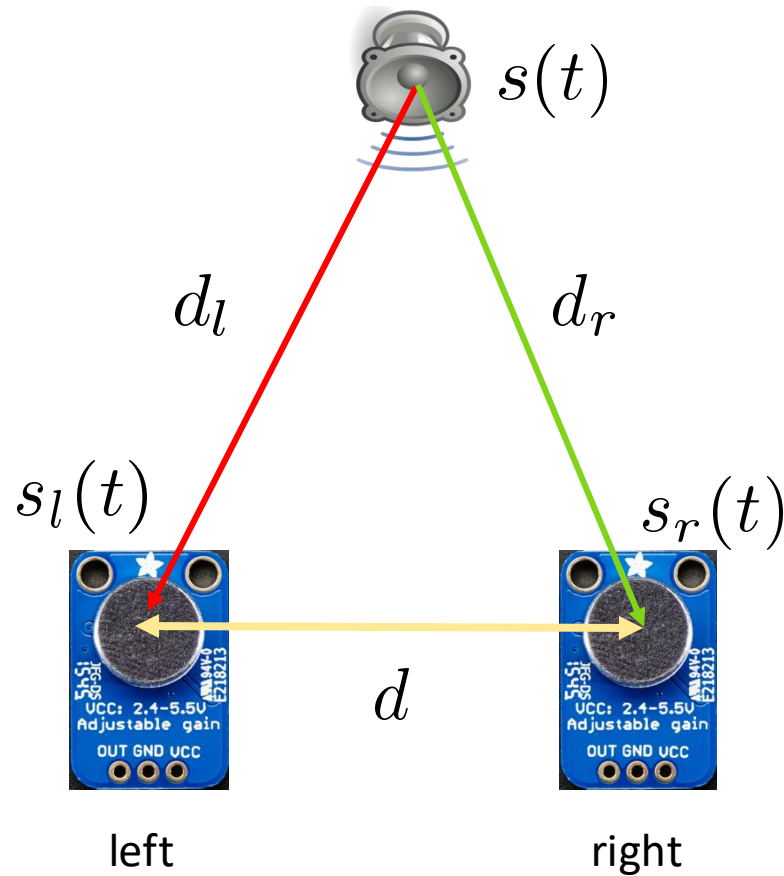
In Air: Approximately 343 meters per second (m/s) at room temperature (20°C).

Solids at room temperature	Liquids	Gases at 1 atm pressure
Titanium 6070 m/s	Sea water 25°C 1534 m/s	Hydrogen 27°C 1320 m/s
Nickel 6040 m/s	Water 25°C 1497 m/s	Helium 25°C 973 m/s
Steel 5940 m/s	Mercury 25°C 1450 m/s	Methane 27°C 450 m/s
Cast iron 4994 m/s	Ethanol 20°C 1159 m/s	Nitrogen 27°C 353 m/s
Brass 4700 m/s	Methanol 20°C 1116 m/s	Dry air 25°C 346 m/s
Silver 3650 m/s		Dry air 20°C 343 m/s
Platinum 3260 m/s		Oxygen 27°C 330 m/s
Gold 3240 m/s		Carbon dioxide 0°C 258 m/s
Polystyrene 2350 m/s		
Rubber 1600 m/s		

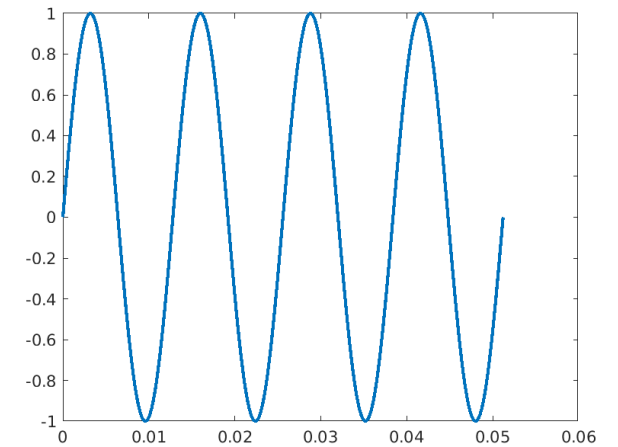
<https://theory.labster.com/sound-speed-table-dbs/>

Basic concepts (II)

Sound Source and a pair of microphones

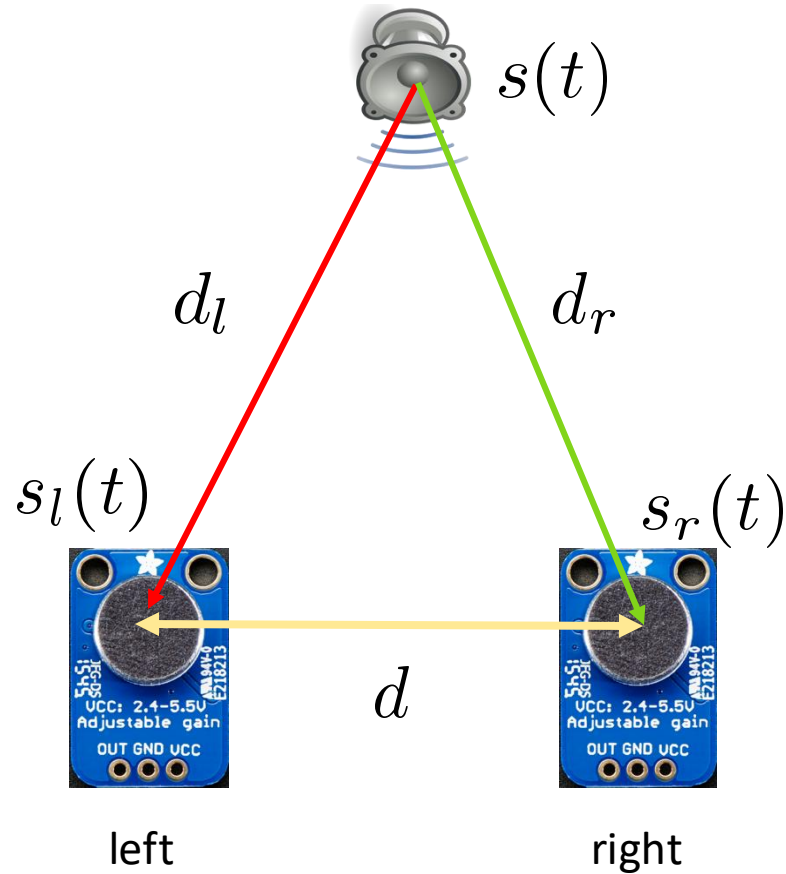


- d_l Distance from source to left microphone
- d_r Distance from source to right microphone
- d Distance from left to right microphones
- $s(t)$ Sound signal emitted by the source
- $s_l(t)$ Sound signal received at the left microphone
- $s_r(t)$ Sound signal received at the right microphone



Basic concepts (III)

Sound Source and a pair of microphones



Assumption: The signals received at the microphones are delayed versions of the source signal

$$s_r(t) = s(t - \Delta_r)$$

$$s_l(t) = s(t - \Delta_l)$$

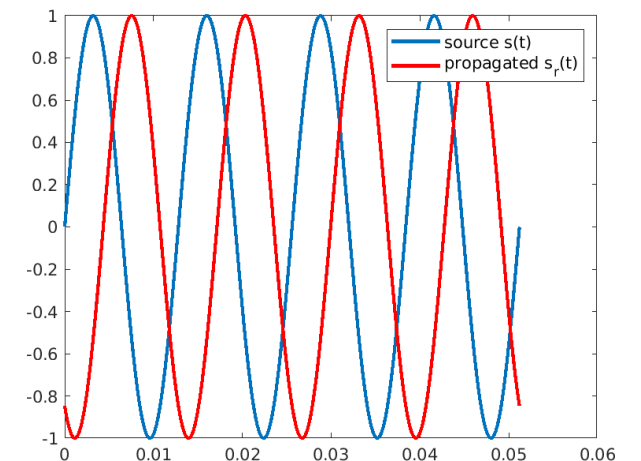
Time delays due to sound propagation

$$\Delta_r = \frac{d_r}{v_s} \quad \Delta_l = \frac{d_l}{v_s}$$

v_s Speed of sound (334 m/s at 20°C)

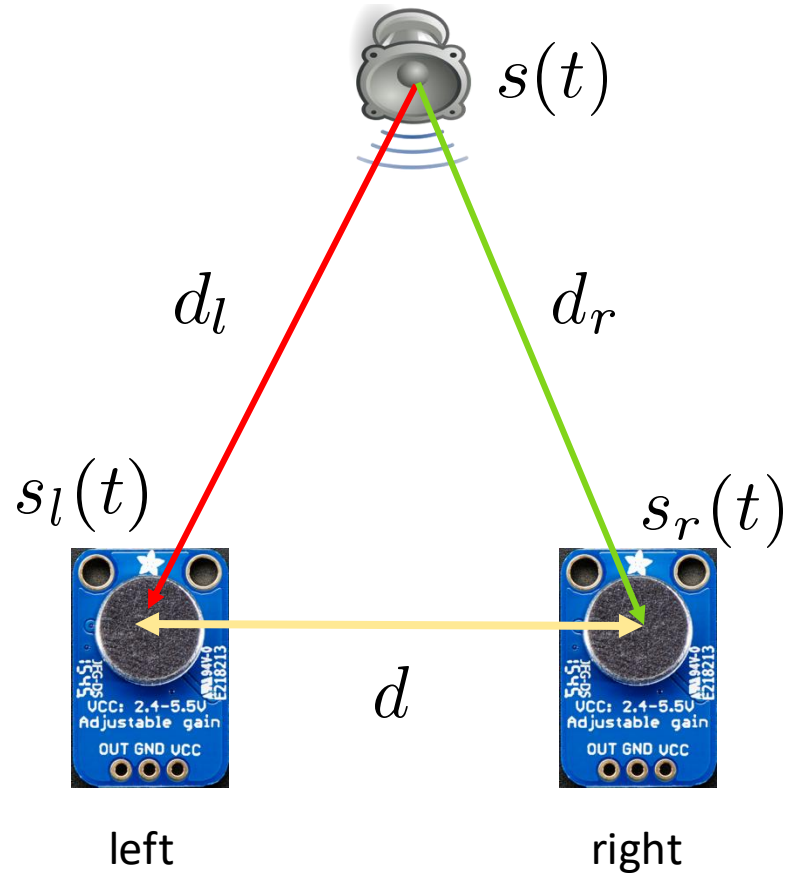
Example:

Source at 10 meters from the microphone



Basic concepts (IV)

Sound Source and a pair of microphones



Assumption: The signal received at the left microphone is a delayed version of the signal received at the right microphone.

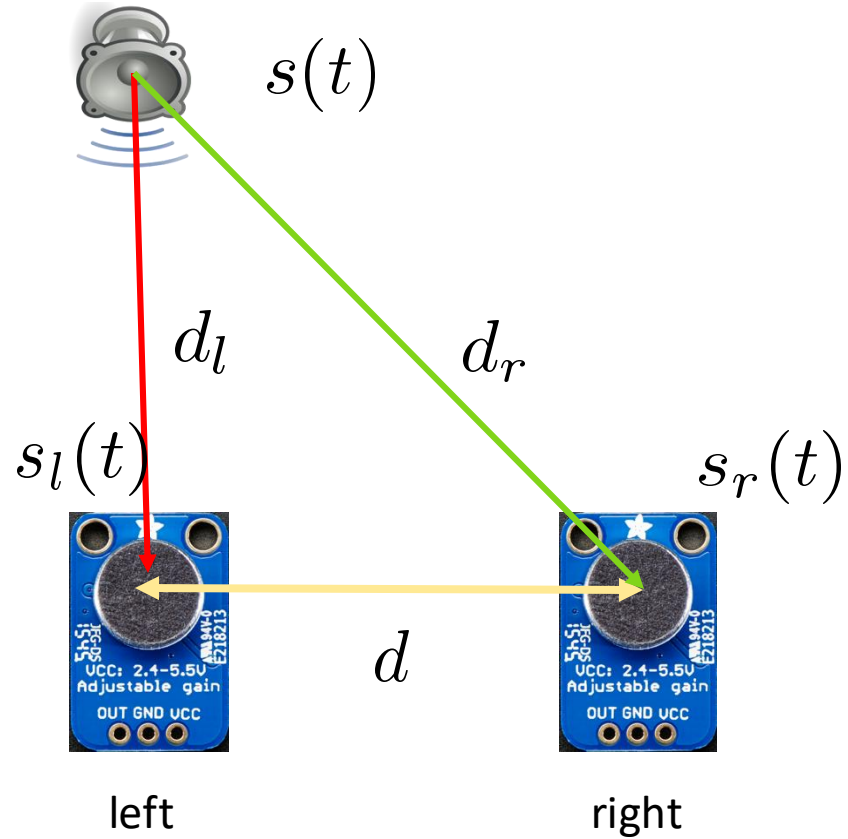
$$s_l(t) = s_r(t + \Delta_r - \Delta_l)$$

$$\Delta_r - \Delta_l = \frac{d_r - d_l}{v_s}$$

The delay is proportional to the difference of distances

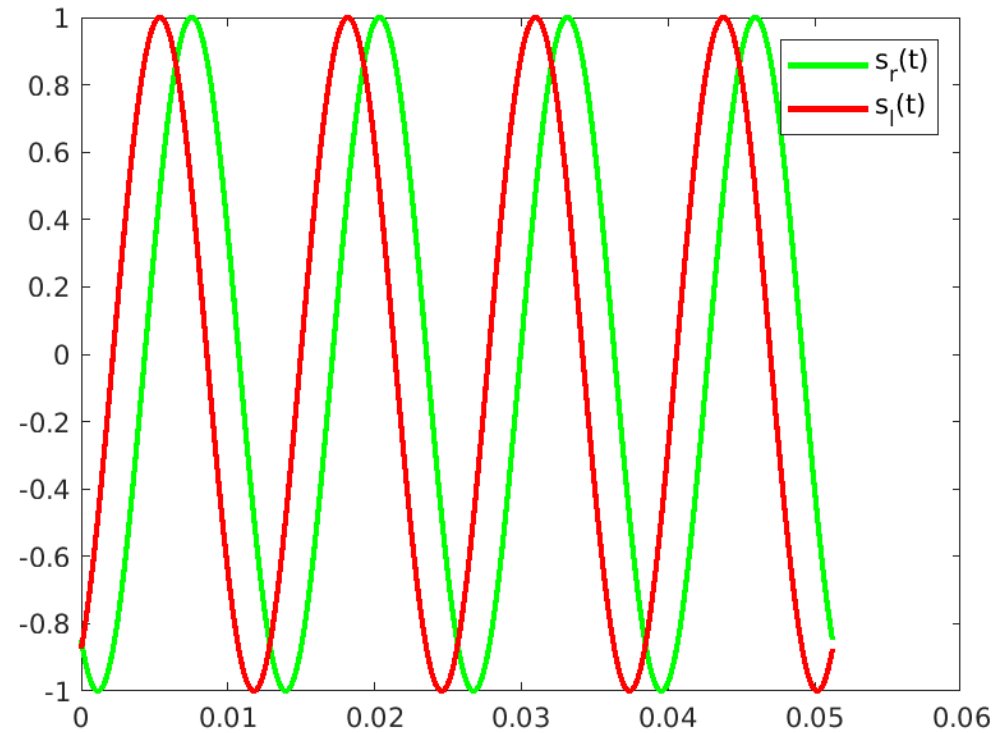
Basic concepts (IV)

Sound Source and a pair of microphones



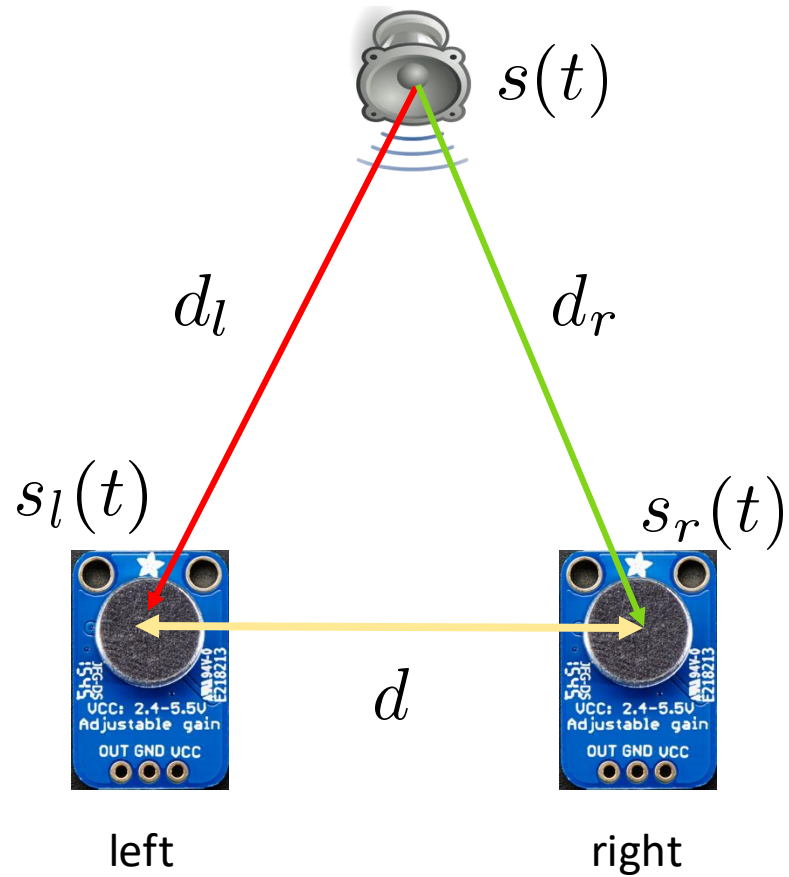
$$d_r > d_l$$

Source is on the left side



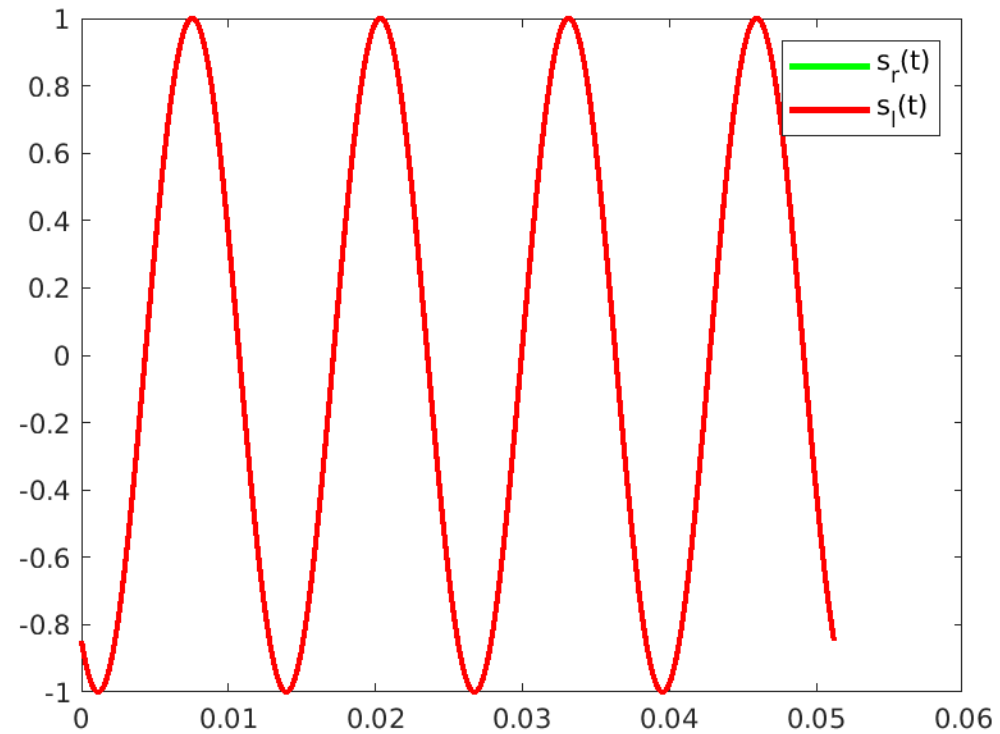
Basic concepts (IV)

Sound Source and a pair of microphones



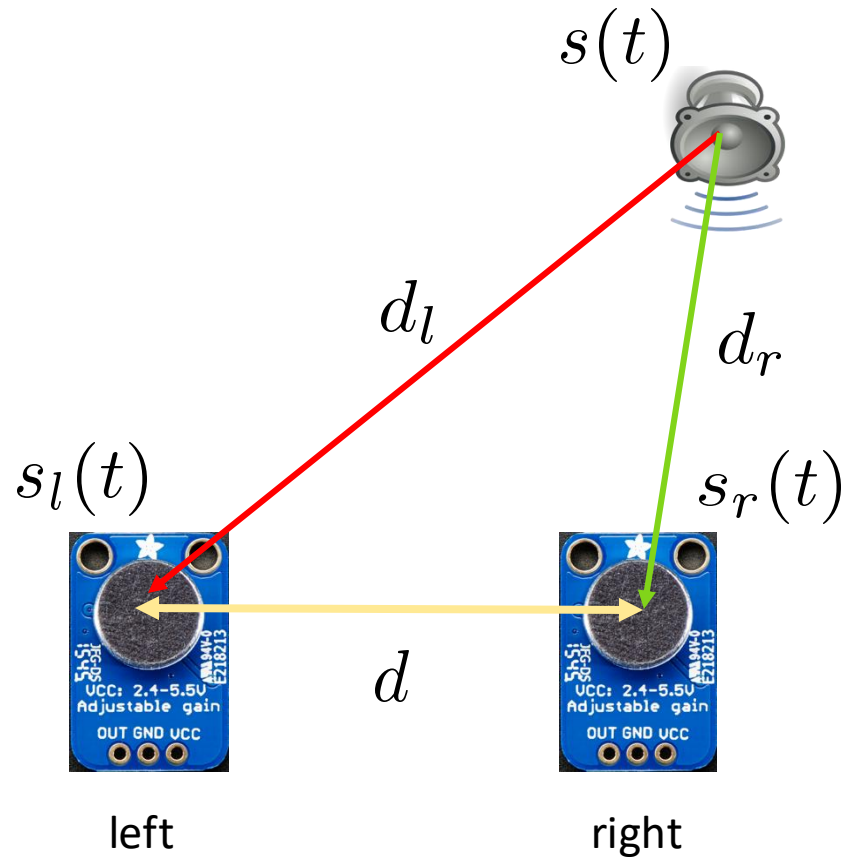
$$d_r = d_l$$

Source is centered



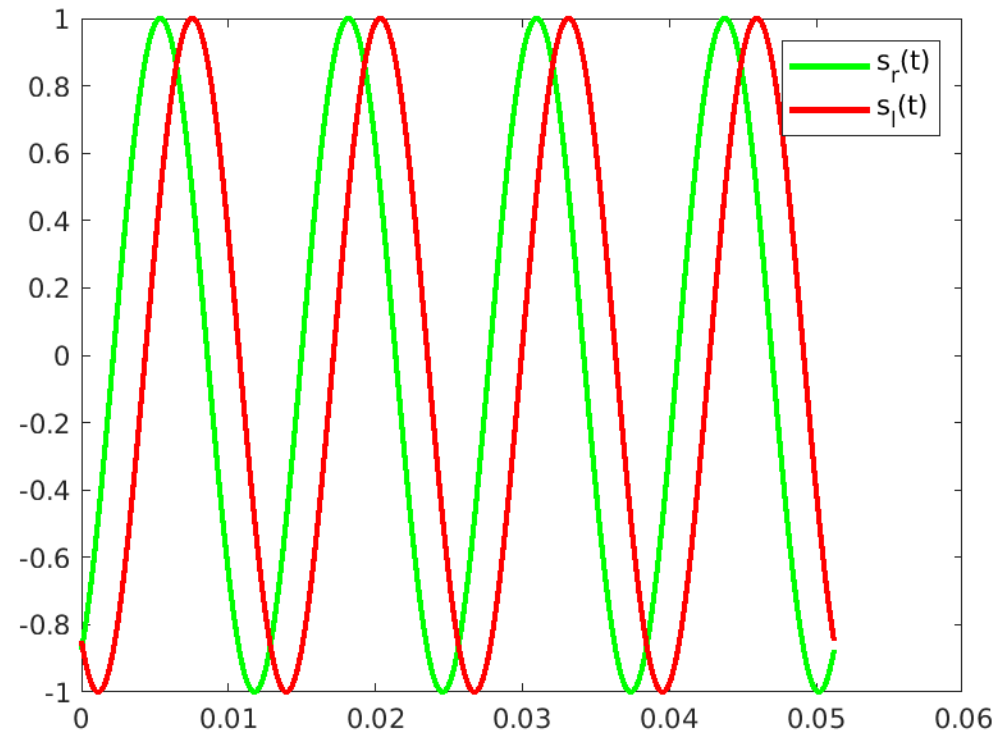
Basic concepts (IV)

Sound Source and a pair of microphones



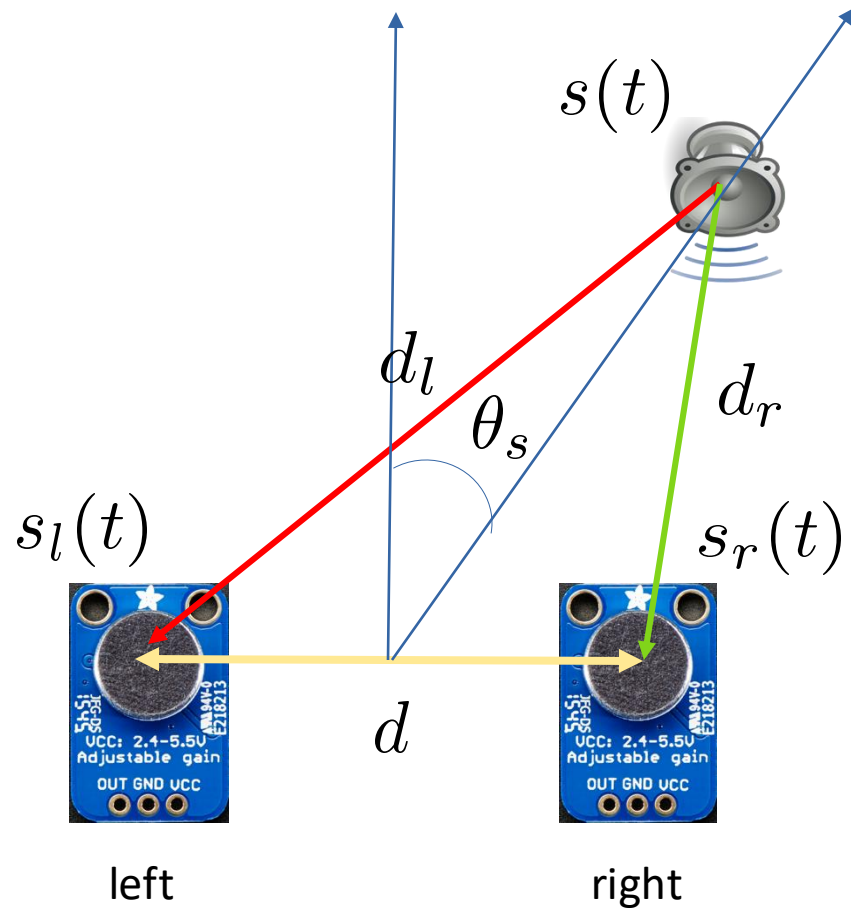
$$d_r > d_l$$

Source is on the right side



Direction of Arrival (DoA) detection

Direction of Arrival (DoA) [2]



θ_s Source DoA angle.

Direction of the source with respect to the microphones

$$\theta_s = \sin^{-1} \left(\frac{\Delta_r - \Delta_l}{d} v_s \right)$$

Assuming $d_r, d_l \gg d$

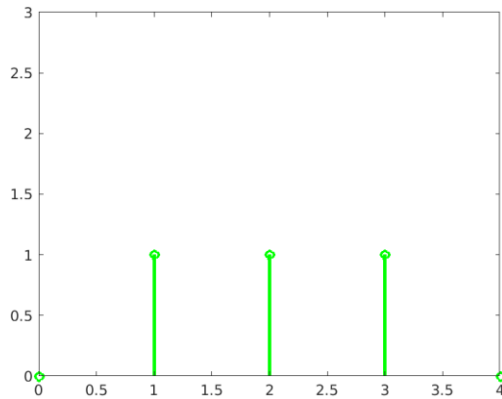
Direction of Arrival (DoA) detection

What is the correlation between two sampled signals ?

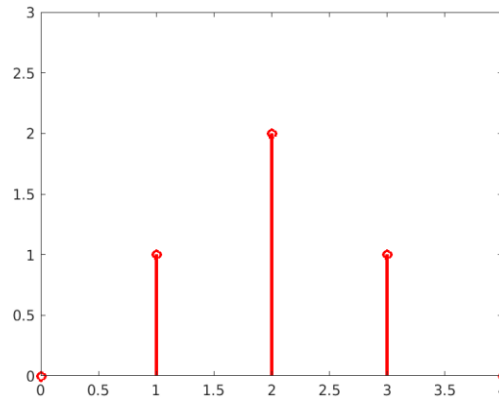
$$c(t) = \sum_{i=0}^{N_s} s_l(t_i) s_r(t + t_i)$$

Example

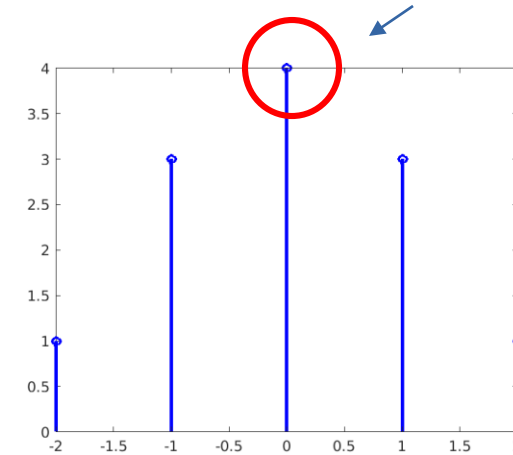
$$c(0) = s_r(0)s_l(0) + s_r(1)s_l(1) + s_r(2)s_l(2) + s_r(3)s_l(3) + s_r(4)s_l(4) = 4$$



$s_l(t)$



$s_r(t)$

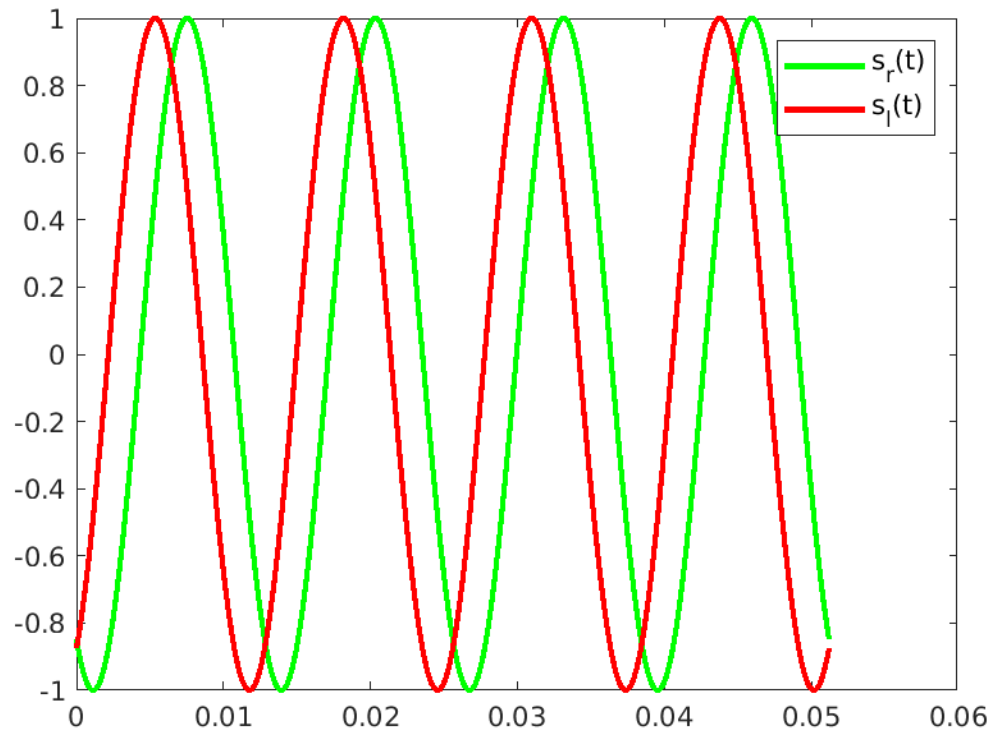


$c(t)$

Direction of Arrival (DoA) detection

Measuring the delay difference with correlation

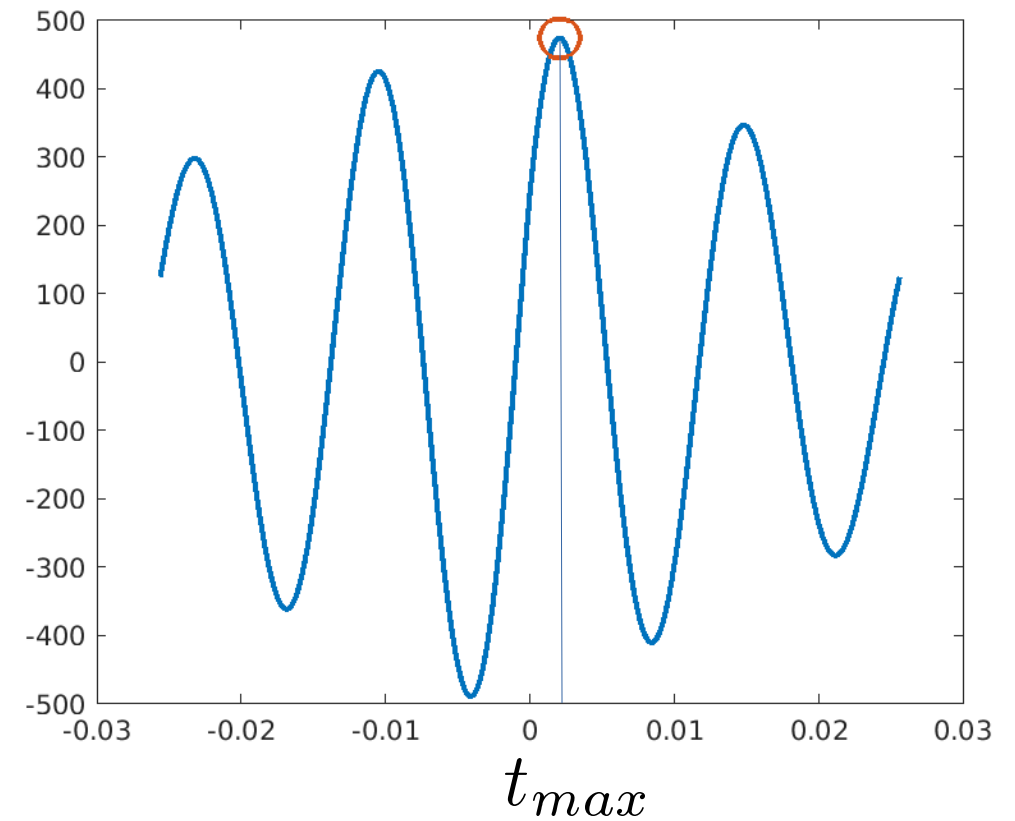
$$d_r > d_l$$



correlation

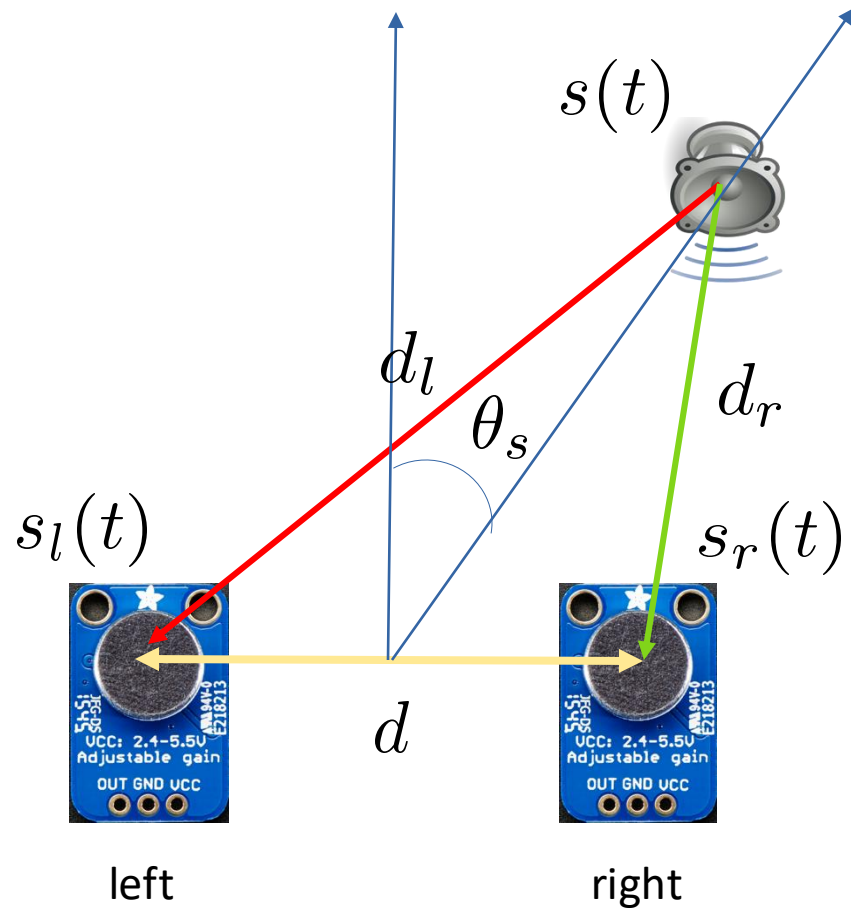


$$\Delta_r - \Delta_l = t_{max}$$



Direction of Arrival (DoA) detection

Sound Source and a pair of microphones



Algorithm to find the DoA [2]

- 1) Capture the left and right microphone signals $s_l(t)$ $s_r(t)$
- 2) Compute correlation

$$c(t) = \sum_{i=0}^{N_s} s_l(t_i) s_r(t + t_i)$$

- 3) Compute the time index where the correlation is maximum

$$t_{max} = \operatorname{argmax}(c(t))$$

- 4) Compute the DoA angle

$$\theta_s = \arcsin\left(\frac{t_{max}}{d} v_s\right)$$

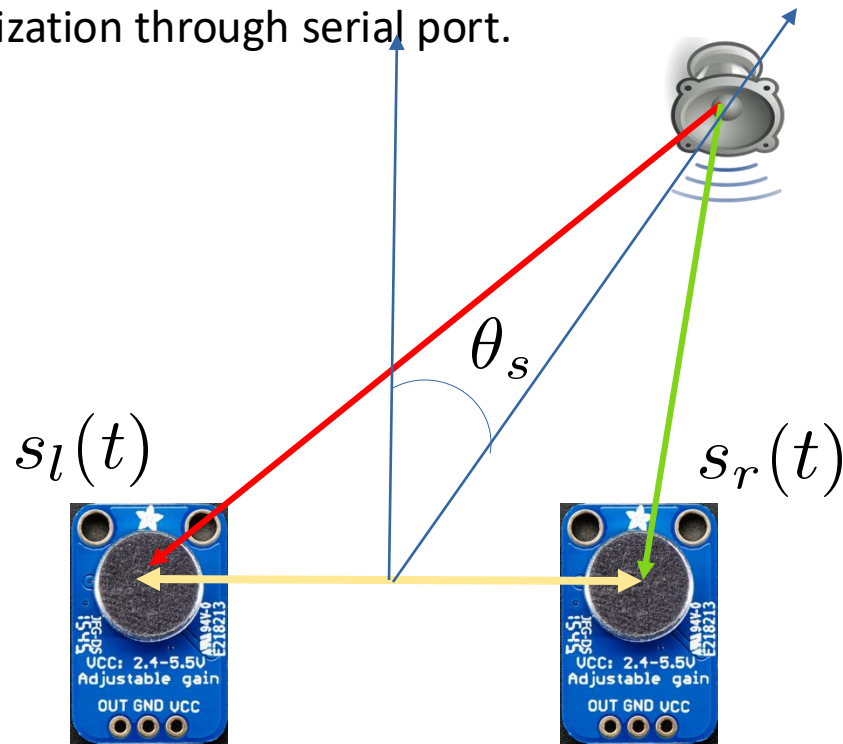
DoA estimation example in Ruby

Objective:

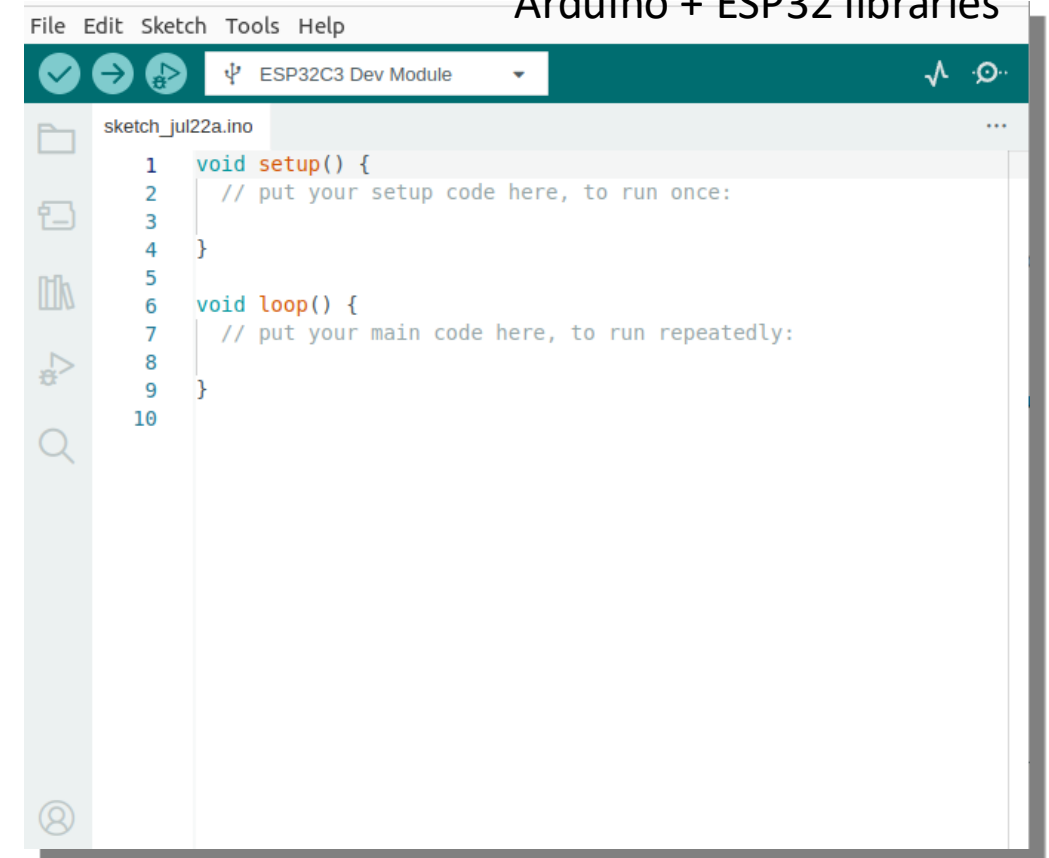
- Capturing audio signals from two microphones connected to ADC1 channels 0 and 1.
- Resolution: 12 bits Sampling frequency: 30 KHz
- Compute Correlation and its maximum
- Compute DoA angle.
- Visualization through serial port.

Environment:

Arduino + ESP32 libraries



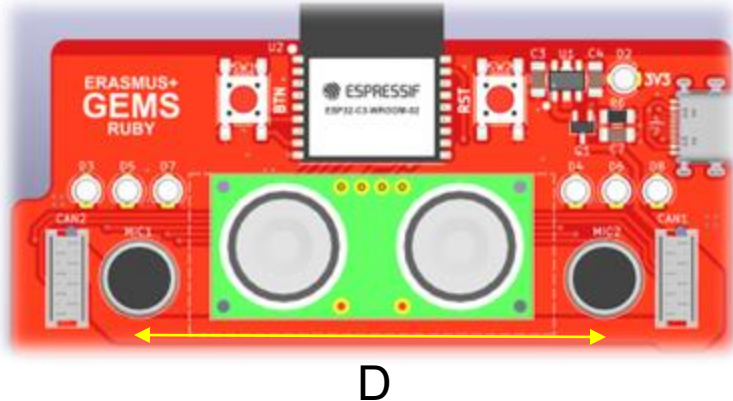
left $d = 6.6\text{cm}$ right



DoA estimation example in Ruby

Code breakdown: Initialization and Setup

- Constants and Variables:
 - CONVERSIONS_PER_PIN: Number of conversions per pin.
 - Nsamples: Number of samples to collect.
 - LAGMAX: size of correlation buffer
 - Fs: sampling frequency
 - Vs: speed of sound
 - D: distance between microphones
 - Arrays sleft and sright for storing samples.
- ADC Pin Configuration:
- Correlation buffer
- Tmax and DoA angle variables



```
1 #define CONVERSIONS_PER_PIN 1
2 uint8_t adc_pins[] = {1, 0};
3 #define Nsamples 725
4 #define LAGMAX 30
5 #define PI 3.1415926
6 #define D 0.066
7 #define vs 334.0
8 #define fs 30000
9 int correlation[2*LAGMAX+1];
10 int n;
11 int sleft[Nsamples];
12 int sright[Nsamples];
13 double tmax=0;
14 double angle=0;
15 uint8_t adc_pins_count = sizeof(adc_pins) / sizeof(uint8_t);
16 volatile bool adc_conversion_done = false;
17 adc_continuous_data_t *result = NULL;
18
```

DoA estimation example in Ruby

Code breakdown: Setup Function

- Serial Communication: Initialized at 115200 bits per second.
- ADC Configuration:
 - Set resolution to 12 bits.
 - Set attenuation to 11db.
 - Configure continuous ADC with pins, conversion count, frequency (fs Hz x 2 channels), and ISR callback.
 - Start continuous ADC conversions.

```
1 void setup() {  
2   Serial.begin(115200);  
3   analogContinuousSetWidth(12);  
4   analogContinuousSetAtten(ADC_11db);  
5   analogContinuous(adc_pins, adc_pins_count, CONVERSIONS_PER_PIN, fs*2, &adcComplete);  
6   analogContinuousStart();  
7 }
```

2-channel Audio Acquisition example

Code breakdown: Data Processing in Loop Function

- ISR Flag Check: Processes data if conversion is complete.
- Data Reading and Storage: Stores mV values in sleft and sright.
- Cross-Correlation and DoA Calculation:
 - Computes cross-correlation.
 - Finds the maximum position to calculate time delay.
 - Computes the DoA angle using the time delay and distance between microphones.

```
1 void loop() {
2   if (adc_conversion_done == true) {
3     adc_conversion_done = false;
4     if (analogContinuousRead(&result, 0)) {
5       sleft[n] = result[0].avg_read_mv - 1200;
6       sright[n] = result[1].avg_read_mv - 1200;
7       n++;
8     } else {
9       Serial.println("Error occurred during reading data.");
10    }
11  }
12
13  if(n >= Nsamples) {
14    analogContinuousStop();
15    n = 0;
16    calculate_cross_correlation(sleft, sright, Nsamples, LAGMAX, correlation);
17    tmax = (((double)find_max_position(correlation, 2*LAGMAX+1))-LAGMAX+1)/((double)
fs);
18    double argument = (tmax/D)*vs;
19    if(argument>1.0) argument=1.0;
20    if(argument<-1.0) argument=-1.0;
21    angle = asin(argument)*180.0/PI;
22    Serial.printf("tmax=%.2f,angle=%.2f\n", tmax, angle);
23    delay(1000);
24    analogContinuousStart();
25  }
26 }
27
```

2-channel Audio Acquisition example

Experiment

- 1 KHz pure tone audio source
- Visualization in Arduino Serial Plotter



`tmax=0.00003,angle=9.98, arg=0.17323`

`tmax=-0.00010,angle=-31.31, arg=-0.51970`



left

right

`tmax=0.00020,angle=90.00, arg=1.03939`



Conclusions

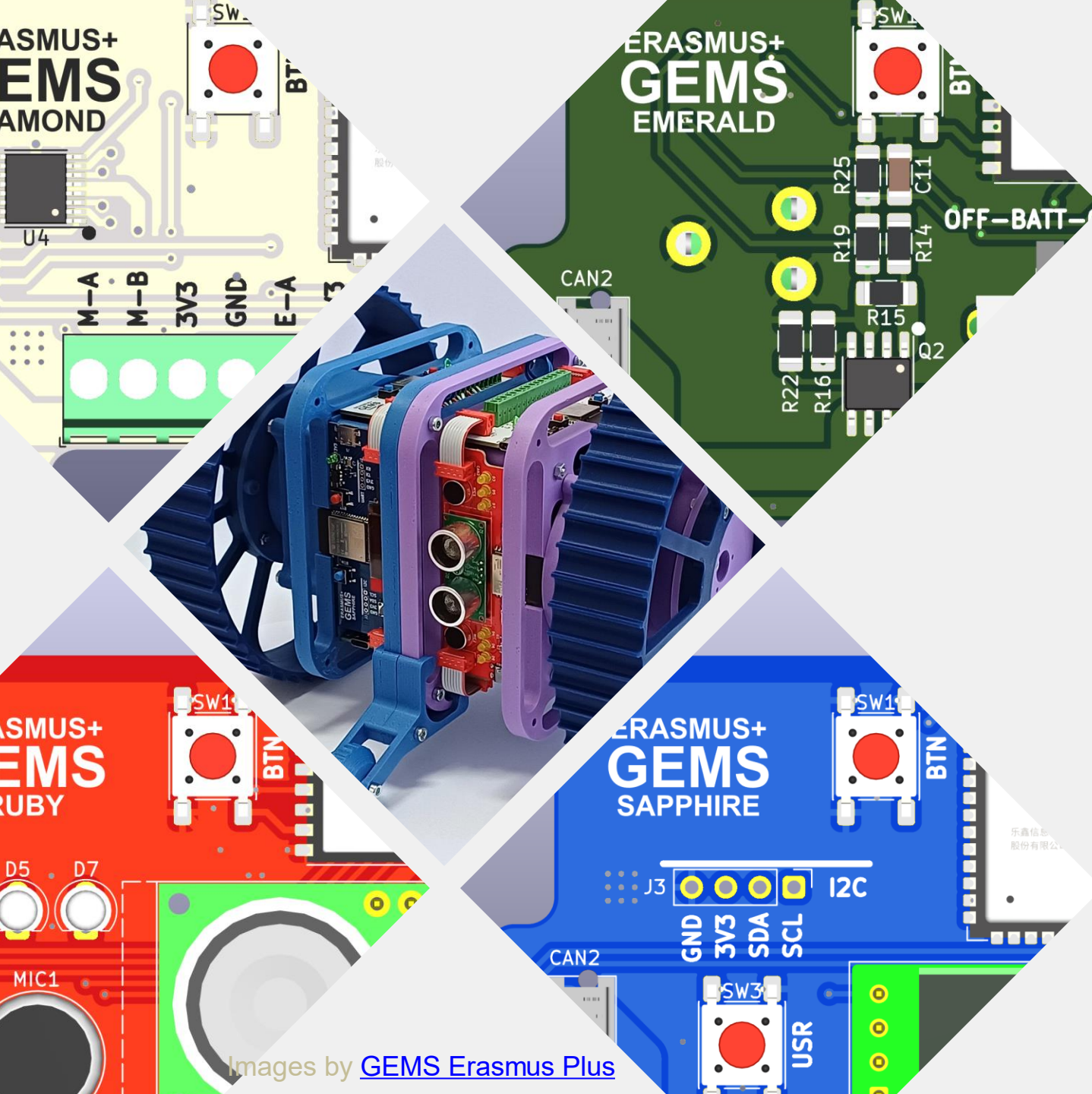
- Effective Signal Capture: Successfully captured audio signals from two microphones using ESP32's ADC in continuous mode.
- Cross-Correlation Analysis: Applied cross-correlation to determine the time delay between signals from two microphones.
- Direction of Arrival (DoA) Estimation: Calculated the DoA of the sound source using the time delay and physical separation of the microphones.
- Practical Applications: Techniques learned can be applied to real-world scenarios such as sound localization, robotic navigation, and acoustic monitoring.

References

[1] Table of Sound Speeds.

<https://theory.labster.com/sound-speed-table-dbs/>

[2] Y. A. Huang, J. Benesty, and J. Chen, “**Time delay estimation and source localization,**” in Springer Handbook of Speech Processing. Springer, Berlin, Heidelberg, pp. 1043–1063, 2008. DOI:10.23919/Eusipco47968.2020.9287466



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