Instituto Superior Técnico

Applications and Computation for the Internet of Things

Lab work: Ultrasound Sensor Array Testbed.

Group:		
Student 1:		
Student 2:		
Student 3:		

Goal:

This work aims to familiarize students with ultrasound sensing technology, with background knowledge of the Arduino UNO microcontroller and the wireless radio network module. This project will utilize the ultrasound sensor JSN-SR04T, the wireless radio module NRF24L01, and components from the Arduino Starter Kit and IDE. This project has 2 phases of implementation. In the first implementation phase, the students can build a master and slave node system in which the slave will include the ultrasound sensor. In the second implementation phase, the students can use ultrasound technology to build a localization and testbed system.

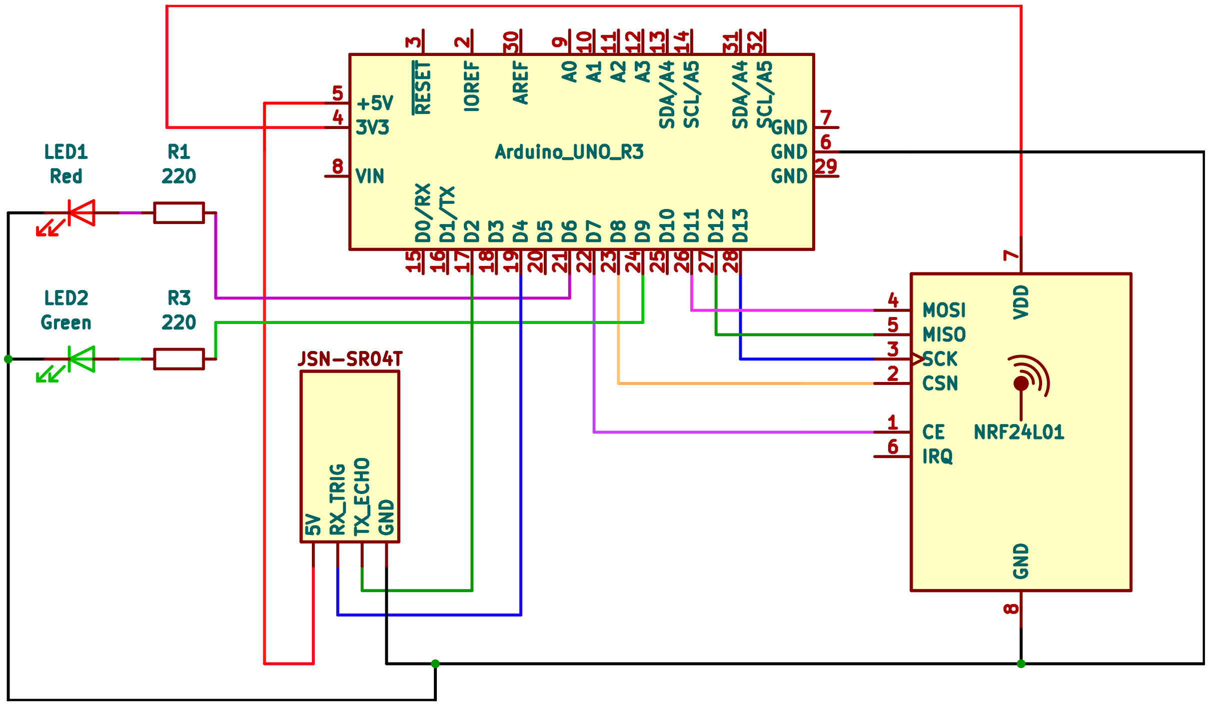
Phase 1

Description:

Build 2 nodes using the Arduino UNO: Master node and slave or sensor node.

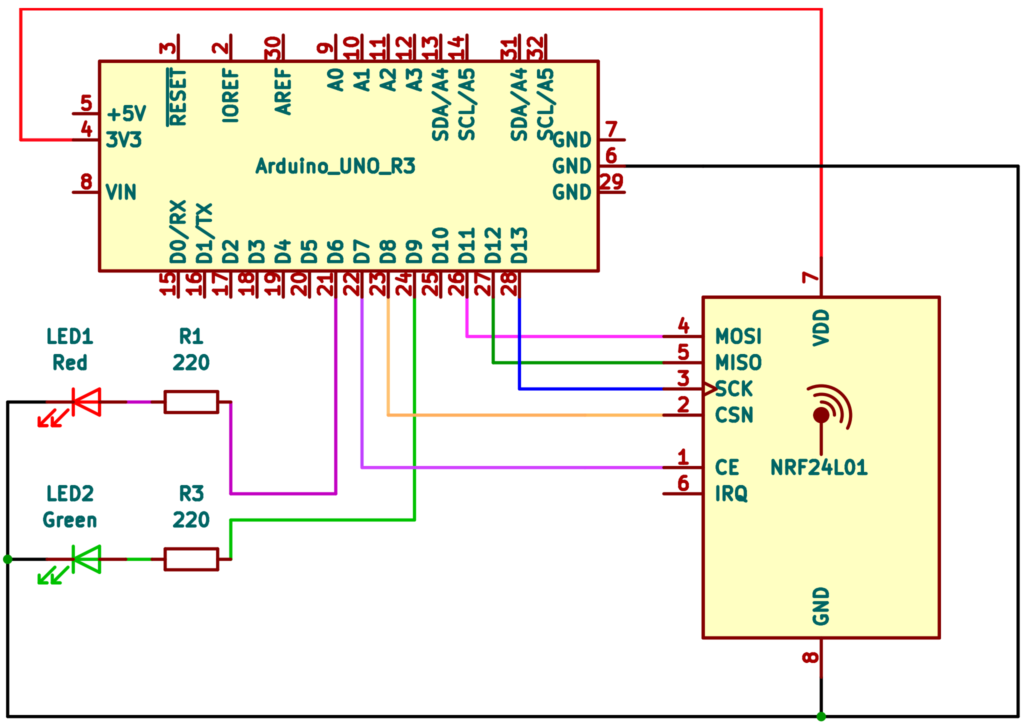
- The **slave node** or **sensor node**, will include the following:
    - Ultrasound sensor, JSN SR-04T,
    - Arduino UNO microcontroller,
    - NRF24L01 wireless radio module,
    - Arduino UNO kit’s Breadboard,
    - 2 color LEDs with the corresponding resistors to indicate the radio communication status.

The following figure represents the assembly diagram of the components in the slave node.



- The **master node** will include:
  - Arduino UNO microcontroller,
  - NRF24L01 wireless radio module,
  - Arduino UNO kit’s Breadboard,
  - 2 color LEDs with the corresponding resistors to indicate the radio communication status.

The following figure represents the assembly diagram of the components in the master node.



Objective: The master node will ask the slave node to execute readings using the ultrasound sensor and send the distance measured back. The messages between the nodes and the information should be presented on the serial monitor.

References:

1. JSN SR-04T tutorial - https://www.makerguides.com/jsn-sr04t-arduino-tutorial/
2. NRF24L01 Tutorial - https://howtomechatronics.com/tutorials/arduino/arduino-wireless-communication-nrf24l01-tutorial/
3. Multiple NRF24L01 Module Network - https://howtomechatronics.com/tutorials/arduino/how-to-build-an-arduino-wireless-network-with-multiple-nrf24l01-modules/
4. LED project - https://projecthub.arduino.cc/arduino_world/blink-led-project-with-arduino-90f185
5. Serial Monitor - https://docs.arduino.cc/software/ide-v2/tutorials/ide-v2-serial-monitor/

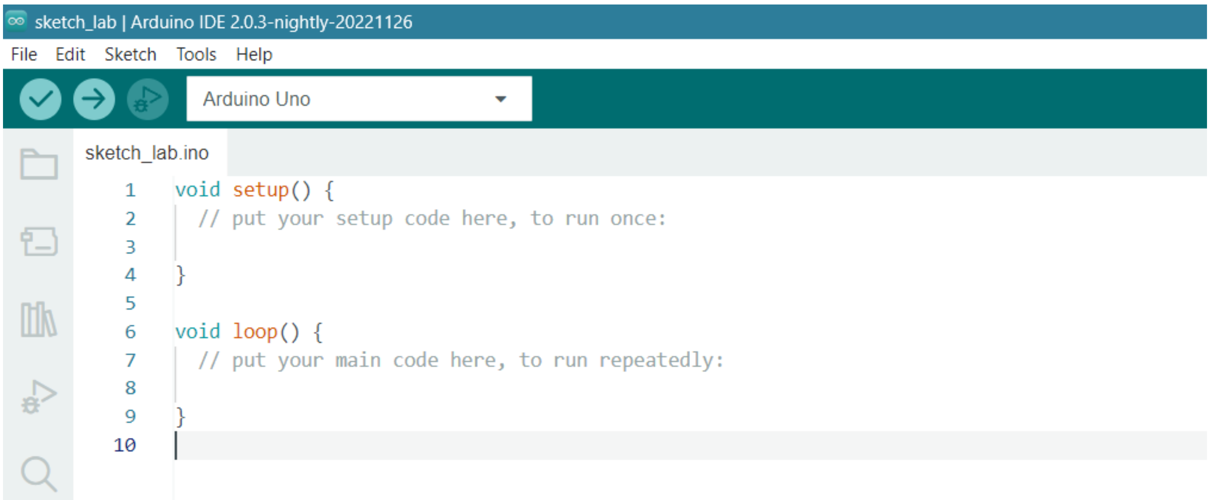
Recommendations:

For a safe working environment and to prevent any damage to the hardware, please adhere to the following recommendations. As you progress with your work, check off each box to ensure all safety measures are followed.

Always ensure that the circuit is disconnected from the power source (either the power supply or the PC) when you are working on it. This includes inserting, connecting, or disconnecting sensors and actuators.	
Before connecting the circuit to the power source and turning it on, please consult with the teacher or the person in charge of the laboratory.	
Verify that all components of the circuit (such as resistors, capacitors) are properly connected. This is crucial to prevent short circuits or hardware damage. For instance, never connect an LED directly to a terminal of the controller and GND, or VCC.	
Use the Serial Monitor and LEDs to execute debugging to the system	
Try to minimize bending the terminals of the components. If bending is necessary (for example, with resistors), ensure that the bend is made approximately 5 mm from the body of the component.	

Program the application:

Based on the projects in the References and the description of the system phase, create your program for each node, using Arduino IDE. Organize your program in “basic blocks” with adequate structures and comments. A basic block is a sequence of instructions with no embedded branches (except at end), and no branch targets (except at the beginning).



Start by establishing communication between the nodes, including the wireless radio module libraries, and defining the node addresses and channels the wireless radio network will use to identify each node. The following figure gives an example in how to include the wireless radio network libraries and define the node information in this network.

Once you have established communication between the nodes, check the JSN SR-04T tutorial on the References and develop the code necessary to execute readings using the ultrasound sensor. The measurements will then be sent to the Master node to be presented in the Serial Monitor.

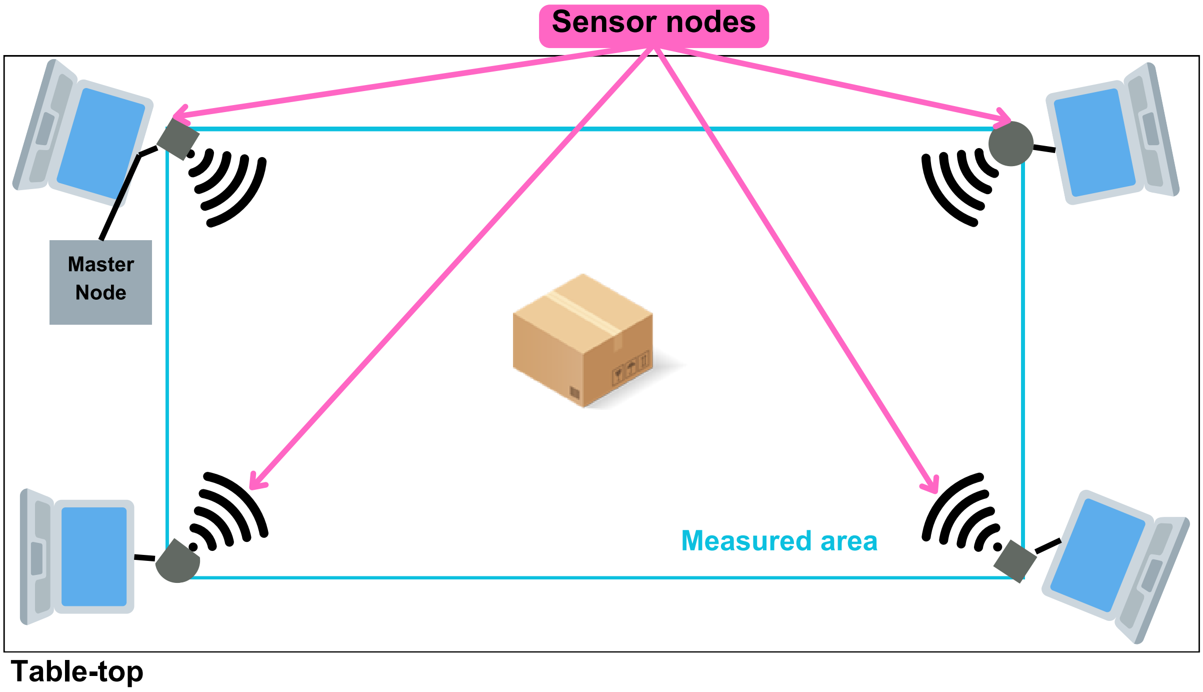
Results:

1. Using a ruler and the systems created, determine the minimum and maximum read by the ultrasound sensor.
2. Using the same object in front of the ultrasound sensor, fix the position of the ultrasound probe as the coordinates (0,0,0). Then, vary the ultrasound probe coordinates in the x, y and z axes. Construct a table in centimeters with all the coordinates, the actual distance (in direct line with the ultrasound probe), and the measured distance by the ultrasound sensor. What do you detect when changing the z-axis coordinates?
3. Estimate the network latency of the wireless radio network.
4. Study the sound reflection index of the surface of different objects. Describe each object, the actual distance of the object, and the distance measured by the ultrasound sensor.

Phase 2

Description:

The second phase of this project aims for the students to be able to build a localization and testbed system using ultrasound technology.
In this phase, the professor will join four student groups to create the whole testbed system. Each student group will operate a slave node, and together, they must create the master node with all of the orchestration, calculation functions, and presentation of the information reached.
The localization testbed system will include 1 master node and 4 slave nodes, each with a distinct node address and channel. The master node will know these addresses and set the channel to communicate with each slave node. The communication between the master node and the slaves must be coordinated using a scheduling pattern chosen by the students.
The slaves and master nodes will need to be implemented in a rectangular form, like the one presented in the following image.



Each slave node will have coordinates, being one of the nodes with the origin at (0,0) and the others with coordinates relative to the origin. The slaves will transmit the distance measured to the master node. The master node will collect all the distances read by each slave, and with a minimum of 3 distances measured, it will calculate the coordinates of the target object in the measured area. The students can use the trilateration function in Attachment A to calculate the target object's coordinates. Note: The trilateration in Attachment A only calculates the target object’s (x,y) coordinates; the students care free to implement the z-axis coordinates in the calculus.
Finally, with the localization system operational, the students can answer the questions in the Results to execute the system as a testbed for the ultrasound array of sensing technology.

References:

1. NRF24L01 Tutorial - https://howtomechatronics.com/tutorials/arduino/arduino-wireless-communication-nrf24l01-tutorial/
2. Multiple NRF24L01 Module Network - https://howtomechatronics.com/tutorials/arduino/how-to-build-an-arduino-wireless-network-with-multiple-nrf24l01-modules/
3. Trilateration - https://ieeexplore.ieee.org/document/7226229

Recommendations:

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Use the Serial Monitor and LEDs to execute debugging to the system	
Try to minimize bending the terminals of the components. If bending is necessary (for example, with resistors), ensure that the bend is made approximately 5 mm from the body of the component.	

Requirements:

1. The master node communicates with each slave node by its address and channel and obtains the distances read by the slave node.
2. The master node calculates the correct coordinates of the target object
    a. First, define a control scenario for the system. The control scenario is the hypothetical configurations of the system that design the normal execution of its functionalities.
    b. Analyze different “ultrasound coverage” areas and the target object coordinates when inserted in those.
        i. Draw a diagram of the measured area where it’s possible to analyze the different intersection areas of the ultrasound sensor signals,
        ii. Create a table with the ultrasound signal intersection area number (e.g., area #1 – 2 ultrasound signals intersect), the correct coordinates of the target object, and the coordinates reported by the system.
    c. Study the sound interferences to the system for both scenarios, register the coordinates of the target object and interferences to the distance measurements.
        i. First, analyze the system without any noise,
        ii. Use a smartphone and induce different sound frequencies into the system, you can use the following video link on Youtube: https://www.youtube.com/watch?v=qNf9nzvnd1k
    d. Experiment with different target objects, dimensions, and surface compositions.
        i. Create a table with the type of object, the dimensions of the target, the correct coordinates in the system, and the coordinates generated by the algorithm.

Results:

For each requirement, explain:

- The implemented procedure and thoughts that lead to the implementation,
- The relevant code with explanations and artifacts,
- Possible problems and limitations to the development of the task,
- Analyzed results and conclusions.

Attachments A

```
#include <vector>
#include <cmath>
#include <iostream>

// Structures of the sensor data
struct SensorNodes {
    double x, y; //Sensor node coordinates, the z axis is not implemented
(yet)
    double objectDistance; // Measured distance from object to sensor
};


// Function to perform trilateration and calculate object coordinates
// - It receives 3 sensor objects and the variables to export the coordinates
(x,y)
bool trilateration(const SensorNodes& s1, const SensorNodes& s2, const
SensorNodes& s3, double& x, double& y) {
    double x1 = s1.x, y1 = s1.y, r1 = s1.objectDistance;
    double x2 = s2.x, y2 = s2.y, r2 = s2.objectDistance;
    double x3 = s3.x, y3 = s3.y, r3 = s3.objectDistance;

    double a = 2 * (x2 - x1);
    double b = 2 * (y2 - y1);
    double c = pow(r1, 2) - pow(r2, 2) - pow(x1, 2) + pow(x2, 2) - pow(y1, 2)
+ pow(y2, 2);
    double d = 2 * (x3 - x2);
    double e = 2 * (y3 - y2);
    double f = pow(r2, 2) - pow(r3, 2) - pow(x2, 2) + pow(x3, 2) - pow(y2, 2)
+ pow(y3, 2);

    double denominator = (a * e - b * d);
    if (denominator == 0) {
        return false; // No valid intersection of circles
    }

    x = (c * e - f * b) / denominator;
    y = (a * f - d * c) / denominator;

    return true;
}

// Function to calculate object coordinates using all combinations of 3
sensors from a set of 4 sensors
void calculateObjectCoordinatesAll(std::vector<SensorNodes>& sensorNodes) {
    if (sensorNodes.size() < 3) {
```

```
        Serial.println("Error: At least 3 sensor nodes are needed for
trilateration.");
        return;
    }

    double sumX = 0, sumY = 0;
    int validCombinations = 0;

    // Loop through all combinations of 3 sensors
    for (size_t i = 0; i < sensorNodes.size() - 2; ++i) {
        for (size_t j = i + 1; j < sensorNodes.size() - 1; ++j) {
            for (size_t k = j + 1; k < sensorNodes.size(); ++k) {
                double x_object = 0, y_object = 0;

                // Perform trilateration on the current set of 3 sensors
                if (trilateration(sensorNodes[i], sensorNodes[j],
sensorNodes[k], x_object, y_object)) {
                    sumX += x_object;
                    sumY += y_object;
                    validCombinations++;
                } else {
                    Serial.print("Error: Sensors ");
                    Serial.print(i);
                    Serial.print(", ");
                    Serial.print(j);
                    Serial.print(", and ");
                    Serial.print(k);
                    Serial.println(" do not intersect properly.");
                }
            }
        }
    }

    if (validCombinations > 0) {
        double avgX = sumX / validCombinations;
        double avgY = sumY / validCombinations;
        Serial.print("Estimated object coordinates: (");
        Serial.print(avgX);
        Serial.print(", ");
        Serial.print(avgY);
        Serial.println(")");
    } else {
        Serial.println("Error: No valid trilateration results.");
    }
}

// Arduino setup function
void setup() {
```

```
    // Start serial communication
    Serial.begin(9600);

    // Define the positions and distances of 4 sensor nodes
    std::vector<SensorNodes> sensorNodes = {
        {0, 0, 10},  // Sensor 1: (x, y, distance)
        {10, 0, 7},  // Sensor 2: (x, y, distance)
        {5, 8, 9},   // Sensor 3: (x, y, distance)
        {7, 7, 6}    // Sensor 4: (x, y, distance)
    };

    // Calculate the object coordinates using trilateration for all
combinations of 3 sensors
    calculateObjectCoordinatesAll(sensorNodes);
}

// Arduino loop function (empty as it's only for setup in this case)
void loop() {
    // Nothing to do here
}
```