German International University
Faculty of Engineering
Major of Automation and Control

Wireless Sensor Network for Robotic Fleet Coordination

Introduction to Computer Networks
Project Report

Team Members

Hassan Yousef	13006567
Pierre George Boshra	13007351
Mohamed Walid	13006513
Abdelhamid ElSharnouby	13006294
Khaled Khaled	14001048
Mahmoud Nasser	13006342

Supervised by
Dr. Yasmine Zaghloul
TA: Eng. Omar Hemeda

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Contents

1 Week 1: Research & Setup

November 17-23, 2025

1.1 Research Phase

To establish a solid foundation for our project, we conducted comprehensive research utilizing multiple academic and expert resources. Our research methodology included:

- **Academic Database Search:** We performed extensive literature review using the Egyptian Knowledge Bank (EKB) database, searching for relevant research papers and technical documentation on wireless sensor networks, ESP-NOW protocol, mesh networking architectures, and robotic coordination systems.
- **Expert Consultation:** We consulted with Professor Yasmine Zaghloul, our course instructor, to discuss the project scope, technical feasibility, and recommended implementation approaches. Her guidance helped us refine our project objectives and identify potential challenges.
- **Technical Advisory:** We met with TA Omar Hemeda to discuss the practical aspects of the project implementation, including hardware selection, programming methodologies, and project timeline management.
- **Laboratory Support:** We worked closely with Lab Engineer Amr Khaled to understand the available laboratory resources, safety protocols, and equipment handling procedures necessary for our project development.

1.2 ESP-NOW Protocol Learning

To gain practical understanding of the ESP-NOW protocol, we studied the tutorial video "*ESPNOW for beginners! #ESP32 #ESP8266*" available at:

https://www.youtube.com/watch?v=Ydi0M3Xd_vs

This resource provided valuable insights into:

- The fundamentals of ESP-NOW as a fast, connectionless peer-to-peer communication protocol
- Setting up ESP-NOW connections between multiple ESP32 devices
- Broadcasting and receiving data packets using callback functions
- MAC address handling and peer registration

1.3 Hardware Setup

We successfully configured the development environment for the ESP32 microcontrollers using the Arduino IDE. The setup process included:

- Installing the Arduino IDE (version 2.x)
- Adding ESP32 board support through the Boards Manager
- Installing necessary libraries: `esp_now`, `WiFi`, `MPU6050_6Axis_MotionApps20`, `WebServer`, `SPIFFS`
- Testing basic functionality with simple sketch uploads
- Verifying serial communication for debugging purposes

1.4 Project Architecture Plan

After thorough analysis and team discussions, we finalized our system architecture as follows:

Information

Hardware Configuration:

- **3 ESP32 Microcontrollers:** Serve as the core processing and communication units
- **2 Remote-Controlled Toy Vehicles:** Provide the mobile platform for our robotic agents
- **Mesh Network Architecture:** All three ESP32 units communicate peer-to-peer via ESP-NOW, with one base station connected to PC for visualization

Note

Sensor Configuration per Vehicle:

- **HC-SR04 Ultrasonic Sensor:** Detects obstacles within 15cm range in the robot's forward direction
- **IR Sensor:** Detects whether the robot is on a white or black square for position tracking
- **MPU6050 IMU (Gyroscope + Accelerometer):** Determines robot orientation (Forward, Right, Backward, Left) using DMP processing

1.5 System Design Specifications

1.5.1 Initial Robot Positions

The robots start at predefined positions on the 4x4 grid:

- **Robot 1:** Position (4, 1) — bottom-left corner
- **Robot 2:** Position (4, 4) — bottom-right corner

1.5.2 Network Topology

The system implements a mesh-like network topology where all three ESP32 devices maintain peer-to-peer connections:

- Robot 1 ↔ Robot 2 (direct communication)
- Robot 1 ↔ Base Station
- Robot 2 ↔ Base Station
- Re-broadcast mechanism ensures all nodes receive updates

1.5.3 Mapping Area Design

The operational environment consists of a 4x4 grid-based area:

- Alternating white and black squares (checkerboard pattern)
- IR sensor detects color transitions to track movement between cells
- Obstacles can be placed statically within the grid
- Each cell is identified by row (1-4) and column (1-4) coordinates

1.5.4 Communication Flow

1. When Robot 1 detects an obstacle, it sends coordinates to Robot 2
2. Robot 2 updates its internal map and re-broadcasts to Robot 1 and Base Station
3. When Robot 2 detects an obstacle, it sends coordinates to Robot 1
4. Robot 1 updates its internal map and re-broadcasts to Robot 2 and Base Station
5. Base Station aggregates all updates and displays the map on PC via web interface

1.6 AI Tools Integration

The strategic utilization of AI-powered development tools played a crucial role in accelerating our project timeline and enhancing code quality:

Information

ChatGPT Integration:

- **Code Generation:** Assisted in generating boilerplate code for ESP-NOW initialization, sensor drivers, and data structure definitions
- **Debugging Support:** Provided insights for troubleshooting ESP32-specific issues and memory management
- **Documentation:** Helped structure technical documentation and explain complex networking concepts

- **Algorithm Optimization:** Suggested efficient approaches for map synchronization and re-broadcast logic

Information

GitHub Copilot Integration:

- **Real-time Code Completion:** Accelerated development with intelligent autocompletion for Arduino/C++ syntax
- **Function Implementation:** Suggested complete function implementations based on comments and context
- **Error Detection:** Identified potential bugs and syntax errors during coding
- **Code Refactoring:** Recommended improvements for code readability and maintainability

Professional Usage Guidelines:

- All AI-generated code was thoroughly reviewed and tested before integration
- AI suggestions were used as starting points, not final solutions
- Team members validated all technical decisions independently
- Critical system logic was designed by the team with AI assistance for implementation details
- Documentation and comments were written to ensure maintainability

1.7 Week 1 Deliverables

- ✓ Completed research on ESP-NOW protocol and mesh networking
- ✓ Set up Arduino IDE development environment with ESP32 support
- ✓ Assembled 2 robot chassis with sensor mounts
- ✓ Finalized project architecture and component selection
- ✓ Established communication with project advisors
- ✓ Created project timeline and milestone definitions

1.8 Challenges and Solutions

- **Challenge:** Understanding ESP-NOW protocol differences from traditional WiFi
- **Solution:** Studied multiple tutorials and documentation, conducted simple experiments
- **Challenge:** Initial plan was to use colour sensor, bit we had to pic 16 differently coloured squares and pick their specific colour frequency.
- **Solution:** Used IR sensor instead of color sensor for simpler black/white detection

1.9 Core Module Development

In the second half of Week 1, we programmed one robot to read its sensors (ultrasonic, IR, IMU) and broadcast obstacle data via ESP-NOW protocol.

1.10 Hardware Pin Configuration

The ESP32 pins are configured as follows for each robot node:

Component	Pin	Function
IR Sensor	GPIO 14	Digital input (white/black detection)
Ultrasonic Trigger	GPIO 26	Digital output
Ultrasonic Echo	GPIO 27	Digital input
MPU6050 SDA	GPIO 12	I2C Data
MPU6050 SCL	GPIO 13	I2C Clock

1.11 Ultrasonic Sensor Implementation

The ultrasonic sensor measures distance to detect obstacles within 15cm range:

```cpp
// Pin definitions
#define TRIG_PIN   26
#define ECHO_PIN   27

const float OBSTACLE_DISTANCE_CM = 15.0;

float readUltrasonicCm() {
  digitalWrite(TRIG_PIN, LOW);
  delayMicroseconds(2);
  digitalWrite(TRIG_PIN, HIGH);
  delayMicroseconds(10);
  digitalWrite(TRIG_PIN, LOW);

  long duration = pulseIn(ECHO_PIN, HIGH, 30000); // 30ms timeout
  if (duration == 0) return -1;  // no echo received
  float distance = duration * 0.0343 / 2.0;  // speed of sound
  return distance;
}
```

Listing 1: Ultrasonic Sensor Distance Measurement

1.12 IMU Integration for Direction Tracking

The MPU6050 IMU with DMP (Digital Motion Processor) provides orientation data:

```cpp
#include <MPU6050_6Axis_MotionApps20.h>

MPU6050 mpu;
bool dmpReady = false;
uint8_t fifoBuffer[64];
Quaternion q;
VectorFloat gravity;
float ypr[3];

```

```
String currentDirection = "FORWARD";
const float ROTATION_THRESHOLD = 70.0;

String getDirection(float yaw) {
  if (yaw < 45 || yaw >= 315) return "FORWARD";
  if (yaw >= 45 && yaw < 135) return "RIGHT";
  if (yaw >= 135 && yaw < 225) return "BACKWARD";
  return "LEFT";  // 225-315
}

void updateIMU() {
  if (!dmpReady) return;

  if (mpu.dmpGetCurrentFIFOPacket(fifoBuffer)) {
    mpu.dmpGetQuaternion(&q, fifoBuffer);
    mpu.dmpGetGravity(&gravity, &q);
    mpu.dmpGetYawPitchRoll(ypr, &q, &gravity);

    float yaw = ypr[0] * 180 / M_PI;
    if (yaw < 0) yaw += 360;

    String newDir = getDirection(yaw);
    float diff = fabs(yaw - directionAngle(currentDirection));
    if (diff > 180) diff = 360 - diff;

    if (newDir != currentDirection && diff >= ROTATION_THRESHOLD) {
      currentDirection = newDir;
      Serial.print("Direction: ");
      Serial.println(currentDirection);
    }
  }
}
```

Listing 2: IMU Direction Detection

1.13 Message Structure Design

The message structure for map updates is defined as a packed struct for efficient transmission:

```
#define MSG_TYPE_MAP_UPDATE  1

#define CELL_UNKNOWN   0
#define CELL_CLEAR     1
#define CELL_OBSTACLE  2

typedef struct __attribute__((packed)) {
  uint8_t type;       // Message type identifier
  uint8_t sourceId;   // Robot ID (1 or 2)
  uint8_t row;        // Grid row (1-4)
  uint8_t col;        // Grid column (1-4)
  uint8_t value;      // Cell state (UNKNOWN/CLEAR/OBSTACLE)
  uint8_t hop;        // Hop count (0=original, 1=forwarded)
} MapMessage;
```

Listing 3: Map Message Data Structure

1.14 ESP-NOW Initialization

```
#define ROBOT_ID 1

uint8_t BASE_MAC[]    = {0xCC, 0xDB, 0xA7, 0x97, 0x7B, 0x6C};
uint8_t OTHER_ROBOT_MAC[] = {0xCC, 0xDB, 0xA7, 0x97, 0x76, 0x9C};

void setup() {
  // ... sensor initialization ...

  WiFi.mode(WIFI_STA);
  WiFi.disconnect();

  if (esp_now_init() != ESP_OK) {
    Serial.println("ESP-NOW init failed");
    while (1);
  }

  esp_now_register_send_cb(onSent);
  esp_now_register_recv_cb(onReceive);

  // Add peers
  esp_now_peer_info_t peer{};
  memcpy(peer.peer_addr, OTHER_ROBOT_MAC, 6);
  peer.channel = 0;
  peer.encrypt = false;
  esp_now_add_peer(&peer);

  memcpy(peer.peer_addr, BASE_MAC, 6);
  esp_now_add_peer(&peer);
}
```

Listing 4: ESP-NOW Setup and Peer Registration

1.15 Sending Map Updates

```
void sendMapUpdate(uint8_t row, uint8_t col, uint8_t value) {
  MapMessage msg;
  msg.type     = MSG_TYPE_MAP_UPDATE;
  msg.sourceId = ROBOT_ID;
  msg.row      = row;
  msg.col      = col;
  msg.value    = value;
  msg.hop      = 0;    // Original message

  esp_now_send(OTHER_ROBOT_MAC, (uint8_t*)&msg, sizeof(msg));
}
```

Listing 5: Broadcasting Obstacle Detection

1.16 Week 1 Additional Deliverables - Core Modules

✓ Functional ultrasonic sensor reading module

✓ Working IMU direction detection with DMP

- ✓ IR sensor integration for position tracking
- ✓ ESP-NOW broadcast implementation
- ✓ Message structure design and implementation
- ✓ Tested single-robot obstacle detection system

2 Week 2: Integration & Base Station

November 24-30, 2025

2.1 Objective

Program both robots to receive broadcasted data, update internal maps, and implement re-broadcast logic for mesh communication.

2.2 ESP-NOW Receive Callback

The receive callback processes incoming map updates and triggers re-broadcast:

```
void onReceive(const esp_now_recv_info *info,
               const uint8_t *data, int len) {
  if (len != sizeof(MapMessage)) return;

  MapMessage msg;
  memcpy(&msg, data, sizeof(msg));

  if (msg.type != MSG_TYPE_MAP_UPDATE) return;
  if (msg.row < 1 || msg.row > BOARD_SIZE ||
      msg.col < 1 || msg.col > BOARD_SIZE) return;

  // Update local map
  mapGrid[msg.row][msg.col] = msg.value;

  Serial.print("[Robot] Map update from Robot ");
  Serial.print(msg.sourceId);
  Serial.print(" -> cell(");
  Serial.print(msg.row); Serial.print(",");
  Serial.print(msg.col); Serial.print(") = ");
  Serial.println(msg.value == CELL_OBSTACLE ? "OBSTACLE" : "CLEAR");

  // Forward only once, never forward our own messages
  if (msg.hop == 0 && msg.sourceId != ROBOT_ID) {
    forwardMapMessage(msg);
  }
}
```

Listing 6: ESP-NOW Data Reception Handler

2.3 Internal Map Implementation

Each robot maintains a local 4x4 grid map:

```
#define BOARD_SIZE 4

int8_t mapGrid[BOARD_SIZE + 1][BOARD_SIZE + 1];  // indices 1..4

// Robot 1 starts at (4,1), Robot 2 starts at (4,4)
int currentRow = 4;
int currentCol = 1;  // or 4 for Robot 2

void initializeMap() {
  for (int r = 1; r <= BOARD_SIZE; r++)
    for (int c = 1; c <= BOARD_SIZE; c++)
      mapGrid[r][c] = CELL_UNKNOWN;

  // Mark starting position as clear
  mapGrid[currentRow][currentCol] = CELL_CLEAR;
}
```

Listing 7: Internal Map Data Structure

2.4 Re-Broadcasting Logic

The forwarding mechanism ensures all nodes receive updates:

```
void forwardMapMessage(const MapMessage &msgIn) {
  MapMessage out = msgIn;
  out.hop = 1;  // Mark as forwarded (prevents infinite loops)

  // Re-broadcast to other robot and to base station
  esp_now_send(OTHER_ROBOT_MAC, (uint8_t*)&out, sizeof(out));
  esp_now_send(BASE_MAC, (uint8_t*)&out, sizeof(out));
}
```

Listing 8: Message Re-Broadcast Implementation

2.5 Position Tracking with IR Sensor

Movement between cells is detected by IR sensor color transitions:

```
#define IR_PIN 14

bool lastIRKnown = false;
bool lastIsWhite = false;

void updatePositionFromDirection() {
  int newRow = currentRow;
  int newCol = currentCol;

  if (currentDirection == "FORWARD")       newRow--;
  else if (currentDirection == "BACKWARD") newRow++;
  else if (currentDirection == "RIGHT")    newCol++;
  else if (currentDirection == "LEFT")     newCol--;

  // Boundary check
  if (newRow < 1 || newRow > BOARD_SIZE ||
      newCol < 1 || newCol > BOARD_SIZE) {
    Serial.println("Move would leave board, ignored");
    return;
  }

  currentRow = newRow;
  currentCol = newCol;

  if (mapGrid[currentRow][currentCol] != CELL_CLEAR) {
    mapGrid[currentRow][currentCol] = CELL_CLEAR;
    sendMapUpdate(currentRow, currentCol, CELL_CLEAR);
  }
}

// In main loop:
void checkMovement() {
  bool isWhite = digitalRead(IR_PIN);

  if (!lastIRKnown) {
    lastIsWhite = isWhite;
    lastIRKnown = true;
  } else if (isWhite != lastIsWhite) {
    // Color changed = crossed into next square
    lastIsWhite = isWhite;
    updatePositionFromDirection();
  }
}
```

Listing 9: IR-Based Movement Detection

2.6 Obstacle Detection Algorithm

The main loop continuously checks for obstacles:

```
unsigned long lastSonarMs = 0;
const unsigned long SONAR_INTERVAL_MS = 200;

void checkObstacles() {
  unsigned long now = millis();
  if (now - lastSonarMs < SONAR_INTERVAL_MS) return;
  lastSonarMs = now;

  float dist = readUltrasonicCm();
  if (dist > 0 && dist < OBSTACLE_DISTANCE_CM) {
    // Calculate obstacle position based on direction
    int r = currentRow;
    int c = currentCol;

    if (currentDirection == "FORWARD")       r--;
    else if (currentDirection == "BACKWARD") r++;
    else if (currentDirection == "RIGHT")    c++;
    else if (currentDirection == "LEFT")     c--;

    if (r >= 1 && r <= BOARD_SIZE && c >= 1 && c <= BOARD_SIZE) {
      if (mapGrid[r][c] != CELL_OBSTACLE) {
        mapGrid[r][c] = CELL_OBSTACLE;
        Serial.print("Obstacle detected at (");
        Serial.print(r); Serial.print(",");
        Serial.print(c); Serial.println(")");
        sendMapUpdate(r, c, CELL_OBSTACLE);
      }
    }
  }
}
```

Listing 10: Periodic Obstacle Scanning

2.7 Week 2 Deliverables - Part 1: Robot Integration

- ✓ Working two-robot communication system
- ✓ Internal map implementation on both robots
- ✓ Functional re-broadcast mechanism with hop counting
- ✓ IR-based movement detection
- ✓ Synchronized map between robots
- ✓ Communication protocol documentation

2.8 Base Station Implementation

In the second half of Week 2, we implemented the base station node with web-based visualization interface for real-time map monitoring.

2.9 Base Station Architecture

The base station operates in dual mode (AP + STA) to serve both ESP-NOW communication and web interface:

```
#include <WiFi.h>
#include <esp_now.h>
#include <WebServer.h>
#include <SPIFFS.h>

uint8_t ROBOT1_MAC[] = {0xCC, 0xDB, 0xA7, 0x97, 0x88, 0x58};
uint8_t ROBOT2_MAC[] = {0xCC, 0xDB, 0xA7, 0x97, 0x76, 0x9C};

WebServer server(80);

void setup() {
  Serial.begin(115200);

  // Initialize SPIFFS for web files
  if (!SPIFFS.begin(true)) {
    Serial.println("SPIFFS Mount Failed");
    return;
  }

  // Initialize 4x4 grid as unknown
  for (int r = 0; r < 4; r++)
    for (int c = 0; c < 4; c++)
      grid[r][c] = CELL_UNKNOWN;

  // Dual mode: AP for PC connection + STA for ESP-NOW
  WiFi.mode(WIFI_AP_STA);
  WiFi.softAP("RobotBase", "12345678");
  Serial.print("AP IP: ");
  Serial.println(WiFi.softAPIP());

  // ESP-NOW setup
  esp_now_init();
  esp_now_register_recv_cb(onReceive);

  // Register robot peers
  esp_now_peer_info_t peer = {};
  peer.channel = 0;
  peer.encrypt = false;

  memcpy(peer.peer_addr, ROBOT1_MAC, 6);
  esp_now_add_peer(&peer);

  memcpy(peer.peer_addr, ROBOT2_MAC, 6);
  esp_now_add_peer(&peer);

  // Web server routes
  server.on("/", handleRoot);
  server.on("/map", handleMapData);
  server.begin();
}
```

Listing 11: Base Station WiFi and ESP-NOW Setup

2.10 Base Station Map Management

```
enum CellType : uint8_t {
  CELL_UNKNOWN  = 0,
  CELL_CLEAR    = 1,
  CELL_OBSTACLE = 2,
  CELL_WHITE    = 3,
  CELL_BLACK    = 4
};

CellType grid[4][4];  // 4x4 board

struct MapMessage {
  uint8_t srcId;   // 1 = Robot1, 2 = Robot2
  uint8_t row;     // 0..3
  uint8_t col;     // 0..3
  uint8_t cell;    // CellType value
};
```

Listing 12: Map Cell Types and Grid Storage

2.11 Receive and Re-broadcast Handler

```
void onReceive(const esp_now_recv_info *info,
               const uint8_t *data, int len) {
  if (len != sizeof(MapMessage)) {
    Serial.println("Unexpected packet size");
    return;
  }

  MapMessage msg;
  memcpy(&msg, data, sizeof(msg));

  if (msg.row >= 4 || msg.col >= 4) {
    Serial.println("Invalid coordinates");
    return;
  }

  // Update grid
  grid[msg.row][msg.col] = static_cast<CellType>(msg.cell);

  Serial.print("Update from Robot ");
  Serial.print(msg.srcId);
  Serial.print(" -> cell (");
  Serial.print(msg.row + 1); Serial.print(",");
  Serial.print(msg.col + 1); Serial.print(") = ");
  Serial.println(msg.cell);

  // Re-broadcast to both robots
  esp_now_send(ROBOT1_MAC, data, len);
  esp_now_send(ROBOT2_MAC, data, len);
}
```

Listing 13: Base Station Receive Callback

2.12 Web API Endpoint

```
void handleMapData() {
  String json = "{\"grid\":[";

  for (int r = 0; r < 4; r++) {
    json += "[";
    for (int c = 0; c < 4; c++) {
      json += String((int)grid[r][c]);
      if (c < 3) json += ",";
    }
    json += "]";
    if (r < 3) json += ",";
  }

  json += "]}";
  server.send(200, "application/json", json);
}

void handleRoot() {
  File file = SPIFFS.open("/index.html", "r");
  if (!file) {
    server.send(404, "text/plain", "File not found");
    return;
  }
  server.streamFile(file, "text/html");
  file.close();
}

void loop() {
  server.handleClient();
}
```

Listing 14: JSON Map Data API

2.13 Web Interface

The web interface provides real-time visualization with automatic polling:

```javascript
// Cell type constants (match Arduino enum)
const CELL_UNKNOWN = 0;
const CELL_CLEAR = 1;
const CELL_OBSTACLE = 2;

async function updateGrid() {
  const res = await fetch('/map');
  const data = await res.json();

  for (let r = 0; r < 4; r++) {
    for (let c = 0; c < 4; c++) {
      const cell = document.getElementById(`cell-${r}-${c}`);
      const cellType = data.grid[r][c];

      cell.className = 'cell';
      switch(cellType) {
        case CELL_CLEAR:
          cell.textContent = 'OK';
          cell.style.background = 'green';
          break;
        case CELL_OBSTACLE:
          cell.classList.add('obstacle');
          cell.textContent = 'X';
          break;
        default:
          cell.textContent = '?';
      }
    }
  }
}

// Update every 2 seconds
setInterval(updateGrid, 2000);
```

Listing 15: Grid Visualization (JavaScript excerpt)

2.14 Week 2 Deliverables - Part 2: Base Station

- ✓ Base station ESP-NOW receiver implementation
- ✓ Web server with SPIFFS file serving
- ✓ Real-time JSON API for map data
- ✓ Responsive web interface with grid visualization
- ✓ Re-broadcast logic from base to robots
- ✓ Dual-mode WiFi (AP + STA) configuration

3 Week 3: Final Testing & Documentation

December 1-7, 2025

3.1 Objective

Demonstrate the complete system with robots coordinating to map an area, detect obstacles, and share information in real-time.

3.2 Complete Robot Node Code

```
void loop() {
  // 1) Update orientation from IMU
  updateIMU();

  // 2) Detect movement via IR color transitions
  bool isWhite = digitalRead(IR_PIN);
  if (!lastIRKnown) {
    lastIsWhite = isWhite;
    lastIRKnown = true;
  } else if (isWhite != lastIsWhite) {
    lastIsWhite = isWhite;
    updatePositionFromDirection();
  }

  // 3) Periodically check ultrasonic for obstacles
  unsigned long now = millis();
  if (now - lastSonarMs >= SONAR_INTERVAL_MS) {
    lastSonarMs = now;
    float dist = readUltrasonicCm();

    if (dist > 0 && dist < OBSTACLE_DISTANCE_CM) {
      int r = currentRow, c = currentCol;

      if (currentDirection == "FORWARD")       r--;
      else if (currentDirection == "BACKWARD") r++;
      else if (currentDirection == "RIGHT")    c++;
      else if (currentDirection == "LEFT")     c--;

      if (r >= 1 && r <= BOARD_SIZE &&
          c >= 1 && c <= BOARD_SIZE) {
        if (mapGrid[r][c] != CELL_OBSTACLE) {
          mapGrid[r][c] = CELL_OBSTACLE;
          sendMapUpdate(r, c, CELL_OBSTACLE);
        }
      }
    }
  }

  delay(20);
}
```

Listing 16: Robot Node Main Loop

3.3 System Test Scenarios

3.3.1 Test 1: Single Robot Obstacle Detection

Note

Description: Robot 1 moves forward and detects an obstacle.
Expected: Robot 1 broadcasts obstacle location to Robot 2 and Base.
Result: Successful. Obstacle appears on web interface within 2 seconds.

3.3.2 Test 2: Bidirectional Communication

Note

Description: Robot 2 detects obstacle while Robot 1 is exploring.
Expected: Robot 2 sends to Robot 1, Robot 1 updates map and re-broadcasts.
Result: Successful. Both robots maintain synchronized maps.

3.3.3 Test 3: Full System Integration

Note

Description: Both robots explore the grid simultaneously.
Expected: All three nodes maintain consistent map state.
Result: Successful. Web interface shows real-time updates from both robots.

3.4 Protocol Summary

Information

Network Topology: Mesh-like with 3 nodes (2 robots + 1 base station)
Message Format: 6-byte packed struct (type, sourceId, row, col, value, hop)
Re-broadcast Rule: Forward messages with hop=0 from other robots (set hop=1)
Update Rate: Obstacle check every 200ms, web refresh every 2000ms

3.5 Performance Metrics

Metric	Measured Value	Notes
Communication Range	>50m (line of sight)	ESP-NOW specification
Message Latency	<10ms	Peer-to-peer
Obstacle Detection Range	15cm	Configurable threshold
IMU Update Rate	100Hz	DMP processing
Web Refresh Rate	2 seconds	Configurable
Grid Size	4x4 (16 cells)	Expandable

3.6 Week 3 Deliverables

- ✓ Complete system demonstration
- ✓ Final tested code for all three nodes
- ✓ Comprehensive protocol documentation
- ✓ Test results and performance metrics
- ✓ Web-based visualization interface
- ✓ Final project report

4 Conclusion

4.1 Project Summary

This project successfully implemented a wireless sensor network for robotic fleet coordination using ESP32 microcontrollers and the ESP-NOW protocol. The system demonstrates:

- Real-time obstacle detection and sharing between two mobile robots
- Mesh-like communication with automatic re-broadcasting
- Web-based visualization for monitoring the shared map
- Integration of multiple sensors (ultrasonic, IR, IMU) for navigation

4.2 Technical Contributions

- Designed efficient 6-byte message format for low-latency communication
- Implemented hop-count mechanism to prevent broadcast storms
- Created dual-mode WiFi configuration for simultaneous ESP-NOW and web serving
- Developed IMU-based direction detection using DMP quaternion processing

4.3 Limitations and Future Work

- Current system uses manual robot control; autonomous navigation could be added
- Grid size is fixed at 4x4; dynamic grid sizing would improve flexibility
- No acknowledgment mechanism; adding ACKs would improve reliability
- Single-hop forwarding; multi-hop routing could extend range

4.4 Acknowledgments

We would like to express our sincere gratitude to:

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5 References

1. ESP-NOW Protocol Documentation. Espressif Systems. https://www.espressif.com/
2. “ESPNOW for beginners! #ESP32 #ESP8266” Tutorial Video. https://www.youtube.com/watch?v=Ydi0M3Xd_vs
3. Egyptian Knowledge Bank (EKB). https://www.ekb.eg/
4. Arduino ESP32 Documentation. https://docs.arduino.cc/
5. MPU6050 Library Documentation. https://github.com/jrowberg/i2cdevlib
6. ESP32 WebServer Library. https://github.com/espressif/arduino-esp32

A MAC Addresses

Node	MAC Address
Robot 1	CC:DB:A7:97:88:58
Robot 2	CC:DB:A7:97:76:9C
Base Station	CC:DB:A7:97:7B:6C

B Pin Configuration Summary

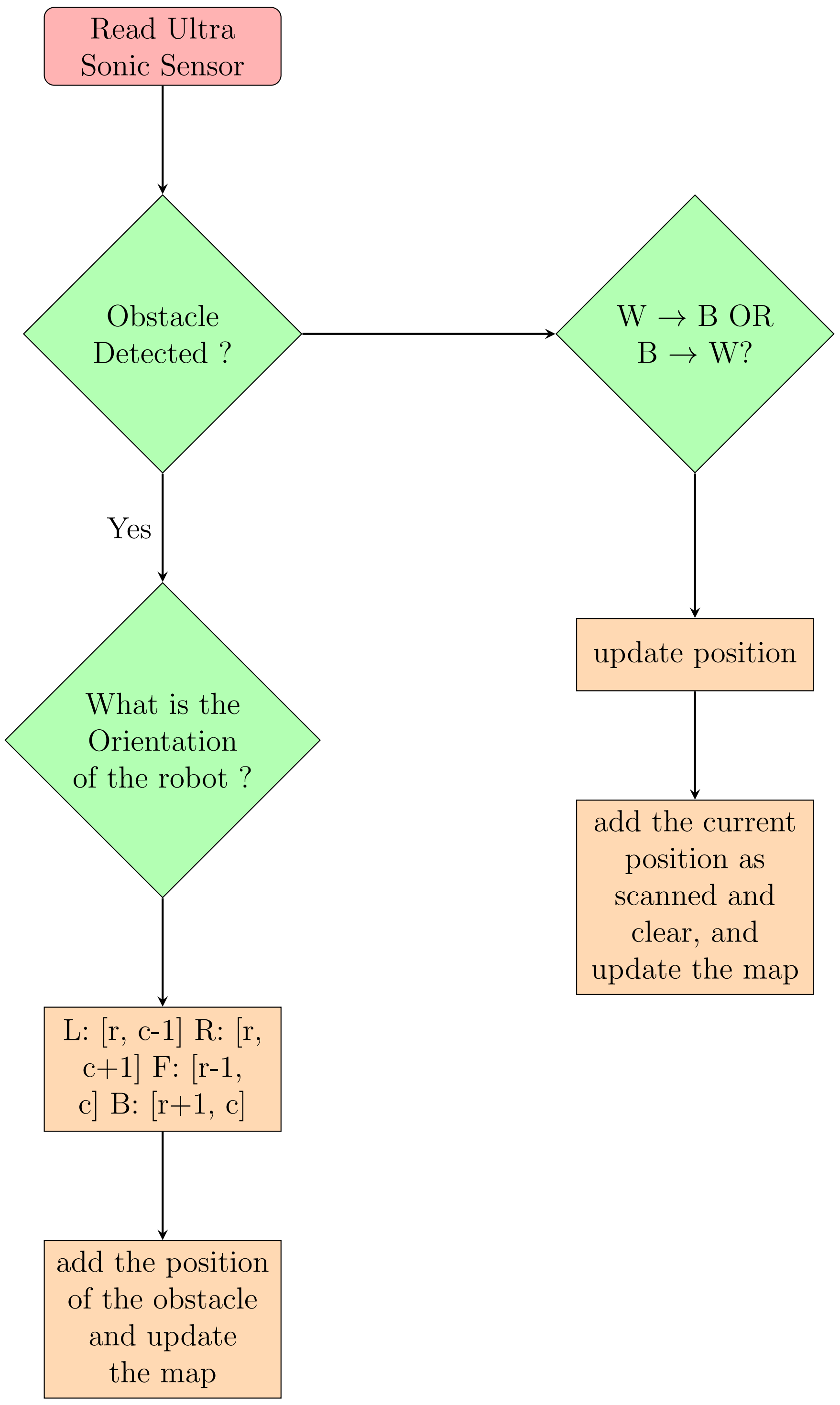
Component	GPIO	Type	Notes
IR Sensor	14	Input	White=HIGH, Black=LOW
Ultrasonic Trigger	26	Output	10μs pulse
Ultrasonic Echo	27	Input	Measure duration
I2C SDA (MPU6050)	12	I2C	Data line
I2C SCL (MPU6050)	13	I2C	Clock line

C Flow Diagram Description

The robot operation follows this algorithm:

1. Read ultrasonic sensor
2. If obstacle detected (<15cm):
   (a) Determine obstacle position based on current direction
   (b) Add to internal map
   (c) Broadcast update to network
3. Check IR sensor for color change (W→B or B→W)
4. If color changed:
   (a) Update position based on direction
   (b) Mark new cell as CLEAR
   (c) Broadcast update to network
5. Repeat

D System Flow Diagram


Read Ultra Sonic Sensor
Obstacle Detected ?
W → B OR B → W?
Yes
What is the Orientation of the robot ?
update position
add the current position as scanned and clear, and update the map
L: [r, c-1] R: [r, c+1] F: [r-1, c] B: [r+1, c]
add the position of the obstacle and update the map