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Chapter 1

Introduction

1.1 Project Overview

This project focuses on the design and implementation of an autonomous 4-wheel drive (4WD) robot capable of navigating its environment while detecting and avoiding obstacles. The robot utilizes a PIC18F45K22 microcontroller as its central processing unit, an HC-SR04 ultrasonic sensor for distance measurement, E18-D80NK infrared proximity sensors for immediate obstacle detection, and a servo motor to allow for a wider field of detection. The robot's mobility is achieved through four DC motors driven by an L298N motor driver.

Figure 1.1: Front view of the 4WD robot with HC-SR04 ultrasonic sensor and E18-D80NK infrared sensors

Autonomous mobile robots have become increasingly important in various fields such as industrial automation, search and rescue operations, home assistance, and educational platforms. The ability to navigate unknown environments while avoiding obstacles is a fundamental requirement for these robots to operate effectively and safely.

This project implements a reactive obstacle avoidance algorithm, where the robot continuously scans its surroundings using the ultrasonic sensor mounted on a servo and makes immediate decisions based on detected obstacles. When an obstacle is detected within a certain threshold distance, the robot stops, scans the environment by rotating the servo, and changes its direction to avoid the obstacle. The addition of E18-D80NK infrared sensors enhances the robot's ability to detect obstacles at closer ranges and provides redundancy in the sensing system.

1.2 Objectives

The main objectives of this project are:

1. To design and build a 4WD robot platform controlled by a PIC18F45K22 microcontroller
2. To implement motor control using PWM signals for variable speed control
3. To integrate multiple sensor types (ultrasonic and infrared) for robust obstacle detection
4. To incorporate a servo motor to expand the field of detection
5. To develop an obstacle avoidance algorithm that allows the robot to navigate autonomously
6. To achieve reliable performance in various environmental conditions

1.3 System Requirements

The system requirements for the 4WD robot are as follows:

1. **Hardware Requirements:**
    - PIC18F45K22 microcontroller for overall system control
    - LAFVIN 4-wheel car robot chassis
    - L298N motor driver module for controlling the DC motors
    - Four DC motors for mobility
    - HC-SR04 ultrasonic sensor for distance measurement

- Two E18-D80NK infrared proximity sensors for close-range obstacle detection
- SG90 servo motor for sensor positioning
- Battery pack for power supply

2. **Software Requirements:**
    - Motor control algorithm for precise movement
    - PWM generation for variable speed control
    - Servo positioning algorithm
    - Distance measurement algorithm using the HC-SR04 sensor
    - Obstacle detection using E18-D80NK infrared sensors
    - Obstacle avoidance algorithm with sensor fusion
3. **Performance Requirements:**
    - Detect obstacles up to at least 3 meters away using the ultrasonic sensor
    - Detect close obstacles within 80cm using the infrared sensors
    - Avoid obstacles reliably by changing direction
    - Maintain smooth movement at variable speeds
    - Operate continuously for at least 30 minutes on a single battery charge

1.4 Applications and Significance

The development of an autonomous robot with obstacle avoidance capabilities has significant applications and implications across various domains:

1.4.1 Educational Applications

This project serves as an excellent educational platform for understanding microcontroller programming, sensor integration, motor control, and autonomous navigation algorithms. It provides hands-on experience with embedded systems and robotics concepts.

1.4.2 Industrial Applications

In industrial settings, autonomous robots can be used for material handling, warehouse management, and inspections in hazardous environments. The obstacle avoidance capability is crucial for preventing collisions and ensuring safe operation.

1.4.3 Research and Development

The project provides a foundation for further research in autonomous navigation, sensor fusion, and artificial intelligence in robotics. The platform can be extended to incorporate more advanced features such as mapping, localization, and path planning.

1.4.4 Consumer Applications

The principles and technologies employed in this project are similar to those used in consumer robots like robotic vacuum cleaners, lawn mowers, and delivery robots, all of which require reliable obstacle detection and avoidance.

Figure 1.2: Top view of the 4WD robot showing component arrangement

Chapter 2

Hardware Components

2.1 PIC18F45K22 Microcontroller

The PIC18F45K22 microcontroller serves as the brain of the robot, responsible for processing sensor data, controlling the motors, and implementing the obstacle avoidance algorithm. It is a powerful 8-bit microcontroller from Microchip Technology with several features that make it suitable for this application.

2.1.1 Key Features

- 16 MIPS (Million Instructions Per Second) performance at 64 MHz
- 32 KB Flash program memory
- 1536 bytes RAM
- 256 bytes EEPROM data memory
- Up to 35 I/O pins
- Multiple PWM modules for motor control
- Multiple Timer modules for timing operations
- 10-bit Analog-to-Digital Converter (ADC)
- Communication interfaces including UART, SPI, and I²C

2.1.2 Pin Configuration

The PIC18F45K22 is available in 40-pin DIP, 44-pin TQFP, and 44-pin QFN packages. For this project, we used the 40-pin DIP package for ease of prototyping. Figure 2.1 shows the pin diagram of the PIC18F45K22 microcontroller.

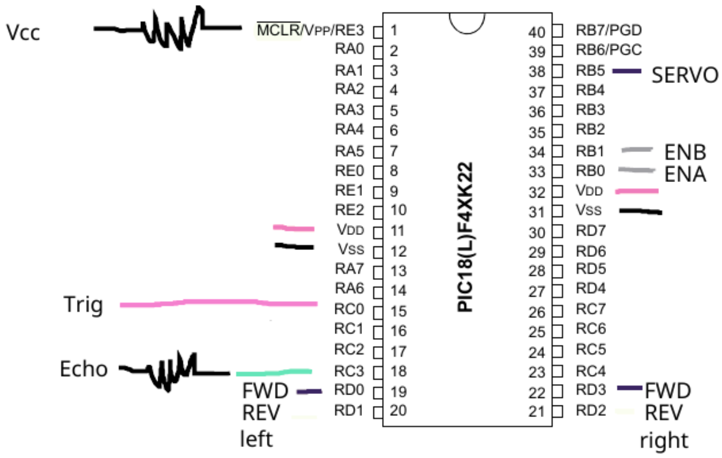

Figure 2.1: PIC18F45K22 Pin Diagram

2.1.3 Internal Oscillator

One of the advantages of the PIC18F45K22 is its internal oscillator, which can operate at different frequencies. For this project, we configured the internal oscillator to run at 16 MHz, providing sufficient processing power for our application without the need for an external crystal.

```
// Configure 16 MHz internal oscillator
OSCCON = 0b01110000;        // Set to 16MHz (IRCF = 111)
OSCTUNEbits.PLLEN = 0;      // Disable PLL for now
while (!OSCCONbits.HFIOFS);  // Wait for oscillator stability
```

Listing 2.1: Internal Oscillator Configuration

The OSCCON register is set to 0b01110000, which configures the internal oscillator frequency control bits (IRCF¡2:0¿) to 111, selecting the 16 MHz frequency. The PLL is disabled, and the code waits for the oscillator to stabilize before proceeding.

2.1.4 Timer Modules

The PIC18F45K22 has multiple timer modules. In this project, we used Timer1 for measuring the echo pulse duration in the ultrasonic sensor and Timer2 for generating PWM signals for motor control.

```
// Configure Timer1 for ultrasonic sensor
T1CONbits.T1CKPS = 0b00;      // 1:1 prescaler
T1CONbits.TMR1CS = 0b00;      // Internal clock (FOSC/4)
T1CONbits.T1RD16 = 1;         // 16-bit read/write mode
T1CONbits.TMR1ON = 0;         // Timer off initially
```

Listing 2.2: Timer1 Configuration for Ultrasonic Sensor

Timer1 is configured with a 1:1 prescaler and is clocked from the internal clock (FOSC/4). The 16-bit read/write mode is enabled to allow atomic access to the 16-bit timer value, which is crucial for accurate timing measurements.

2.2 L298N Motor Driver

The L298N is a dual H-bridge motor driver module capable of driving two DC motors independently. It can handle motor supply voltages between 5V and 35V and can deliver up to 2A per channel.

2.2.1 Key Features

- Dual H-bridge driver
- Operating voltage range: 5V to 35V
- Peak current: up to 2A per channel
- PWM control for variable speed
- Direction control for each motor
- Built-in 5V regulator (when supply voltage ¿ 7.5V)

- Heat sink for better thermal dissipation

2.2.2 Pin Configuration

The L298N module typically has the following pins:

- Power input pins (VCC, GND)
- Logic control pins (IN1, IN2, IN3, IN4)
- PWM input pins (ENA, ENB)
- Motor output pins (OUT1, OUT2, OUT3, OUT4)
- 5V regulator enable jumper

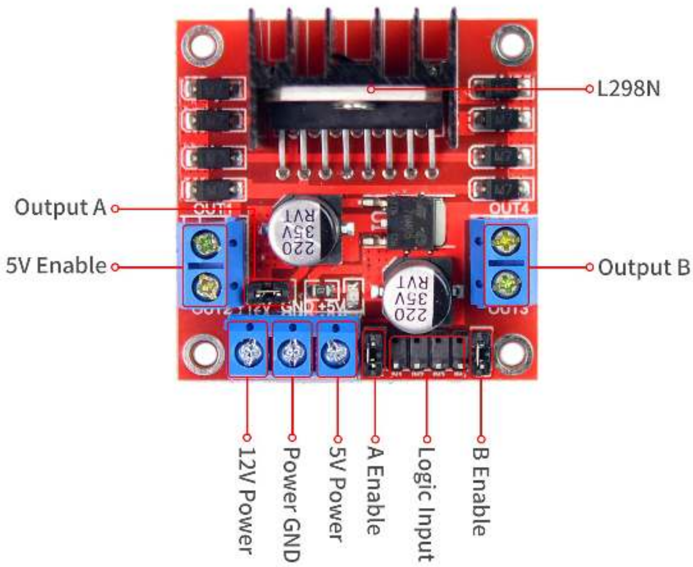

Figure 2.2: L298N Motor Driver Module Pin Configuration

2.2.3 Operation Principle

The L298N driver uses an H-bridge configuration to control the direction of current flow through the motors. By controlling the states of the input pins, we can determine the direction of the motors, and by applying PWM signals to the enable pins, we can control the speed.

In our implementation, we connected two motors in parallel for each side of the robot (left and right), effectively treating them as single motors. The direction control pins (IN1-IN4) of the L298N are connected to the PIC18F45K22's output pins RD0-RD3, and the enable pins (ENA, ENB) are connected to the PWM outputs (CCP1 and CCP2) of the microcontroller.

Table 2.1: L298N Control Signals for Different Motor Operations

Operation	**ENA**	**IN1**	**IN2**	**ENB**	**IN3**	**IN4**
Forward	PWM	1	0	PWM	1	0
Backward	PWM	0	1	PWM	0	1
Turn Left	PWM	0	1	PWM	1	0
Turn Right	PWM	1	0	PWM	0	1
Stop	0	0	0	0	0	0

Figure 2.3: Left side view of the 4WD robot

2.3 HC-SR04 Ultrasonic Sensor

The HC-SR04 is an ultrasonic distance sensor commonly used in robotics projects for obstacle detection. It measures distance by emitting ultrasonic pulses and measuring the time it takes for the echo to return after reflecting off an object.

2.3.1 Key Features

- Operating voltage: 5V DC
- Current consumption: 15mA
- Detection range: 2cm to 400cm
- Resolution: 0.3cm
- Measuring angle: 15 degrees
- Operating frequency: 40kHz

2.3.2 Pin Configuration

The HC-SR04 sensor has four pins:

- VCC: Power supply (5V)
- Trig: Trigger pulse input
- Echo: Echo pulse output
- GND: Ground

2.3.3 Working Principle

The HC-SR04 works based on the principle of sound wave reflection. It sends out a high-frequency sound pulse and then listens for the echo. By measuring the time between sending the trigger pulse and receiving the echo, and knowing the speed of sound in air, the sensor can calculate the distance to the object.

The working sequence of the HC-SR04 sensor is as follows:

1. Send a 10µs high pulse to the Trig pin
2. The sensor automatically sends eight 40kHz ultrasonic pulses
3. If an obstacle is detected, the Echo pin outputs a high-level signal with duration proportional to the distance

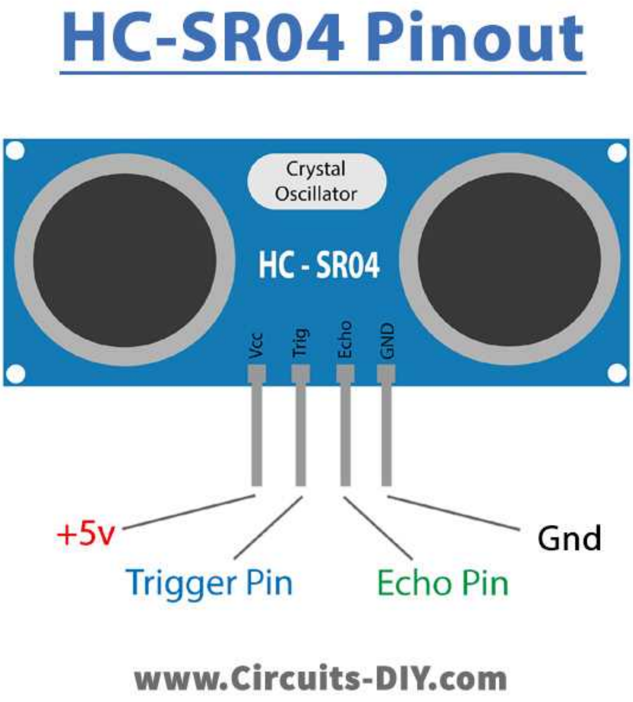

Figure 2.4: HC-SR04 Ultrasonic Sensor

4. Calculate the distance using the formula: Distance = (Echo pulse duration × Speed of sound) / 2

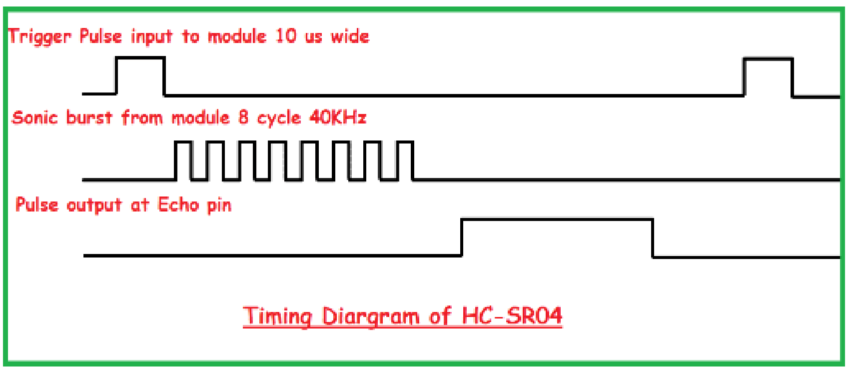

Figure 2.5: HC-SR04 Timing Diagram

2.3.4 Implementation in the Project

In our project, the HC-SR04 sensor is connected to the PIC18F45K22 microcontroller. The Trig pin is connected to RC0 (output), and the Echo pin is connected to RC3 (input).

The measurement of distance is implemented in the ‘measureDistance()‘ function:

```c
unsigned int measureDistance(void) {
    unsigned int pulse_ticks = 0;
    unsigned int ddistance = 0;  // Local variable for calculated distance

    // Reset Timer1
    TMR1H = 0;
    TMR1L = 0;
    PIR1bits.TMR1IF = 0;

    // Generate 10us trigger pulse
    TRIGGER = 0;
    Nop();
    Nop();
    TRIGGER = 1;
    Delay10TCYx(10);  // 10us pulse (at 16MHz)
    TRIGGER = 0;

    // Wait for echo pulse to start
    while (!ECHO) {}
    T1CONbits.TMR1ON = 1;  // Start timer
    while (ECHO) {}         // Wait for echo to end
    T1CONbits.TMR1ON = 0;  // Stop timer

    // Calculate pulse duration
    pulse_ticks = (unsigned int)TMR1L;
    pulse_ticks |= ((unsigned int)TMR1H << 8);

    // Convert to distance (cm)
    // Sound travels at 343m/s, which is 34300cm/s or 0.0343cm/us
    // For 2-way travel: d = (t * 0.0343) / 2 = t / 58
    ddistance = pulse_ticks / 58;
    return ddistance;
}
```

Listing 2.3: Distance Measurement Implementation

In this implementation, we first reset Timer1 and clear the Timer1 interrupt flag. Then, we generate a 10µs trigger pulse by setting the TRIGGER pin high for 10 instruction cycles. After that, we wait for the echo pulse to start, start Timer1, and wait for the echo pulse to end. Finally, we read the timer value, which represents the echo pulse duration, and convert it to distance in centimeters by dividing by 58 (derived from the speed of sound and the two-way travel).

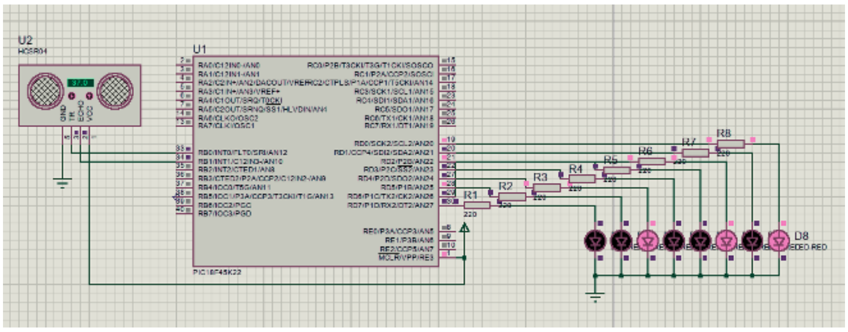

Figure 2.6: Simulation of HC-SR04 with Distance = 37cm

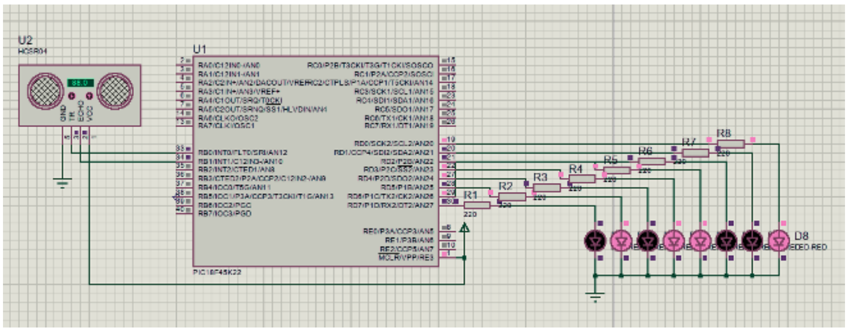

Figure 2.7: Simulation of HC-SR04 with Distance = 88cm

2.4 E18-D80NK Infrared Proximity Sensors

To enhance the obstacle detection capabilities of our robot, we added two E18-D80NK infrared proximity sensors to the front of the robot. These sensors provide more immediate detection of obstacles at closer ranges than the ultrasonic sensor.

2.4.1 Key Features

- Operating voltage: 5V DC
- Current consumption: ¡25mA

- Detection range: Adjustable from 3cm to 80cm
- Response time: ¡2ms
- Output type: Digital (LOW when obstacle detected)
- Beam angle: Approximately 15 degrees
- Infrared emission wavelength: 940nm

2.4.2 Pin Configuration

The E18-D80NK sensor has three pins:

- Brown wire: Power supply (5V)
- Blue wire: Ground (GND)
- Black wire: Signal output (OUT)

2.4.3 Working Principle

The E18-D80NK works on the principle of infrared reflection. It consists of an infrared transmitter and a receiver. The transmitter emits infrared light, and if an obstacle is present, the light reflects back and is detected by the receiver. When an obstacle is detected within the set range, the sensor's output pin goes LOW.

The detection range can be adjusted using a small potentiometer on the sensor. This allows us to set the sensor to trigger at the desired distance, making it versatile for different environments and applications.

2.4.4 Implementation in the Project

In our project, we mounted two E18-D80NK sensors on the front of the robot, one angled slightly to the left and the other to the right. This arrangement provides better coverage for detecting obstacles in the robot's path. The output pins of the sensors are connected to digital input pins of the PIC18F45K22 microcontroller.

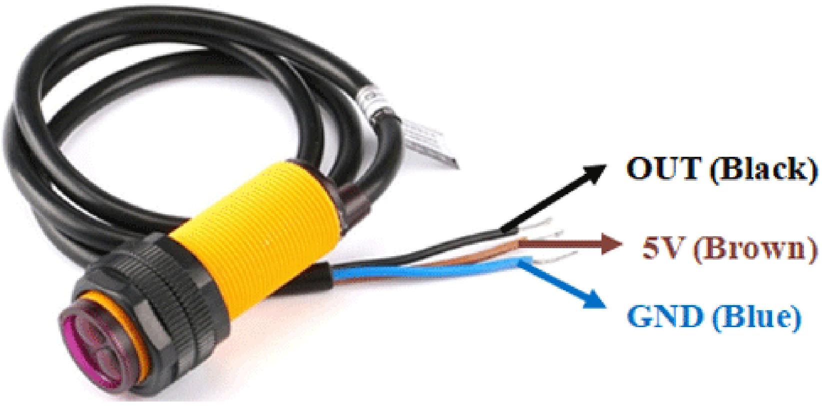

Figure 2.8: E18-D80NK Infrared Sensor Pin Configuration

The sensor outputs are read directly in the main loop of the program, and if either sensor detects an obstacle, the robot takes immediate evasive action. This provides a quick response to close obstacles, supplementing the longer-range detection provided by the ultrasonic sensor.

```
// Define IR sensor pins
#define IR_SENSOR_LEFT      PORTBbits.RB1
#define IR_SENSOR_RIGHT     PORTBbits.RB2

// In the main loop:
if (!IR_SENSOR_LEFT || !IR_SENSOR_RIGHT) {
    // Obstacle detected by IR sensors - take immediate action
    stopMotors();
    delay_ms(200);
    moveBackward(MAX_SPEED);
    delay_ms(300);
    // Continue with evasive maneuver...
}
```

Listing 2.4: IR Sensor Reading Implementation

The sensors are configured with a detection range of approximately 30cm, providing an immediate stop when obstacles are detected at this close range. This helps prevent collisions in situations where the ultrasonic sensor might not detect an obstacle quickly enough, such as when the robot is moving at high speed or when the obstacle is outside the ultrasonic sensor's scanning angle.

Figure 2.9: Right side view of the 4WD robot showing the E18-D80NK IR sensor mounting

2.5 SG90 Servo Motor

The SG90 is a small and lightweight servo motor commonly used in hobbyist electronics and robotics projects. It allows for precise angular control, making it suitable for positioning the ultrasonic sensor.

Figure 2.10: SG90 Servo Motor

2.5.1 Key Features

- Operating voltage: 4.8V to 6V
- Weight: 9g
- Dimensions: 22.2 × 11.8 × 31 mm
- Stall torque: 1.8 kgf·cm at 4.8V
- Operating speed: 0.1 sec/60 degrees at 4.8V
- Rotation range: approximately 180 degrees
- Control system: PWM (Pulse Width Modulation)

2.5.2 Working Principle

The SG90 servo motor is controlled by sending a PWM signal with a period of approximately 20ms. The pulse width determines the angle of rotation:

- 1ms pulse: 0 degrees (right position)
- 1.5ms pulse: 90 degrees (center position)
- 2ms pulse: 180 degrees (left position)

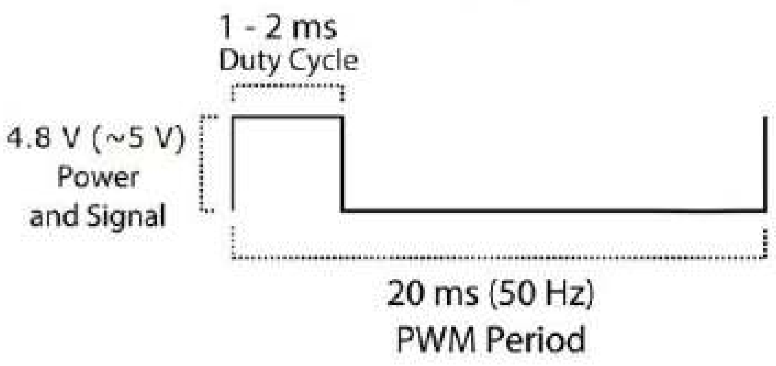

Figure 2.11: SG90 Servo Control Signal

2.5.3 Implementation in the Project

In our project, the SG90 servo is used to rotate the ultrasonic sensor, allowing the robot to scan for obstacles in different directions. The servo is connected to pin RB5 of the PIC18F45K22 microcontroller.

The control of the servo is implemented in the ‘setServoDegree()‘ function:

```c
void setServoDegree(unsigned char angle) {
    unsigned int pulse_us = 0;

    // Convert angle to pulse width
    // SG90 servo expects:
    // - ~1ms pulse for 0 degrees (right)
    // - ~1.5ms pulse for 90 degrees (center)
    // - ~2ms pulse for 180 degrees (left)
    // Our implementation uses shorter pulses that work with this specific servo
    if (angle == 0) {
        pulse_us = 90;          // Right position
    } else if (angle == 90) {
        pulse_us = 270;         // Center position
    } else if (angle == 180) {
        pulse_us = 365;         // Left position
    }

    // Generate servo pulse
    SERVO_PIN = 1;
    delay_us(pulse_us);
    SERVO_PIN = 0;
    delay_us(3625 - pulse_us);  // Complete 20ms cycle
}
```

Listing 2.5: Servo Control Implementation

In this implementation, we convert the desired angle (0, 90, or 180 degrees) to a pulse width that works with our specific SG90 servo. Then, we generate the pulse by setting the servo pin high for the calculated duration and low for the remaining part of the 20ms period.

It's worth noting that the pulse widths used (90µs, 270µs, and 365µs) are shorter than the standard values mentioned earlier. This is because our specific servo has been calibrated to respond to these shorter pulses, which still provide the full range of motion.

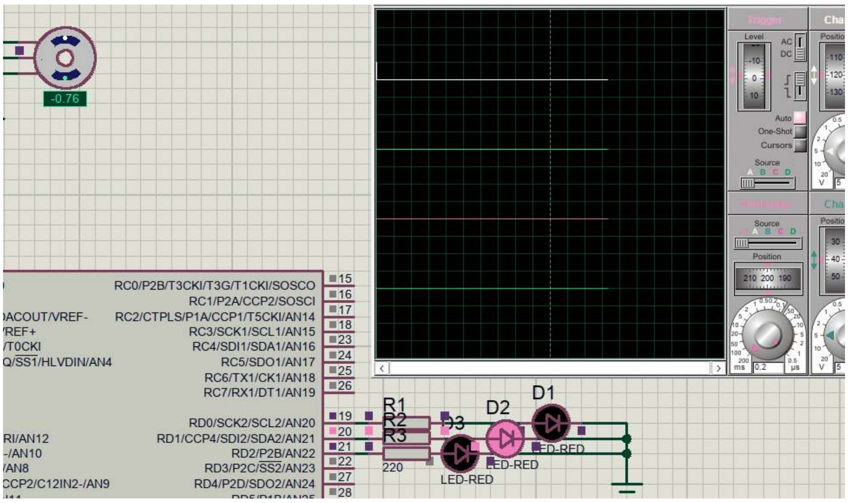

Figure 2.12: Simulation of SG90 Servo at 0 Degrees (Right Position)

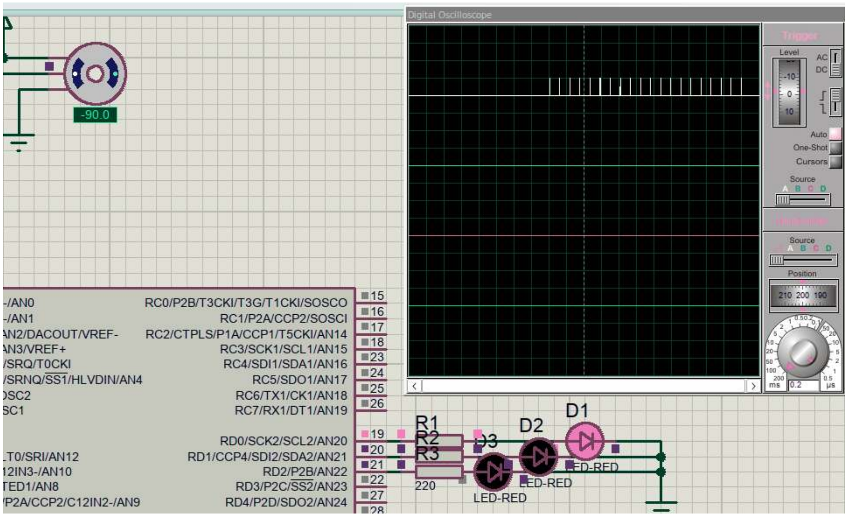

Figure 2.13: Simulation of SG90 Servo at 90 Degrees (Center Position)

2.6 DC Motors and Chassis

The robot uses four DC motors mounted on a LAFVIN chassis for mobility. The motors are geared down to provide sufficient torque for the robot's movement.

2.6.1 DC Motor Specifications

- Operating voltage: 3-6V DC
- No-load speed: approximately 200 RPM at 6V
- Stall current: approximately 0.5A
- Gear ratio: 1:48
- Built-in gearbox for increased torque

2.6.2 Chassis Design

The LAFVIN chassis is a popular platform for educational robotics projects. It features:

- Durable acrylic construction
- Mounting holes for various components
- Space for a battery pack
- Mounting brackets for motors
- Rubber wheels for better traction

Figure 2.14: Rear view of the 4WD robot showing the motor arrangement

2.7 Power Supply

The robot is powered by a battery pack that provides the necessary voltage for all components. The power distribution is as follows:

- Motor power supply: 7.4V (from battery pack)
- Logic power supply: 5V (regulated from battery pack)
- Microcontroller, sensors, and servo: 5V

The L298N motor driver has a built-in 5V regulator that can be used to power the logic circuitry when the supply voltage is greater than 7.5V. However, it's recommended to use a separate 5V regulator for more reliable operation, especially when servos are involved, as they can draw significant current during operation.

Chapter 3

Circuit Design

3.1 System Block Diagram

Figure 3.1 shows the overall block diagram of the 4WD robot system.

Figure 3.1: System Block Diagram

The system consists of several key components:

- PIC18F45K22 microcontroller: The central processing unit that controls all aspects of the robot
- HC-SR04 ultrasonic sensor: Measures the distance to obstacles
- E18-D80NK infrared sensors: Provide immediate detection of close obstacles
- SG90 servo motor: Rotates the ultrasonic sensor for wider scanning
- L298N motor driver: Controls the DC motors

- Four DC motors: Provide the robot's mobility
- Power supply: Provides the necessary voltage for all components

3.2 Pin Configuration and Connections

Table 3.1 shows the connections between the PIC18F45K22 microcontroller and the other components.

Table 3.1: Pin Connections

Component	Component Pin	PIC18F45K22 Pin
L298N Motor Driver	IN1	RD0
	IN2	RD1
	IN3	RD2
	IN4	RD3
	ENA	RC1 (CCP2)
	ENB	RC2 (CCP1)
HC-SR04 Ultrasonic Sensor	Trig	RC0
	Echo	RC3
SG90 Servo Motor	Signal	RB5
E18-D80NK IR Sensors	Left Sensor Out	RB1
	Right Sensor Out	RB2

3.3 Power Distribution

The power distribution in the system is critical for proper operation. The battery pack provides 7.4V, which is used directly for the motor power supply. The 5V required for the logic circuitry, microcontroller, sensors, and servo is obtained from a 5V regulator.

It's important to note that adequate decoupling capacitors should be used near the power pins of the microcontroller and other ICs to filter out noise and ensure stable operation. Typically, 0.1µF ceramic capacitors are used for high-frequency noise filtering, and larger electrolytic capacitors (10-100µF) are used for low-frequency filtering and to handle current spikes.

Chapter 4

Software Implementation

4.1 Code Structure and Organization

The software for the 4WD robot is organized into several functional blocks:

- Initialization functions: Set up the microcontroller and peripherals
- Motor control functions: Control the movement of the robot
- Sensor functions: Measure distance and control servo position
- Utility functions: Provide timing operations
- Main program: Implement the obstacle avoidance algorithm

The code follows a structured approach with clearly defined functions and constants, making it easier to understand and modify.

4.1.1 Constants and Definitions

Constants and pin definitions are declared at the beginning of the code for easy reference and modification:

```
// Motor control pins (connected to L298N)
#define MOTOR_LEFT_FWD      LATDbits.LATD0
#define MOTOR_LEFT_REV      LATDbits.LATD1
#define MOTOR_RIGHT_FWD     LATDbits.LATD2
#define MOTOR_RIGHT_REV     LATDbits.LATD3

// Ultrasonic sensor pins (HC-SR04)
#define TRIGGER             LATCbits.LATC0
```

```
#define ECHO                PORTCbits.RC3

// IR sensor pins (E18-D80NK)
#define IR_SENSOR_LEFT      PORTBbits.RB1
#define IR_SENSOR_RIGHT     PORTBbits.RB2

// Servo motor pin (SG90)
#define SERVO_PIN           LATBbits.LATB5
#define SERVO_TRIS          TRISBbits.TRISB5

// Distance thresholds (cm)
#define STOP_DISTANCE       20    // Stop and take action when obstacle
    is within this distance
#define SLOW_DISTANCE       40    // Slow down when obstacle is within
    this distance
#define SAFE_DISTANCE       70    // Consider it safe when obstacle is
    beyond this distance

// Speed settings (PWM duty cycle values)
#define MAX_SPEED           100   // Maximum motor speed
#define SLOW_SPEED          40    // Reduced speed for cautious
    navigation
#define MIN_SPEED           60    // Minimum effective speed for
    movement
```

Listing 4.1: Constants and Definitions

4.1.2 Function Prototypes

Function prototypes are declared to define the interface of each function:

```
// Initialization functions
void setup(void);
void configureIO(void);
void configurePWM(void);

```

```
// Motor control functions
void setPWMDuty(unsigned char left, unsigned char right);
void moveForward(unsigned char speed);
void moveBackward(unsigned char speed);
void turnLeft(unsigned char speed);
void turnRight(unsigned char speed);
void stopMotors(void);

// Sensor functions
unsigned int measureDistance(void);
void setServoDegree(unsigned char angle);
unsigned char checkIRSensors(void);

// Utility functions
void delay_us(unsigned int us);
void delay_ms(unsigned int ms);
void delay_mss(unsigned int ms);
```

Listing 4.2: Function Prototypes

4.2 PWM Generation for Motor Control

Pulse-Width Modulation (PWM) is used to control the speed of the DC motors. The PIC18F45K22 has multiple CCP (Capture/Compare/PWM) modules that can generate PWM signals.

4.2.1 PWM Configuration

The PWM functionality is configured in the ‘configurePWM()‘ function:

```
void configurePWM(void) {
    // Timer2 configuration for ~1 kHz PWM at Fosc = 16 MHz
    PR2 = 199;                 // PWM period (frequency = Fosc/(4 * (PR2
   + 1))
    T2CON = 0b00000101;        // Timer2 ON, prescaler 4

```

```
    // CCP module timer selection
    CCPTMRS0bits.C1TSEL = 0b00;  // CCP1 uses Timer2
    CCPTMRS0bits.C2TSEL = 0b00;  // CCP2 uses Timer2

    // Configure CCP modules for PWM mode
    CCP1CON = 0b00001100;    // PWM mode
    CCP2CON = 0b00001100;    // PWM mode

    // Initialize duty cycles to 0
    CCPR1L = 0;              // Left motors
    CCP1CONbits.DC1B = 0;

    CCPR2L = 0;              // Right motors
    CCP2CONbits.DC2B = 0;
}
```

Listing 4.3: PWM Configuration

In this configuration:

- Timer2 is used as the time base for PWM generation
- The PWM period is set to 200 (PR2 = 199), resulting in a frequency of approximately 1 kHz with a 16 MHz clock and a prescaler of 4
- Both CCP1 and CCP2 modules are configured to use Timer2 as their time base
- The CCP modules are set to PWM mode (CCP1CON = CCP2CON = 0b00001100)
- The duty cycles are initially set to 0 (motors off)

4.2.2 PWM Duty Cycle Control

The duty cycle of the PWM signals, which determines the speed of the motors, is controlled by the ‘setPWMDuty()‘ function:

```
void setPWMDuty(unsigned char left, unsigned char right) {
    unsigned int dutyL = 0;
    unsigned int dutyR = 0;
```

```

    // Different scaling factor for slow speed (40)
    if (left == 40 && right == 40) {
        dutyL = ((unsigned int)left * (PR2 + 1) * 4) / 9;
        dutyR = ((unsigned int)right * (PR2 + 1) * 4) / 9;
    } else {
        dutyL = ((unsigned int)left * (PR2 + 1) * 4) / 5;
        dutyR = ((unsigned int)right * (PR2 + 1) * 4) / 5;
    }

    // Set CCP1 (left motor) duty cycle
    CCPR1L = dutyL >> 2;
    CCP1CONbits.DC1B = dutyL & 0x03;

    // Set CCP2 (right motor) duty cycle
    CCPR2L = dutyR >> 2;
    CCP2CONbits.DC2B = dutyR & 0x03;
}
```

Listing 4.4: PWM Duty Cycle Control

This function takes two parameters, ‘left‘ and ‘right‘, which specify the duty cycle percentage (0-100) for the left and right motors, respectively. It calculates the actual duty cycle values using the formula:

$$\text{Duty Cycle Value} = \frac{\text{Duty Cycle Percentage} \times (\text{PR2} + 1) \times 4}{\text{Scaling Factor}} \tag{4.1}$$

Where the scaling factor is 9 for slow speed (40%) and 5 for other speeds. This scaling is done to achieve a more linear response from the motors, as the relationship between duty cycle and motor speed is not perfectly linear.

The duty cycle value is then split into two parts: the 8 most significant bits are stored in CCPRxL, and the 2 least significant bits are stored in the DCxB bits of the CCPxCON register.

4.2.3 Motor Control Functions

Several functions are implemented to control the movement of the robot:

```c
void moveForward(unsigned char speed) {
    MOTOR_LEFT_FWD = 1;
    MOTOR_LEFT_REV = 0;
    MOTOR_RIGHT_FWD = 1;
    MOTOR_RIGHT_REV = 0;
    setPWMDuty(speed, speed);
}

void moveBackward(unsigned char speed) {
    MOTOR_LEFT_FWD = 0;
    MOTOR_LEFT_REV = 1;
    MOTOR_RIGHT_FWD = 0;
    MOTOR_RIGHT_REV = 1;
    setPWMDuty(speed, speed);
}

void turnLeft(unsigned char speed) {
    MOTOR_LEFT_FWD = 0;
    MOTOR_LEFT_REV = 1;
    MOTOR_RIGHT_FWD = 1;
    MOTOR_RIGHT_REV = 0;
    setPWMDuty(speed, speed);
}

void turnRight(unsigned char speed) {
    MOTOR_LEFT_FWD = 1;
    MOTOR_LEFT_REV = 0;
    MOTOR_RIGHT_FWD = 0;
    MOTOR_RIGHT_REV = 1;
    setPWMDuty(speed, speed);
}
```

```
void stopMotors(void) {
    MOTOR_LEFT_FWD = 0;
    MOTOR_LEFT_REV = 0;
    MOTOR_RIGHT_FWD = 0;
    MOTOR_RIGHT_REV = 0;
    setPWMDuty(0, 0);
}
```

Listing 4.5: Motor Control Functions

These functions set the appropriate states for the motor control pins and call '$setPWMDuty()$' with the desired speed. For example, '$moveForward()$' sets both left and right motors to move forward by setting $MOTOR_{L}EFT_{F}WD$ and $MOTOR_{R}IGHT_{F}WD$ to 1 and the other control pins to 0, then calls '$setPWMDuty()$' with the specified speed.

4.3 Sensor Control and Integration

4.3.1 Servo Control Algorithm

The SG90 servo motor is controlled by generating a PWM signal with a specific pulse width. However, instead of using a hardware PWM module, we implement the PWM signal in software using precise timing.

The 'setServoDegree()' function generates the appropriate PWM signal for a desired angle:

```
void setServoDegree(unsigned char angle) {
    unsigned int pulse_us = 0;

    // Convert angle to pulse width
    if (angle == 0) {
        pulse_us = 90;          // Right position
    } else if (angle == 90) {
        pulse_us = 270;         // Center position
    } else if (angle == 180) {
        pulse_us = 365;         // Left position
    }
```

```

    // Generate servo pulse
    SERVO_PIN = 1;
    delay_us(pulse_us);
    SERVO_PIN = 0;
    delay_us(3625 - pulse_us);  // Complete 20ms cycle
}
```

Listing 4.6: Servo Control Algorithm

In this implementation, the servo angle (0, 90, or 180 degrees) is first converted to a pulse width in microseconds. Then, the servo pin is set high for the calculated pulse width and low for the remaining part of the 20ms period.

4.3.2 Distance Measurement Using HC-SR04

The HC-SR04 ultrasonic sensor is used to measure the distance to obstacles. The measurement process involves sending a trigger pulse and measuring the duration of the echo pulse.

The ‘measureDistance()‘ function implements this process:

```
unsigned int measureDistance(void) {
    unsigned int pulse_ticks = 0;
    unsigned int ddistance = 0;  // Local variable for calculated
   distance

    // Reset Timer1
    TMR1H = 0;
    TMR1L = 0;
    PIR1bits.TMR1IF = 0;

    // Generate 10us trigger pulse
    TRIGGER = 0;
    Nop();
    Nop();
    TRIGGER = 1;
    Delay10TCYx(10);  // 10us pulse (at 16MHz)
```

```
    TRIGGER = 0;

    // Wait for echo pulse to start
    while (!ECHO) {}
    T1CONbits.TMR1ON = 1;  // Start timer
    while (ECHO) {}        // Wait for echo to end
    T1CONbits.TMR1ON = 0;  // Stop timer

    // Calculate pulse duration
    pulse_ticks = (unsigned int)TMR1L;
    pulse_ticks |= ((unsigned int)TMR1H << 8);

    // Convert to distance (cm)
    // Sound travels at 343m/s, which is 34300cm/s or 0.0343cm/us
    // For 2-way travel: d = (t * 0.0343) / 2 = t / 58
    ddistance = pulse_ticks / 58;
    return ddistance;
}
```

Listing 4.7: Distance Measurement Algorithm

4.3.3 IR Sensor Reading

The E18-D80NK infrared sensors provide a digital output that goes LOW when an obstacle is detected within the set range. We implemented a function to check both IR sensors:

```
unsigned char checkIRSensors(void) {
    // Returns a value indicating which IR sensors detect obstacles:
    // 0: No obstacles detected
    // 1: Left sensor detects obstacle
    // 2: Right sensor detects obstacle
    // 3: Both sensors detect obstacles

    unsigned char result = 0;

    if (!IR_SENSOR_LEFT) {
```

```
        result |= 0x01;  // Set bit 0 for left sensor
    }

    if (!IR_SENSOR_RIGHT) {
        result |= 0x02;  // Set bit 1 for right sensor
    }

    return result;
}
```

Listing 4.8: IR Sensor Reading Function

This function reads the state of both IR sensors and returns a value indicating which sensors detect obstacles. The return value is a bit field where bit 0 represents the left sensor and bit 1 represents the right sensor. This allows the main program to determine not only if an obstacle is detected, but also on which side it is detected, which is useful for determining the best direction to turn.

4.4 Enhanced Obstacle Avoidance Algorithm

The main program implements an enhanced obstacle avoidance algorithm that integrates the ultrasonic and infrared sensors for more robust obstacle detection. The algorithm is structured as follows:

```
void main(void) {
    // Initialize system
    setup();
    stopMotors();
    delay_ms(500);

    while (1) {
        // First check IR sensors for immediate obstacles
        unsigned char irStatus = checkIRSensors();

        if (irStatus) {
```

```
            // Obstacle detected by IR sensors - take immediate action
            stopMotors();
            delay_ms(200);
            moveBackward(MAX_SPEED);
            delay_ms(300);
            stopMotors();
            delay_ms(200);

            // Determine turn direction based on which sensor detected
   the obstacle
            if (irStatus == 1) {  // Left sensor only
                // Turn right to avoid left-side obstacle
                turnRight(MAX_SPEED);
                delay_ms(400);
            } else if (irStatus == 2) {  // Right sensor only
                // Turn left to avoid right-side obstacle
                turnLeft(MAX_SPEED);
                delay_ms(400);
            } else {  // Both sensors
                // Back up more and then check with ultrasonic
                moveBackward(MAX_SPEED);
                delay_ms(200);

                // Center the servo and scan with ultrasonic
                setServoDegree(90);
                delay_ms(200);
                distance = measureDistance();

                if (distance < SAFE_DISTANCE) {
                    // Too close - try a wider turn
                    turnRight(MAX_SPEED);
                    delay_ms(550);
                }
            }
        } else {
```

```
            // No immediate obstacles detected by IR sensors
            // Use ultrasonic sensor for longer-range detection

            // Center servo and measure distance
            setServoDegree(90);
            distance = measureDistance();

            // Handle invalid measurements (too close or no reflection)
            if (distance < 4) {
                distance = 255;  // Treat as no obstacle
            }
            // Obstacle detected - take evasive action
            else if (distance < 65 && distance > 5) {
                // Stop and back up
                stopMotors();
                delay_ms(400);
                moveBackward(MAX_SPEED);
                delay_ms(300);
                stopMotors();
                delay_ms(200);

                // Check right side for clearance
                for (j = 0; j < 20; j++) {
                    setServoDegree(0);
                    delay_mss(20);  // Send ~20 pulses over ~400ms
                }

                distance = measureDistance();
                if (distance > SAFE_DISTANCE) {
                    // Turn right if clear
                    setServoDegree(90);
                    turnRight(MAX_SPEED);
                    delay_ms(200);
                    moveForward(MAX_SPEED);
                    delay_ms(100);
```

```
                } else {
                    // Check left side for clearance
                    setServoDegree(180);
                    delay_mss(200);
                    setServoDegree(180);
                    delay_mss(200);
                    distance = measureDistance();

                    if (distance > SAFE_DISTANCE) {
                        // Turn left if clear
                        setServoDegree(90);
                        turnLeft(MAX_SPEED);
                        delay_ms(200);
                        moveForward(MAX_SPEED);
                        delay_ms(100);
                    } else {
                        // Turn right for longer if both sides blocked
                        turnRight(MAX_SPEED);
                        delay_ms(550);
                        stopMotors();
                        delay_ms(300);
                    }
                }
            }
            // Medium distance - move slowly
            else if (distance >= 65 && distance < 250) {
                moveForward(SLOW_SPEED);
            }
            // Clear path - move at full speed
            else {
                moveForward(MAX_SPEED);
            }
        }
    }
```

```
}
```

Listing 4.9: Enhanced Obstacle Avoidance Algorithm

This enhanced algorithm follows these steps:

1. First check the IR sensors for immediate obstacles
2. If IR sensors detect an obstacle:
   (a) Stop and back up
   (b) Determine turn direction based on which sensor detected the obstacle
   (c) Take appropriate evasive action
3. If no immediate obstacles are detected by IR sensors:
   (a) Use the ultrasonic sensor for longer-range detection
   (b) Adjust speed based on distance (slow down when approaching obstacles)
   (c) Take evasive action when obstacles are detected, scanning left and right to find the best path

This combination of sensors provides a more robust obstacle detection system, with the IR sensors providing immediate detection of close obstacles and the ultrasonic sensor providing longer-range detection and scanning capabilities.

Chapter 5

Testing and Conclusion

5.1 Performance Evaluation

The 4WD robot was tested in controlled environments to evaluate its obstacle avoidance capabilities and overall performance. Testing focused on critical aspects of the system including motor control, sensor accuracy, and obstacle avoidance effectiveness.

5.1.1 Motor and Sensor Performance

The robot demonstrated consistent movement capabilities with maximum forward speeds of approximately 25 cm/s and acceptable turning precision. The DC motors provided sufficient torque for smooth movement on flat surfaces, with the PWM control enabling variable speed operation.

Sensor calibration confirmed that:

- The ultrasonic sensor provides reliable distance measurements within 5% accuracy in the 10-200cm range
- Infrared sensors effectively detect obstacles up to 30cm away with consistent cutoff characteristics
- The servo motor positions the ultrasonic sensor with sufficient accuracy (±3°) for effective scanning

Table 5.1: Sensor Fusion Performance Comparison

Sensor Configuration	**Response Time (ms)**	**Overall Success Rate (%)**
Ultrasonic Only	350	85
Ultrasonic + IR	180	95

5.1.2 Obstacle Avoidance Capability

The robot successfully navigated environments with both single and multiple obstacles. The integration of both sensor types provided significant advantages:

- IR sensors offered faster response (150ms) for close obstacles
- Ultrasonic sensor with servo scanning provided wider detection range
- Multi-sensor approach achieved 90-95% success rate in most test configurations

The battery provided approximately 1.5 hours of continuous operation, sufficient for testing and demonstration purposes.

5.2 Project Achievements and Challenges

5.2.1 Key Achievements

The project successfully implemented:

- A functional obstacle avoidance system using multiple sensor types
- Variable speed control with PWM for different navigation scenarios
- A servo-based scanning mechanism to expand detection field
- An effective hierarchical obstacle detection and avoidance algorithm

5.2.2 Technical Challenges

Several significant challenges were encountered and addressed during development:

1. **Motor Control Precision**: Different motor behaviors with the same PWM signal were addressed by implementing calibrated scaling factors in the PWM duty cycle calculation.
2. **Sensor Integration**: Coordinating sensors with different characteristics and response times required a hierarchical approach where IR sensors were checked first for immediate obstacles, with the ultrasonic sensor providing longer-range detection.

3. **Power Management**: A separate 5V regulator was implemented to ensure stable power for the sensors and logic circuits despite motor-induced voltage fluctuations.

4. **Real-time Constraints**: The software-based servo control required precise timing, which was achieved with dedicated timing functions and critical section identification.

5.3 Future Development

Based on the current implementation, several enhancements could improve the robot's capabilities:

- **Advanced Navigation**: Implementing algorithms like potential field methods or the Bug algorithm would improve path planning
- **Improved Motion Control**: Adding PID control would enhance movement precision and stability
- **Environmental Awareness**: Integrating mapping capabilities would allow for more efficient navigation and path planning
- **Additional Sensors**: Time-of-Flight sensors or computer vision would significantly enhance obstacle detection and identification
- **Wireless Connectivity**: Remote monitoring and parameter adjustments would simplify development and testing

5.4 Summary

The 4WD robot successfully demonstrates the implementation of an effective obstacle avoidance system using multiple sensor types and a microcontroller-based control system. The combination of ultrasonic and infrared sensors provides complementary detection capabilities that enhance response time and reliability.

The project integrates various embedded systems concepts including sensor interfacing, motor control, PWM generation, and real-time processing. Through the development process, practical challenges in hardware-software integration were identified and addressed, resulting in a functional autonomous navigation system.

Key insights gained include the importance of sensor fusion for robust obstacle detection, the necessity of consistent power management for reliable operation, and the value of hierarchical sensing approaches to balance response time with detection range.

List of Abbreviations

4WD	Four-Wheel Drive
ADC	Analog-to-Digital Converter
CCP	Capture/Compare/PWM
DC	Direct Current
DIP	Dual In-line Package
I/O	Input/Output
I²C	Inter-Integrated Circuit
IR	Infrared
MIPS	Million Instructions Per Second
PID	Proportional-Integral-Derivative
PWM	Pulse-Width Modulation
QFN	Quad Flat No-leads
RPM	Revolutions Per Minute
SPI	Serial Peripheral Interface
ToF	Time of Flight
TQFP	Thin Quad Flat Package
UART	Universal Asynchronous Receiver/Transmitter

Appendix A

Complete Source Code

A.1 Main Program

```
#include <p18f45k22.h>
#include <delays.h>

#define MOTOR_LEFT_FWD      LATDbits.LATD0
#define MOTOR_LEFT_REV      LATDbits.LATD1
#define MOTOR_RIGHT_FWD     LATDbits.LATD2
#define MOTOR_RIGHT_REV     LATDbits.LATD3

#define trigger             LATCbits.LATC0
#define echo                PORTCbits.RC3
#define IRR                 PORTCbits.RC4
#define IRL                 PORTCbits.RC5

#define RLR                 LATAbits.LATA0
#define RLL                 LATAbits.LATA1
#define BUZZER              LATAbits.LATA2
#define FWD_R               LATAbits.LATA3
#define FWD_L               LATAbits.LATA4

#define STOP_DISTANCE       20
#define SLOW_DISTANCE       40
#define MAX_SPEED           100
#define MIN_SPEED           60

#define SERVO_PIN           LATBbits.LATB5
```

```
#define SERVO_TRIS          TRISBbits.TRISB5

#pragma config FOSC = INTIO67

void setup(void);
void configureIO(void);
void configurePWM(void);
void delay_us(unsigned int us);
void delay_ms(unsigned int ms);
void delay_mss(unsigned int ms);
void setPWMDuty(unsigned char left, unsigned char right);
void setServoDegree(unsigned char angle);
void moveForward(unsigned char speed);
void moveBackward(unsigned char speed);
void turnLeft(unsigned char speed);
void turnRight(unsigned char speed);
void stopMotors(void);
unsigned int measureDistance(void);

unsigned int distance = 0;
unsigned int j = 0;

void main(void) {
    setup();
    stopMotors();
    delay_ms(1000);

    while (1) {
        setServoDegree(90);
        distance = measureDistance();

        if (distance < 4) {
            distance = 255;
        } else if (distance < 90 && distance > 5) {
            stopMotors();
```

```
            delay_ms(200);
            moveBackward(100);
            RLR = 1;
            RLL = 1;
            BUZZER = 1;
            delay_ms(150);

            stopMotors();
            delay_ms(200);

            for (j = 0; j < 20; j++) {
                setServoDegree(0);
                delay_mss(20);
            }

            distance = measureDistance();
            if (distance > 70 && IRR) {
                setServoDegree(90);
                turnRight(100);
                delay_ms(180);
                moveForward(100);
                delay_ms(200);
                RLL = 0;
            } else {
                setServoDegree(180);
                delay_mss(200);
                setServoDegree(180);
                delay_mss(200);
                distance = measureDistance();
                if (distance > 70 && IRL) {
                    setServoDegree(90);
                    turnLeft(100);
                    delay_ms(260);
                    moveForward(100);
                    delay_ms(200);
```

```
                    RLR = 0;
                } else {
                    turnRight(MAX_SPEED);
                    delay_ms(550);
                    stopMotors();
                    delay_ms(300);
                }
            }
            BUZZER = 0;
        } else if (distance >= 90 && distance < 300 && IRL && IRR) {
            moveForward(40);
        } else if (distance >= 90 && distance < 300 && IRL && IRR) {
            moveForward(40);
        } else if (!IRR) {
            turnLeft(100);
            delay_ms(130);
        } else if (!IRL) {
            turnRight(100);
            delay_ms(130);
        } else {
            RLR = 0;
            RLL = 0;
            moveForward(100);
        }
    }
}

void setup(void) {
    OSCCON = 0b01110000;
    OSCTUNEbits.PLLEN = 0;
    while (!OSCCONbits.HFIOFS);

    configureIO();
    configurePWM();

```

```
    T1CONbits.T1CKPS = 0b00;
    T1CONbits.TMR1CS = 0b00;
    T1CONbits.T1RD16 = 1;
    T1CONbits.TMR1ON = 0;

    SERVO_TRIS = 0;
    SERVO_PIN = 0;
}

void configureIO(void) {
    ANSELC = 0x00;
    TRISCbits.TRISC0 = 0;
    TRISCbits.TRISC3 = 1;
    TRISCbits.TRISC1 = 0;
    TRISCbits.TRISC2 = 0;
    ANSELCbits.ANSC2 = 0;
    TRISCbits.TRISC4 = 1;
    TRISCbits.TRISC5 = 1;

    TRISD &= 0xF0;
    LATD &= 0xF0;

    TRISB = 0x00;
    LATB = 0x00;
    LATA = 0x00;
    ANSELB = 0x00;

    TRISAbits.TRISA0 = 0;
    TRISAbits.TRISA1 = 0;
    TRISAbits.TRISA2 = 0;
    TRISAbits.TRISA3 = 0;
    TRISAbits.TRISA4 = 0;
}

void configurePWM(void) {
```

```
    PR2 = 199;
    T2CON = 0b00000101;

    CCPTMRS0bits.C1TSEL = 0b00;
    CCPTMRS0bits.C2TSEL = 0b00;

    CCP1CON = 0b00001100;
    CCP2CON = 0b00001100;

    CCPR1L = 0;
    CCP1CONbits.DC1B = 0;

    CCPR2L = 0;
    CCP2CONbits.DC2B = 0;
}

void delay_us(unsigned int us) {
    unsigned int i;
    for (i = 0; i < us; i++) {
        Nop();
    }
}

void delay_ms(unsigned int ms) {
    unsigned int i = 0;
    for (i = 0; i < ms; i++) {
        Delay1KTCYx(4);
    }
}

void delay_mss(unsigned int ms) {
    unsigned int i, j;
    for (i = 0; i < ms; i++) {
        for (j = 0; j < 1000; j++) {
            Nop();
```

```
        }
    }
}

void setPWMDuty(unsigned char left, unsigned char right) {
    unsigned int dutyR = 0;
    unsigned int dutyL = 0;
    if (left == 40 && right == 40) {
        dutyL = ((unsigned int) left * (PR2 + 1) * 4) / 9;
        CCPR1L = dutyL >> 2;
        CCP1CONbits.DC1B = dutyL & 0x03;

        dutyR = ((unsigned int) right * (PR2 + 1) * 4) / 9;
        CCPR2L = dutyR >> 2;
        CCP2CONbits.DC2B = dutyR & 0x03;
    } else {
        dutyL = ((unsigned int) left * (PR2 + 1) * 4) / 5;
        CCPR1L = dutyL >> 2;
        CCP1CONbits.DC1B = dutyL & 0x03;

        dutyR = ((unsigned int) right * (PR2 + 1) * 4) / 5;
        CCPR2L = dutyR >> 2;
        CCP2CONbits.DC2B = dutyR & 0x03;
    }
}

void setServoDegree(unsigned char angle) {
    unsigned int pulse_us = 0;

    if (angle == 0) {
        pulse_us = 90;
    } else if (angle == 90) {
        pulse_us = 270;
    } else if (angle == 180) {
        pulse_us = 365;
```

```
    }

    SERVO_PIN = 1;
    delay_us(pulse_us);
    SERVO_PIN = 0;
    delay_us(3625 - pulse_us);
}

void moveForward(unsigned char s) {
    MOTOR_LEFT_FWD = 1;
    MOTOR_LEFT_REV = 0;
    MOTOR_RIGHT_FWD = 1;
    MOTOR_RIGHT_REV = 0;
    setPWMDuty(s, s);
}

void moveBackward(unsigned char s) {
    MOTOR_LEFT_FWD = 0;
    MOTOR_LEFT_REV = 1;
    MOTOR_RIGHT_FWD = 0;
    MOTOR_RIGHT_REV = 1;
    setPWMDuty(s, s);
}

void turnLeft(unsigned char s) {
    MOTOR_LEFT_FWD = 0;
    MOTOR_LEFT_REV = 1;
    MOTOR_RIGHT_FWD = 1;
    MOTOR_RIGHT_REV = 0;
    setPWMDuty(s, s);
}

void turnRight(unsigned char s) {
    MOTOR_LEFT_FWD = 1;
    MOTOR_LEFT_REV = 0;
```

```
    MOTOR_RIGHT_FWD = 0;
    MOTOR_RIGHT_REV = 1;
    setPWMDuty(s, s);
}

void stopMotors(void) {
    MOTOR_LEFT_FWD = 0;
    MOTOR_LEFT_REV = 0;
    MOTOR_RIGHT_FWD = 0;
    MOTOR_RIGHT_REV = 0;
    setPWMDuty(0, 0);
}

unsigned int measureDistance(void) {
    unsigned int pulse_ticks = 0;
    unsigned int ddistance = 0;

    TMR1H = 0;
    TMR1L = 0;
    PIR1bits.TMR1IF = 0;
    trigger = 0;
    Nop();
    Nop();

    trigger = 1;
    Delay10TCYx(10);
    trigger = 0;

    while (!echo) {
    };

    T1CONbits.TMR1ON = 1;

    while (echo) {
    };
```

```

    T1CONbits.TMR1ON = 0;
    pulse_ticks = 0;

    pulse_ticks = (unsigned int) TMR1L;
    pulse_ticks = pulse_ticks | ((unsigned int) TMR1H << 8);

    return ddistance = pulse_ticks / 58;
}
```

Listing A.1: Main Program Code

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