Advanced Driver Assistance System (ADAS)

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Lastly, We dedicate this project to everyone who shares a passion for advancing automotive safety and innovation through technologies like ADAS. It is my hope that this work contributes meaningfully to the ongoing efforts to create safer and smarter transportation systems.

Abstract

Advanced Driver Assistance Systems (ADAS) are revolutionizing the automotive industry by enhancing road safety, improving driving comfort, and paving the way for autonomous vehicles. In this project, we present the design and implementation of a comprehensive ADAS framework that integrates several critical driver assistance features, including Blind Spot Detection (BSD), Adaptive Cruise Control (ACC), Traffic Sign Recognition (TSR), Automatic Parking, Autonomous Lane Change, and Driver Drowsiness Detection.

Our system leverages a combination of sensor fusion, computer vision, machine learning algorithms, and real-time data processing to ensure accurate and reliable performance across diverse driving scenarios. The Blind Spot Detection module uses ultrasonics inputs to monitor adjacent lanes and alert the driver of potential collision risks. The Adaptive Cruise Control system maintains a safe distance from the vehicle ahead by automatically adjusting speed using PID control algorithms.

Traffic Sign Recognition utilizes deep learning models to detect and classify road signs, providing the driver with timely visual or auditory alerts. The Automatic Parking feature enables the vehicle to detect suitable parking spaces and execute parking maneuvers autonomously. The Autonomous Lane Change system ensures safe and smooth lane transitions when necessary, while the Driver Drowsiness Detection monitors facial features and driving behavior to prevent accidents caused by fatigue.

All modules are integrated into a unified platform, tested under various simulated and real-world conditions to validate their functionality and robustness. This project aims to contribute to safer, smarter, and more intuitive driving experiences by combining cutting-edge technologies within a single ADAS architecture.

Keywords: Advanced Driver Assistance System (ADAS), Embedded Systems, Artificial Intelligence, Computer Vision, CAN Bus, PID Control, Sensor Fusion, Mecanum Wheels, STM32, Raspberry Pi

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Project Initiation

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1.1 Introduction

The rapid advancement of technology has revolutionized the automotive industry, paving the way for safer and more efficient driving experiences. Advanced Driver Assistance Systems (ADAS) have emerged as a critical innovation, aiming to enhance road safety, reduce driver fatigue, and improve overall vehicular performance. By leveraging technologies such as sensors, cameras, radar, and artificial intelligence, ADAS bridges the gap between traditional vehicles and the fully autonomous cars of the future.

Road traffic accidents remain a significant global concern, with human error accounting for nearly 90% of all incidents. As urbanization and vehicle ownership continue to rise, so does the need for intelligent systems capable of supporting drivers in navigating complex traffic conditions. ADAS addresses this challenge by providing real-time assistance and corrective actions, such as lane-keeping, adaptive cruise control, and collision avoidance.

This thesis explores the development and application of ADAS in modern vehicles. It delves into the technical challenges, market dynamics, and societal impacts associated with these systems. By examining the current state of ADAS technology and identifying areas for improvement, this project aims to contribute to the ongoing efforts in making roads safer and driving more accessible for all.

1.2 Problem Definition

The global transportation landscape faces a persistent challenge in ensuring road safety and minimizing traffic-related incidents. According to the World Health Organization (WHO), over 1.19 million lives are lost annually due to road traffic accidents, with millions more suffering injuries[1]. Alarmingly, studies reveal that human error accounts for nearly 90% of these accidents[2], including factors such as distracted driving, fatigue, and poor decision-making.

In addition to safety concerns, modern drivers contend with increasing traffic congestion, leading to inefficiencies, environmental concerns, and heightened stress. The growing complexity of road networks and the rapid increase in vehicle ownership further exacerbate these issues, demanding innovative solutions to support drivers in managing these challenges effectively.

While traditional safety mechanisms like seatbelts and airbags mitigate the impact of accidents, they do little to prevent incidents from occurring. Advanced Driver Assistance Systems (ADAS) present a transformative solution by actively assisting drivers with real-time decision-making, collision avoidance, and situational awareness. However, despite their potential, ADAS faces limitations in adoption due to technological challenges, cost barriers, and varying levels of reliability across different environments.

This project seeks to address these gaps by exploring the development and optimization of ADAS technologies. By identifying existing shortcomings and proposing enhancements, this project aims to contribute to making roads safer and driving more efficiently for all.

[1] https://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries
[2] https://cyberlaw.stanford.edu/blog/2013/12/human-error-cause-vehicle-crashes/

1.3 Literature Review

Advanced Driver Assistance Systems (ADAS) represent a critical step toward autonomous driving, leveraging technologies such as sensors, cameras, radar, and artificial intelligence. Over the past two decades, significant research has been conducted to develop and refine ADAS technologies, focusing on features like collision avoidance, lane-keeping assistance, adaptive cruise control, and automated parking.

1.3.1 Historical Development of ADAS

Early iterations of ADAS, such as anti-lock braking systems (ABS) and electronic stability control (ESC), laid the groundwork for more advanced functionalities. These systems primarily relied on mechanical and electrical components to enhance vehicle stability and safety. Recent advancements in sensor technologies and computing power have enabled the integration of real-time data processing, significantly improving the capabilities of ADAS.

1.3.2 Core Components and Technologies

Research highlights the importance of several key components in ADAS:

1. **Sensor Systems:** Cameras, LiDAR, radar, compass, gyroscope, MPU and ultrasonic sensors provide essential data for vehicle perception. Studies demonstrate the increasing accuracy of multi-sensor fusion in detecting obstacles and road conditions.
2. **Artificial Intelligence:** Machine learning algorithms play a crucial role in interpreting sensor data, predicting driver behavior, and making split-second decisions. Research explores deep-learning models for object recognition and decision-making in ADAS.
3. **Human-Machine Interaction:** User experience and system usability are critical to ADAS adoption. Research emphasizes the importance of intuitive interfaces and minimizing driver distraction.

1.3.3 Challenges in Current Systems

Despite advancements, ADAS faces several limitations:

- **Reliability in Diverse Conditions:** Many systems struggle with environmental variability, such as poor lighting, heavy rain, or fog.
- **Affordability:** High costs of sensors and computational components limit the accessibility of ADAS to mid-range and low-income markets.
- **Ethical and Legal Considerations:** Studies highlight the need for clear regulations and ethical frameworks, particularly regarding liability in ADAS-enabled vehicles.

1.3.4 Gaps in Existing Research

While current research has made significant strides, gaps remain in areas such as:

- **Standardization:** A lack of uniform standards for ADAS development and testing.
- **Edge Case Scenarios:** Limited studies on rare but critical driving scenarios, such as interactions with non-standard road users.
- **Driver Adaptation:** Insufficient focus on how drivers adapt to and trust ADAS functionalities over time.

1.4 ADAS Market

The global automotive industry has witnessed a significant transformation over the past decade, driven by advancements in technology and increasing emphasis on road safety. Advanced Driver Assistance Systems (ADAS) are at the forefront of this evolution, with their market showing exponential growth due to rising consumer demand, regulatory mandates, and technological innovations.

1.4.1 Market Overview

The ADAS market has been expanding at a robust pace. Reports indicate a compound annual growth rate (CAGR) of approximately 10–15% over the past five years, with projections suggesting a market size exceeding $50 billion by 2030. This growth is fueled by increasing vehicle automation levels, advancements in sensor technology, and the rising integration of artificial intelligence.

1.4.2 Key Market Drivers

1. **Regulatory Support:** Governments worldwide have introduced stringent safety regulations mandating the inclusion of ADAS features, such as autonomous emergency braking (AEB) and lane departure warning (LDW), in new vehicles.
2. **Consumer Awareness:** Growing awareness of road safety and vehicle efficiency among consumers has led to increased demand for ADAS-equipped vehicles.
3. **Technological Advancements:** Innovations in machine learning, sensor fusion, and connectivity have made ADAS features more reliable and cost-effective.

1.4.3 Regional Market Analysis

1. **North America:** Dominates the ADAS market, driven by high disposable incomes, regulatory mandates, and early adoption of advanced technologies.
2. **Europe:** The second-largest market, with strict safety regulations like the European New Car Assessment Program (Euro NCAP) driving adoption.

3. **Asia-Pacific:** Emerging as a key market due to rapid urbanization, increased vehicle ownership, and growing awareness of road safety in countries like China, India, and Japan.
4. **Middle East and Africa:** A nascent market with significant growth potential as infrastructure and regulatory frameworks develop.

1.4.4 Market Segmentation

The ADAS market is segmented based on:

- **Components:** Sensors (LiDAR, radar, cameras), software, and actuators.
- **Vehicle Type:** Passenger cars, commercial vehicles, and electric vehicles.
- **ADAS Features:** Lane-keeping assistance, adaptive cruise control, blind-spot monitoring, and auto parking.

1.4.5 Challenges in the Market

- **High Costs:** The integration of ADAS features increases vehicle costs, limiting adoption in low-income markets.
- **Infrastructure Limitations:** The effectiveness of ADAS systems depends on robust infrastructure, which is lacking in many developing regions.
- **Cybersecurity Concerns:** As vehicles become more connected, ensuring data security and preventing hacking attempts is a growing challenge.

1.5 Project Objectives

The primary objective of this project is to design and develop a cost-effective Advanced Driver Assistance System (ADAS) that maintains high reliability and safety standards. This involves:

1. **Minimizing Component Costs:**
    - Identify affordable alternatives to high-cost components, such as sensors and processors, without compromising functionality.
2. **Optimizing System Design:**
    - Simplify system architecture to reduce manufacturing and integration costs.
3. **Leveraging Open-Source Technologies:**
    - Utilize open-source software and frameworks to lower development costs while maintaining flexibility and scalability.
4. **Balancing Performance and Affordability:**

- Ensure that the proposed ADAS achieves core functionalities such as lane-keeping, collision avoidance, and adaptive cruise control at a competitive price point.

5. **Adaptability for Low-Income Markets:**
   - Develop a system that can be widely adopted in regions with budget-sensitive consumers.
6. **Enhancing Accessibility:**
   - Design the ADAS to be compatible with mid-range vehicles, broadening its market reach.
7. **Scalability and Manufacturability:**
   - Ensure the proposed solution can be scaled for mass production efficiently and affordably.

1.6 Stakeholder

The success of Advanced Driver Assistance Systems (ADAS) depends on the collaboration and engagement of various stakeholders. Each stakeholder has distinct interests, responsibilities, and expectations, influencing the development and deployment of ADAS technologies. The key stakeholders in this project include:

1.6.1 1. Vehicle Manufacturers

- **Role:** Develop, integrate, and market ADAS technologies within their vehicles.
- **Interest:** Enhance vehicle safety and functionality to meet consumer demand and regulatory requirements.
- **Impact:** Adoption and advancement of ADAS features depend on their willingness to invest in research and development.

1.6.2 2. Technology Providers

- **Role:** Supply critical components such as sensors, cameras, radar, and software algorithms.
- **Interest:** Develop cost-effective, high-performance technologies to maintain competitiveness in the market.
- **Impact:** The efficiency and reliability of ADAS largely rely on the quality and innovation of these components.

1.6.3 3. Governments and Regulatory Bodies

- **Role:** Set safety standards, mandates, and regulations for vehicle features.
- **Interest:** Reduce traffic accidents, promote road safety, and establish legal frameworks for liability and compliance.
- **Impact:** Regulatory mandates drive the adoption of essential ADAS functionalities, influencing market trends.

1.6.4 4. Drivers and Vehicle Owners

- **Role:** End-users who directly interact with ADAS features in real-world driving conditions.
- **Interest:** Seek systems that are reliable, easy to use, and improve their driving experience.
- **Impact:** User feedback and adoption rates shape the market demand for ADAS technologies.

1.6.5 5. Insurance Companies

- **Role:** Adjust policies and premiums based on the implementation and effectiveness of ADAS in reducing accidents.
- **Interest:** Use ADAS data to assess risk and offer incentives for vehicles equipped with advanced safety features.
- **Impact:** Adoption of ADAS could reduce insurance claims and reshape the insurance landscape.

1.6.6 6. Researchers and Academic Institutions

- **Role:** Conduct studies to improve ADAS algorithms, validate performance, and explore new applications.
- **Interest:** Advance the knowledge base of ADAS technologies and address challenges in system design and implementation.
- **Impact:** Their work forms the foundation for technological breakthroughs in ADAS.

1.6.7 7. Society and Communities

- **Role:** Indirect beneficiaries of safer roads and reduced traffic accidents.
- **Interest:** Achieve lower accident rates, reduced traffic congestion, and improved road safety.
- **Impact:** Widespread use of ADAS can have significant societal and economic benefits, including saving lives and reducing healthcare costs.

1.6.8 8. Automotive Aftermarket and Service Providers

- **Role:** Provide maintenance, upgrades, and retrofitting services for ADAS-equipped vehicles.
- **Interest:** Expand business opportunities by supporting the lifecycle of ADAS components.
- **Impact:** Ensure long-term reliability and usability of ADAS systems.

1.7 Scope

This project focuses on the design, analysis, and development of Advanced Driver Assistance Systems (ADAS) to enhance vehicle safety, driver convenience, and overall road efficiency. The scope of the project is defined as follows:

1.7.1 In-Scope Activities

1. **Development of ADAS Features:**
   - Focus on key functionalities such as lane-keeping assistance, adaptive cruise control, blind spot detection and auto parking.
   - Explore the integration of sensor fusion, artificial intelligence, and real-time data processing for improved system performance.
2. **Hardware Testing:**
   - Use a Hardware market to test ADAS algorithms under various driving conditions, including urban, rural, and highway scenarios.
   - Evaluate performance metrics such as system accuracy, reliability, and response time.
3. **Cost Analysis:**
   - Assess the cost-effectiveness of proposed ADAS technologies and identify strategies to reduce production costs.

1.7.2 Out-of-Scope Activities

1. **Full Autonomy:**
   - This project focuses solely on driver assistance systems and does not aim to develop fully autonomous driving solutions.
2. **Hardware Manufacturing:**
   - While the project will explore the use of sensors and other hardware, the actual manufacturing of these components is beyond its scope.
3. **Long-Term Field Deployment:**
   - The project includes testing and simulations but does not cover extended field trials or commercialization of the developed technologies.

4. **Legal and Ethical Frameworks:**
    - Although these are critical aspects of ADAS adoption, they are not the primary focus of this project.

1.8 Constraints

The development of Advanced Driver Assistance Systems (ADAS) involves several challenges and limitations that must be addressed to ensure the feasibility and success of the project. These constraints include:

1.8.1 1. Technical Constraints

- **Sensor Limitations:**
    - The accuracy and reliability of ADAS heavily depend on sensors such as cameras, ultrasonic, gyroscope, and compass which can be affected by environmental conditions like rain, fog, and glare, noise and quality which is dependent on budget.
- **Computational Resources:**
    - Real-time data processing requires high-performance processors, which may increase costs and power consumption.
- **Integration Challenges:**
    - Ensuring seamless integration of various components, such as sensors, actuators, and software, is complex and time-consuming.

1.8.2 2. Budgetary Constraints

- **High Development Costs:**
    - Research and development of ADAS technologies, including advanced sensors and machine learning algorithms, require significant financial investment.
- **Cost Optimization:**
    - Balancing performance and affordability is a key challenge, especially for targeting mid-range and budget vehicles.

1.8.3 3. Regulatory and Safety Constraints

- **Compliance with Standards:**
    - The developed system must adhere to stringent international safety and regulatory requirements, which can vary by region.
- **Ethical Considerations:**

  - Decisions made by ADAS, such as in emergency scenarios, must align with ethical and legal guidelines.

1.8.4 4. Environmental Constraints

- **Road Infrastructure:**
  - Variability in road quality, lane markings, and traffic signage across different regions can affect ADAS performance.
- **Climate Conditions:**
  - Extreme weather conditions, such as snow or heavy rain, pose challenges for sensor accuracy and system reliability.

1.8.5 5. Time Constraints

- **Project Deadlines:**
  - The limited timeframe of the project may restrict the depth of analysis and the extent of testing that can be conducted.

1.8.6 6. Data Constraints

- **Data Availability:**
  - Developing and testing ADAS requires access to large datasets of driving scenarios, which might be limited or costly.
- **Privacy Concerns:**
  - Collecting and using real-world driving data must comply with privacy regulations and ethical considerations.

Chapter 2

Planning and System Requirements

Contents

2.1 Hardware Components

2.1.1 Controllers

STM32f401rct6

The **STM32F401RCT6** is a microcontroller from STMicroelectronics' STM32F4 series, part of the STM32 family of 32-bit ARM Cortex-M4 microcontrollers. It is designed for high-performance, low-power applications and is widely used in embedded systems. Below is a detailed breakdown of its specifications:

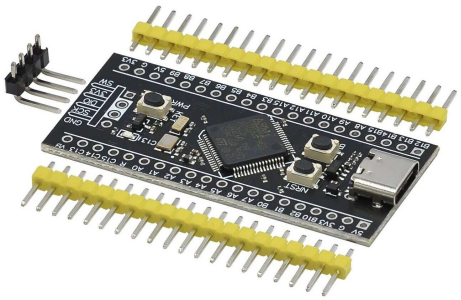


Figure 2.1: STM32F401RCT6 Microcontroller

1. Core Architecture

- **Processor**: ARM Cortex-M4
- **Clock Speed**: Maximum: **84 MHz**; Adaptive real-time (ART) accelerator for zero-wait-state execution from Flash memory.
- **Floating Point Unit (FPU)**: Single-precision FPU (IEEE 754 compliant).
- **DSP Instructions**: Support for Digital Signal Processing (DSP) instructions.

2. Memory

- **Flash Memory**: 256 KB (up to 256 Kbytes of embedded Flash memory).
- **SRAM**: 64 KB of SRAM.
- **Memory Protection Unit (MPU)**: Yes, for enhanced memory protection.

3. Power Supply and Consumption

- **Operating Voltage**: 1.7 V to 3.6 V (wide voltage range for flexibility).
- **Low Power Modes**: Sleep mode, Stop mode, Standby mode.
- **Power Consumption**: Ultra-low power consumption optimized for battery-powered applications. Typical current consumption in Run mode: 2.4 mA/MHz.

4. Connectivity and Communication Interfaces

- **UART/USART**: Up to 3 UART/USART interfaces.
- **I²C**: Up to 3 I^2C interfaces.
- **SPI**: Up to 3 SPI interfaces.
- **I²S**: Audio support via I^2S interface.

- **SDIO**: SD card/MMC interface for external storage.
- **USB**: 1 USB 2.0 OTG FS (On-The-Go Full-Speed) with LPM (Link Power Management).
- **CAN**: 1 CAN interface for automotive and industrial applications.

5. Analog Peripherals

- **ADC (Analog-to-Digital Converter)**: 3 ADCs (12-bit resolution), up to 16 channels, sampling rate up to 2.4 MSPS.
- **DAC (Digital-to-Analog Converter)**: 2 DACs (12-bit resolution).

6. Timers

- **General-Purpose Timers**: Up to 6 timers (16-bit or 32-bit).
- **Advanced-Control Timers**: 1 advanced-control timer for motor control and PWM generation.
- **Basic Timers**: 2 basic timers for simple timing functions.
- **Watchdog Timers**: Independent watchdog and window watchdog for system reliability.
- **SysTick Timer**: Built-in for real-time operating systems (RTOS).

7. GPIO (General Purpose Input/Output)

- **Number of Pins**: 51 GPIO pins (multiplexed with other peripheral functions).
- **Features**: Configurable as input, output, alternate function, or analog mode. External interrupt capability on all GPIO pins.

8. Clock System

- **Internal RC Oscillator**: 16 MHz internal RC oscillator.
- **External Oscillator**: Supports external crystal oscillators up to 25 MHz.
- **PLL (Phase-Locked Loop)**: For clock multiplication and frequency scaling.
- **System Clock**: Up to 84 MHz.

10. Operating Conditions

- **Temperature Range**: Industrial grade: -40°C to +85°C.
- **Humidity**: Non-condensing environment.

11. Security Features

- **CRC (Cyclic Redundancy Check)**: For data integrity verification.
- **Read-Out Protection (RDP)**: Protects firmware from unauthorized access.
- **Write Protection**: Protects specific memory sectors from accidental writes.

The **STM32F401RCT6** strikes a balance between performance, power efficiency, and cost, making it an excellent choice for a wide range of embedded applications. Its rich set of peripherals and robust ecosystem make development easier and faster.

ESP32

The **ESP32** is a highly versatile and powerful microcontroller developed by Espressif Systems. It is widely used in IoT (Internet of Things) applications, embedded systems, and wireless communication projects due to its integrated Wi-Fi and Bluetooth capabilities, along with its robust processing power. Below is a detailed breakdown of the **ESP32 specifications**:

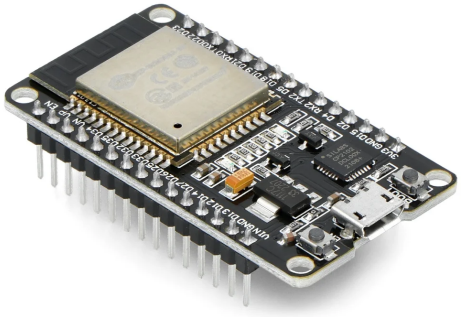


Figure 2.2: ESP32 Development Board

1. Processor (SoC - System on Chip)

- **Model**: ESP32-D0WDQ6 (or other variants depending on the specific chip).
- **Architecture**: Dual-core or single-core Tensilica LX6 microprocessor.
  - **Clock Speed**: Up to 240 MHz per core.
  - **Word Size**: 32-bit.
  - **Floating Point Unit (FPU)**: Single-precision FPU for efficient floating-point calculations.
  - **Ultra-Low Power Co-Processor**: An additional low-power co-processor for tasks like sensor monitoring while the main cores are in sleep mode.

2. Memory

- **Flash Memory**: External SPI flash memory, typically ranging from 4 MB to 16 MB (depending on the module variant).
- **SRAM**: 520 KB of internal SRAM (448 KB for data/instruction, 72 KB for system and cache).
- **RTC Memory**: 8 KB of RTC SRAM for ultra-low-power operations, 8 KB of RTC slow memory for storing data during deep sleep.

3. Wireless Communication

- **Wi-Fi**: IEEE 802.11 b/g/n (2.4 GHz band), up to 150 Mbps data rate, Wi-Fi Direct (P2P), Soft-AP, and Station modes.
- **Bluetooth**: Bluetooth 4.2 BR/EDR, Bluetooth Low Energy (BLE) 5.0 features (on some variants), integrated RF balun and power amplifier.

4. GPIO (General Purpose Input/Output)

- **Number of Pins**: Typically 34–48 GPIO pins depending on the module variant.
- **Features**: Configurable as input, output, or alternate function (e.g., UART, SPI, I^2C, PWM).
- **ADC Inputs**: Up to 18 channels.
- **DAC Outputs**: 2 channels of 8-bit resolution.
- **Touch Sensors**: 10 capacitive touch GPIOs for touch-sensitive interfaces.

5. Analog Peripherals

- **ADC (Analog-to-Digital Converter)**: 12-bit SAR ADC, up to 18 channels (multiplexed across GPIO pins), measurement range: 0–3.3V.
- **DAC (Digital-to-Analog Converter)**: 2 channels of 8-bit DAC.

6. Timers

- **General-Purpose Timers**: 4 timers (54-bit resolution).
- **Watchdog Timers**: 2 watchdog timers (one for interrupt handling and one for system reset).
- **Real-Time Clock (RTC)**: Built-in RTC for timekeeping and wake-up from deep sleep.

7. Connectivity Interfaces

- **UART**: 3 UART interfaces (supporting hardware flow control).
- **I^2C**: 2 I^2C interfaces for communication with sensors and peripherals.
- **SPI**: 4 SPI interfaces (including HSPI and VSPI).
- **I^2S**: 2 I^2S interfaces for audio data transmission.
- **SDIO**: SD card interface for external storage.
- **PWM**: 16 independent channels of PWM outputs.

8. Security Features

- **Cryptographic Hardware Acceleration**: AES (up to 256-bit), SHA (up to 256-bit), RSA, ECC (Elliptic Curve Cryptography).
- **Secure Boot**: Ensures only signed firmware can run on the device.
- **Flash Encryption**: Encrypts data stored in external flash memory.
- **Random Number Generator (RNG)**: Hardware-based RNG for cryptographic applications.

9. Power Management

- **Operating Voltage**: 2.2 V to 3.6 V.
- **Power Modes**: Active Mode, Modem Sleep Mode, Light Sleep Mode, Deep Sleep Mode (ultra-low-power, RTC and ULP co-processor active). Typical current consumption in Deep Sleep: <10 µA.

10. Operating Conditions

- **Temperature Range**: Industrial grade: -40°C to +85°C.
- **Humidity**: Non-condensing environment.

11. Package Details

- **Package Types**: QFN (Quad Flat No-leads) packages. Module variants include ESP32-WROOM, ESP32-WROVER, and ESP32-S2.
- **Pin Count**: Common modules have 38 pins (e.g., ESP32-WROOM-32).

The **ESP32** is a highly capable microcontroller that combines powerful processing, wireless connectivity, and low-power operation, making it ideal for a wide range of IoT and embedded applications. Its rich ecosystem and extensive community support make development easier and faster.

Raspberry Pi 5

The **Raspberry Pi 5** is the latest iteration of the Raspberry Pi single-board computer series, developed by the Raspberry Pi Foundation. It offers substantial improvements in CPU performance, GPU capabilities, and I/O bandwidth over its predecessors, making it suitable for both embedded systems and desktop-class applications.

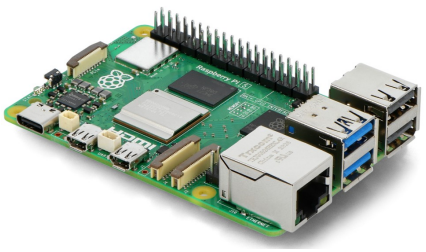


Figure 2.3: Raspberry Pi 5 Board

1. **Processor and Architecture**

   - **SoC**: Broadcom BCM2712.
   - **CPU**: Quad-core ARM Cortex-A76, 64-bit architecture.
   - **Clock Speed**: Up to 2.4 GHz.
   - **GPU**: VideoCore VII GPU.
   - **AI/ML Acceleration**: Supports lightweight AI/ML tasks via GPU and third-party accelerators.

2. **Memory**

   - **RAM Options**: 4 GB or 8 GB LPDDR4X-4267 SDRAM.
   - **Storage**: microSD card slot for OS and storage, PCIe Gen 2 support for external NVMe SSD (via adapter).

3. **Wireless and Networking**

   - **Wi-Fi**: Dual-band 802.11ac Wi-Fi.
   - **Bluetooth**: Bluetooth 5.0, BLE.
   - **Ethernet**: Gigabit Ethernet (via PCIe for true gigabit speeds).

4. **GPIO (General Purpose Input/Output)**

   - **GPIO Header**: 40-pin GPIO header, backward-compatible with previous models.
   - **Features**: Multiple UART, I^2C, SPI, PWM, and GPIO pins.

5. **Multimedia and Display**

   - **Video Output**: 2 × micro-HDMI ports (up to 4K@60fps dual display).
   - **Camera Interface**: 2 × MIPI CSI camera connectors.
   - **Display Interface**: 2 × MIPI DSI display connectors.
   - **Audio**: Digital audio via HDMI and USB; analog via accessory HATs.

6. USB and Expansion

- **USB Ports**: 2 × USB 3.0, 2 × USB 2.0.
- **PCIe**: 1-lane PCIe Gen 2 via FPC connector for expansion (e.g., NVMe SSD, network cards).

7. Power Management

- **Power Input**: USB-C, 5V/5A recommended.
- **Power Management IC**: Improved power delivery and thermal performance.
- **Real-Time Clock (RTC)**: Built-in RTC with battery backup support (via external coin cell).

8. Operating Conditions

- **Temperature Range**: 0°C to +50°C (official specification, can vary with heatsink).
- **Humidity**: Non-condensing environment.

9. Software and Ecosystem

- **Operating System**: Raspberry Pi OS (64-bit), Ubuntu, and other Linux distributions.
- **Development Support**: Python, C/C++, Node.js, and full support for IDEs like VS Code.
- **Community**: Extensive open-source community and documentation resources.

The **Raspberry Pi 5** significantly expands the capabilities of the Raspberry Pi platform, offering desktop-class performance and flexible I/O options. It is well-suited for high-performance embedded applications, educational use, IoT gateways, and software development platforms.

2.1.2 Sensors

MPU6050 Gyroscope

The **MPU6050** is a 6-axis motion tracking device combining a 3-axis gyroscope and a 3-axis accelerometer on a single chip. It's frequently used in motion tracking, balancing robots, drones, and wearables due to its compact size and built-in Digital Motion Processor (DMP).

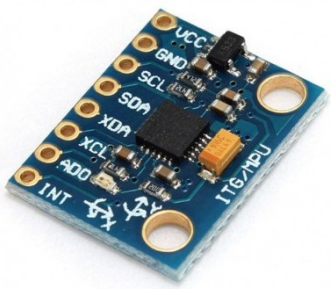


Figure 2.4: MPU6050 Gyroscope and Accelerometer

Key Features

- **Gyroscope Range**: ±250, ±500, ±1000, ±2000°/s.
- **Accelerometer Range**: ±2g, ±4g, ±8g, ±16g.
- **Digital Motion Processor (DMP)**: On-chip processing.
- **Communication Interface**: I^2C up to 400 kHz.
- **Supply Voltage**: 3.3V–5V.
- **Temperature Sensor**: Built-in for compensation.

Pin Configuration

- **VCC**: Power supply input (3.3V or 5V).
- **GND**: Ground.
- **SCL**: I^2C clock.
- **SDA**: I^2C data.
- **INT**: Interrupt output for DMP/event signals.
- **AD0**: I^2C address select (default 0x68 or 0x69).

HMC5883L Compass

The **HMC5883L** is a 3-axis magnetometer designed for low-field magnetic sensing. It is widely used in electronic compasses, GPS systems, and orientation detection applications.

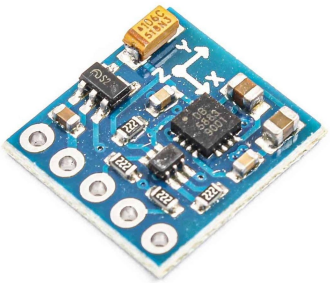


Figure 2.5: HMC5883L Digital Compass

Key Features

- **Magnetic Field Range**: ±8 gauss.
- **Resolution**: 5 milli-gauss.
- **Output Data Rate**: 0.75 Hz to 75 Hz.
- **Sensitivity**: Configurable gain control.
- **Interface**: I^2C (7-bit address: 0x1E).
- **Power Supply**: 2.16V–3.6V (typical 3.3V).

Pin Configuration

- **VCC**: 3.3V power input.
- **GND**: Ground.
- **SCL**: I^2C clock line.
- **SDA**: I^2C data line.
- **DRDY**: Data Ready output (optional use).

HC-SR04 Ultrasonic

The **HC-SR04** is an ultrasonic sensor used for non-contact distance measurement. It emits a 40 kHz ultrasonic burst and listens for the echo to calculate the distance to an object.

Figure 2.6: HC-SR04 Ultrasonic Distance Sensor

Key Features

- **Measurement Range**: 2 cm to 400 cm.
- **Accuracy**: ±3 mm.
- **Operating Voltage**: 5V DC.
- **Working Frequency**: 40 kHz.
- **Measuring Angle**: 15°.
- **Response Time**: Less than 50 ms.

Pin Configuration

- **VCC**: 5V power supply.
- **GND**: Ground.
- **TRIG**: Trigger input pin (10 µs HIGH to start measurement).
- **ECHO**: Echo output pin (pulse width proportional to distance).

Its reliability and low cost make it a go-to choice for embedded systems requiring object detection or distance measurement.

Camera

This camera module provides 720p HD resolution, making it suitable for basic vision tasks in robotics and surveillance. It can be used for object detection, image processing, or streaming over a network.

Figure 2.7: 720p Camera Module

Specifications:

- Resolution: 1280 × 720 pixels (720p HD)
- Interface: USB or CSI (varies by module version)
- Frame rate: Typically 25–30 FPS
- Focus type: Fixed-focus (some modules support manual focus)
- Power supply: 3.3V or 5V depending on interface
- Compatibility: Raspberry Pi, Arduino (via USB host), and other microcontrollers with supported drivers

2.1.3 Communication Module

MCP2515 CAN Bus Module

The **MCP2515** is a stand-alone CAN controller based on the CAN 2.0B specification. It communicates with microcontrollers via the SPI bus and requires an external transceiver such as the TJA1050 or SN65HVD230 to interface with the physical CAN bus. This module is ideal for distributed control systems in vehicles, robotics, and industrial automation.

Figure 2.8: MCP2515 CAN Bus Module

Key Features

- **CAN Protocol Support**: Fully compliant with ISO 11898-1, CAN 2.0B.
- **SPI Interface**: Compatible with standard SPI (up to 10 MHz).
- **Baud Rate**: Configurable up to 1 Mbps.
- **Buffering**: 2 receive buffers with prioritized message storage.
- **Filters**: 6 acceptance filters and 2 masks for message filtering.
- **Voltage**: 5V operating level (some modules include 3.3V regulator).

Pin Configuration

- **VCC**: Power supply input (typically 5V).
- **GND**: Ground.
- **MISO, MOSI, SCK, CS**: SPI communication pins.
- **INT**: Interrupt output, goes low when a message is received.
- **CANH/CANL**: Differential CAN bus lines connected to the transceiver.

The MCP2515 handles message arbitration, error detection, and message filtering internally, relieving the host microcontroller from the complexities of CAN protocol handling.

HC-05 Bluetooth Module

The **HC-05** is a Bluetooth serial module that provides a simple interface for wireless data transmission. It supports full-duplex UART communication and can operate in either Master or Slave mode, configurable via AT commands. It is frequently used in microcontroller-based systems to allow communication with PCs, smartphones, or other Bluetooth-enabled devices.

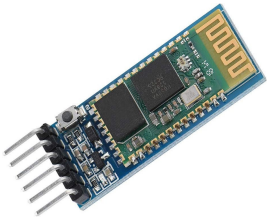


Figure 2.9: HC-05 Bluetooth Communication Module

Key Features

- **Bluetooth Protocol**: Bluetooth v2.0 + EDR.
- **Default Baud Rate**: 9600 bps (configurable up to 1382400 bps).
- **Modulation**: GFSK (Gaussian Frequency Shift Keying).
- **Operating Range**: Approximately 10 meters.
- **Power Supply**: 3.3V (can accept 5V on VCC via onboard regulator).
- **Profile Support**: Serial Port Profile (SPP).

Pin Configuration

- **VCC**: Connects to 3.3V–5V (internally regulated).
- **GND**: Ground.
- **TXD**: Transmits data (connects to RX of microcontroller).
- **RXD**: Receives data (connects to TX of microcontroller via voltage divider).
- **EN (KEY)**: Enables AT command mode when held high at power-up.
- **STATE**: Indicates connection status (high = connected).

The HC-05 can enter AT command mode to adjust parameters such as name, baud rate, and role (Master/Slave), making it highly flexible for various wireless communication setups.

2.1.4 Motors and Drivers

JGY-370-1285 Miniature Worm Gear Motor

The **JGY-370-1285** is a brushed DC motor with an integrated worm gearbox, providing high torque and precise control at low speeds. It is widely used in robotics and automation systems due to its self-locking ability and optional encoder feedback.

Figure 2.10: JGY-370-1285 Worm Gear Motor

Key Features

- **Gear Ratio**: 1:285.
- **Operating Voltage**:
  6–12V DC (optimal performance at 12V).
- **No-Load Speed**: 210 RPM at 12V.
- **Stall Torque**: Up to 6.4 kg·cm.
- **Motor Type**: Brushed DC with worm gear reduction.
- **Shaft Diameter**: 6 mm D-shaped shaft.

Pin Configuration (Encoder Version) When equipped with a quadrature encoder, the motor typically has a 6-pin output:

- **Red** – Motor Power (+12V).
- **Black** – Motor Ground.
- **Yellow** – Encoder Channel A.
- **White** – Encoder Channel B.
- **Green** – Encoder VCC (often 5V).
- **Blue** – Encoder GND.

Encoder Details The encoder is usually an optical or Hall-effect type, generating quadrature signals on channels A and B. This allows:

- **Direction detection** (based on phase shift between A and B).
- **Speed and position measurement** (via pulse counting).
- **Resolution**: Varies — often 11–13 pulses per motor shaft revolution, scaled by gear ratio for high-resolution output shaft tracking.

The encoder adds valuable feedback for closed-loop motor control, especially in applications like PID speed control, odometry, and autonomous navigation.

L298 Motor Driver

The **L298N** is a dual full-bridge motor driver capable of controlling two DC motors or one stepper motor. It supports bi-directional movement and speed control using PWM.

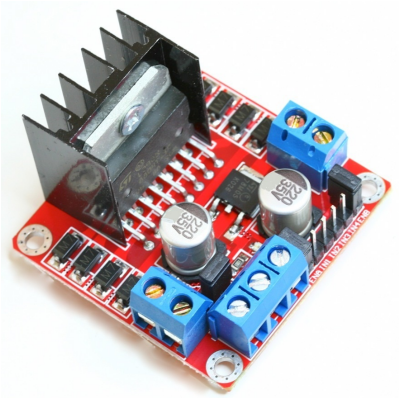


Figure 2.11: L298 Dual H-Bridge Motor Driver Module

Key Features

- **Operating Voltage**: 5V (logic) to 35V (motor).
- **Output Current**: Up to 2A per channel.
- **Dual H-Bridge**: Independent control of two DC motors.
- **PWM Speed Control**: Compatible with microcontrollers (e.g., Arduino).
- **Overheat Protection**: Built-in thermal shutdown.

Pin Configuration

- **IN1, IN2, IN3, IN4**: Logic inputs for direction control.
- **ENA, ENB**: Enable pins (PWM control).
- **OUT1–OUT4**: Motor outputs.
- **VCC**: Motor voltage input (up to 35V).
- **5V**: Logic power supply (optional, with jumper).
- **GND**: Ground connection.

The L298N module is widely used due to its robust design and ease of interfacing with common microcontrollers for motor-based robotics.

Mecanum Wheels

Mecanum wheels enable omnidirectional movement, allowing a robot to move forward, backward, sideways, and diagonally without changing its orientation. This is achieved using angled rollers mounted around the wheel's circumference.

Figure 2.12: Omni-directional Mecanum Wheels

Key Characteristics

- **Roller Angle**: 45° for optimal lateral movement.
- **Material**: Durable plastic with rubber rollers.

- **Sizes**: Common diameters include 60 mm, 80 mm, and 100 mm.
- **Mounting**: Compatible with standard DC motor shafts.
- **Configuration**: Requires four wheels—two mirrored left and two right.

Applications
Ideal for holonomic drive systems in robotics competitions, AGVs (Automated Guided Vehicles), and systems where high maneuverability in tight spaces is essential.

2.1.5 Electronics

LEDs

Light Emitting Diodes (LEDs) are widely used for indication, signaling, and low-power lighting. In embedded systems, they serve as status indicators or visual feedback.

Figure 2.13: Standard 5mm LEDs

Common specifications:

- Forward voltage: 1.8 V (red/yellow), 2.2–3.3 V (green/blue/white)
- Forward current: 10–20 mA typical
- Polarity: longer leg is anode (positive), shorter is cathode (negative)
- Wavelength (color): varies by material (e.g., 625 nm for red)

A current-limiting resistor is required in series to prevent overdriving the LED, typically 220–330 Ω when used with 5 V logic.

Buzzers

Buzzers are audio signaling devices used to produce beeps, alarms, or tones. They can be either active (self-oscillating) or passive (requires external signal).

Figure 2.14: Piezoelectric Buzzer

Types and characteristics:

- Operating voltage: 3 V to 12 V (commonly 5 V)
- Sound pressure level: 85 dB at 10 cm
- Frequency: 2–4 kHz (active), user-defined (passive)

- Interface: digital (on/off) or PWM (for passive buzzers)
- Polarity: positive and negative pins marked on casing

Active buzzers are simpler to use, while passive buzzers allow tone generation via frequency-controlled signals.

IRFZ44V MOSFET

The IRFZ44V is an N-channel power MOSFET designed for high-current switching in motor control, power regulation, and logic-level load driving applications.

Figure 2.15: IRFZ44V N-Channel Power MOSFET

Electrical characteristics:

- Drain-source voltage (V_{DS}): 55 V
- Continuous drain current (I_D): up to 49 A
- Gate threshold voltage ($V_{GS(th)}$): 2.0–4.0 V
- $R_{DS(on)}$: 17 mΩ at V_{GS} = 10 V
- Gate charge: 67 nC (fast switching)

Pin configuration (TO-220 package):

- Pin 1 – Gate
- Pin 2 – Drain (connected to tab)
- Pin 3 – Source

This MOSFET is commonly used in switching power supplies, motor drivers, and digital load control circuits due to its high efficiency and fast switching speed.

2.1.6 Power

Buck Converters

XL4015 DC-DC Step Down Converter

The XL4015 is a high-efficiency buck converter designed for converting higher DC voltages down to a desired lower level. It is commonly used in battery charging, LED driving, and power regulation for embedded systems.

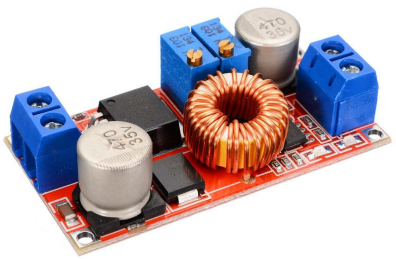


Figure 2.16: XL4015 Buck Converter Module

Specifications:

- Input voltage: 4–38 V

- Output voltage: 1.25–36 V (adjustable)
- Output current: up to 5 A
- Efficiency: up to 96
- Switching frequency: 180 kHz
- Built-in heat sink and current-limiting features

XL4016 DC-DC Step Down Converter

A more powerful variant, the XL4016 is suitable for high-load applications such as motor power supplies or regulated charging systems.

Specifications:

- Input voltage: 8–40 V
- Output voltage: 1.25–36 V (adjustable)
- Output current: up to 8 A
- Efficiency: up to 95
- Cooling: onboard aluminum heat sink for better thermal performance

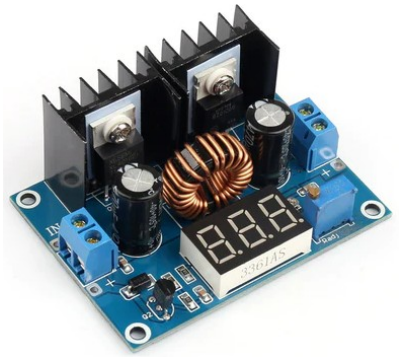


Figure 2.17: XL4016 High-Power Buck Converter

MT3608 DC-DC Step Up Boost Module

The MT3608 module is a compact boost (step-up) converter ideal for raising lower voltages to a usable level for microcontrollers or small modules.

Specifications:

- Input voltage: 2–24 V
- Output voltage: up to 28 V (adjustable)
- Output current: up to 2 A (with adequate cooling)
- Efficiency: 93
- Applications: powering 5V circuits from 3.7V batteries or solar cells

Figure 2.18: MT3608 Boost Converter

Fan

The cooling fan shown is designed for use with Raspberry Pi boards and other small-form-factor single-board computers. It helps dissipate heat generated by the CPU and voltage regulators during prolonged operation.

Specifications:

- Operating voltage: 5 V DC
- Current: 0.1–0.2 A typical
- Size: 25 mm or 30 mm (depends on model)
- Interface: 2-pin (VCC and GND)

Figure 2.19: Raspberry Pi Cooling Fan

Battery

The 18650 Lithium-Ion battery is a popular rechargeable power source due to its high energy density and reusability. Commonly used in portable electronics, torches, and robotics.

Specifications:

- Model: 18650 cylindrical cell
- Voltage: 3.7 V nominal
- Capacity: 1800 mAh (typical), varies by brand (A&S, HONGLI)
- Recharge cycles: up to 250 times
- Size: 18 mm × 65 mm
- Weight: 40 grams

Figure 2.20: 18650 Lithium-Ion Battery

2.1.7 Debuggers

ST-Link Debugger

The **ST-Link V2** is a popular USB in-circuit debugger and programmer for STM32 and STM8 microcontrollers. It enables flashing firmware, stepping through code, and viewing register-level data via STM32CubeIDE or other tools like OpenOCD.

Key Features:

- Supports SWD and JTAG protocols
- Compatible with STM32CubeIDE, Keil, IAR, and PlatformIO

Figure 2.21: ST-Link V2 Debugger

- USB-powered

Pinout:

- **SWDIO** – Serial Wire Debug I/O
- **SWCLK** – Serial Wire Clock
- **GND** – Ground
- **3.3V** – Target Voltage Reference (detect only)
- **NRST** – Optional Reset

Logic Analyzer

A logic analyzer is a digital signal capture device used to debug and analyze communication protocols like I^2C, SPI, UART, and more.

Figure 2.22: 8-Channel Logic Analyzer

Key Features:

- 8 digital channels
- Sampling rate: up to 24 MHz (depends on software and PC)
- USB interface for data transfer
- Compatible with PulseView (Sigrok) software

Pinout:

- **CH0–CH7** – Digital input channels
- **GND** – Common ground

This tool is invaluable for diagnosing timing issues and verifying protocol-level data during embedded system development.

2.1.8 3D Frame

The 3D frame design is a critical component of the ADAS system, serving as the structural foundation that houses all electronic components, sensors, and mechanical systems. The design process involved careful consideration of component placement, weight distribution, accessibility, and overall system integration.

Design Software and Methodology

The frame was designed using **SolidWorks**, a professional 3D CAD software widely used in mechanical engineering and product design. SolidWorks was chosen for its advanced modeling capabilities, assembly management features, and ability to perform structural analysis. The design process followed a systematic approach:

Figure 2.23: 3D Frame Design in SolidWorks

- **Conceptual Design**: Initial sketches and requirements analysis
- **Component Modeling**: Individual 3D models of all electronic and mechanical components
- **Assembly Design**: Integration of components into a cohesive system
- **Structural Analysis**: Verification of mechanical integrity and load-bearing capacity
- **Iterative Refinement**: Continuous improvement based on testing and feedback

Two-Floor Architecture

The frame employs a **two-floor design** to optimize space utilization and component organization. This architectural approach provides several advantages:

- **Modular Organization**: Clear separation of different system components
- **Improved Accessibility**: Easy access to components for maintenance and debugging
- **Better Heat Management**: Separation allows for more effective thermal management
- **Reduced Interference**: Minimizes electromagnetic interference between components
- **Scalability**: Easy to add or modify components without major structural changes

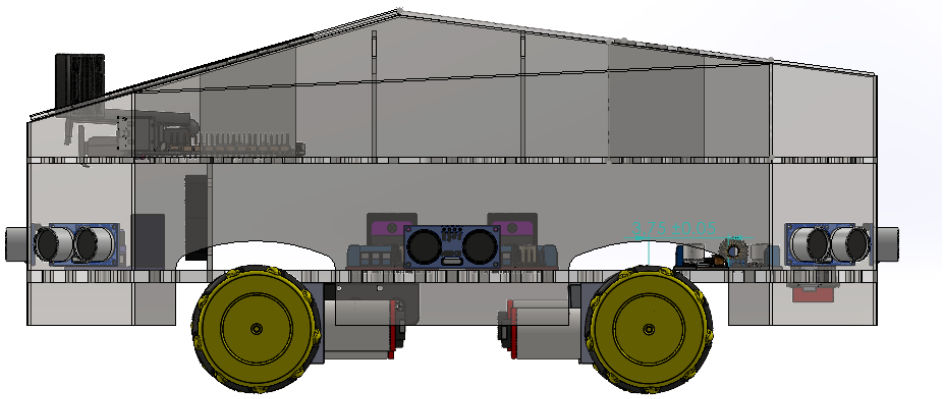


Figure 2.24: Side View of the 3D Frame

Component Integration Considerations

Special attention was given to the integration of critical components that require specific mounting and positioning:

- **Ultrasonic Sensors**: Dedicated mounting slots positioned at strategic locations around the vehicle perimeter for optimal obstacle detection coverage
- **LED Indicators**: Integrated LED mounting points for status indication and visual feedback systems
- **Camera System**: Specially designed camera mount with adjustable positioning for optimal field of view and image capture
- **Sensor Arrays**: Organized sensor placement to minimize interference and maximize detection accuracy

Weight Distribution and Center of Mass

Weight distribution was a primary concern in the frame design, particularly given the significant weight of certain components:

- **Battery Weight Consideration**: Batteries represent the heaviest components in the system, requiring careful placement to maintain proper center of mass
- **Balanced Distribution**: Components were strategically positioned to achieve optimal weight distribution across the vehicle
- **Stability Optimization**: The design ensures the vehicle maintains stability during operation, especially during turns and acceleration
- **Load-Bearing Structure**: The frame was designed to support the total weight of all components while maintaining structural integrity

Tesla CyberTruck Reference Design

The frame design drew inspiration from the **Tesla CyberTruck**, incorporating several key design principles:

- **Angular Geometry**: Sharp, geometric lines and angles for a modern, futuristic appearance
- **Robust Construction**: Emphasis on durability and structural strength
- **Functional Aesthetics**: Design elements that serve both form and function
- **Modular Approach**: Component organization that allows for easy maintenance and upgrades
- **Integrated Systems**: Seamless integration of various subsystems into a cohesive whole

Figure 2.25: Tesla CyberTruck: Design Inspiration Reference

Floor Organization and Component Distribution

First Floor - Power and Propulsion Systems:

- **Power Management**: Battery packs, voltage regulators, and power distribution systems
- **Motor Systems**: Drive motors, motor controllers, and associated mechanical components
- **Power Electronics**: Buck converters, voltage regulators, and power conditioning circuits
- **Cooling Systems**: Heat sinks, fans, and thermal management components

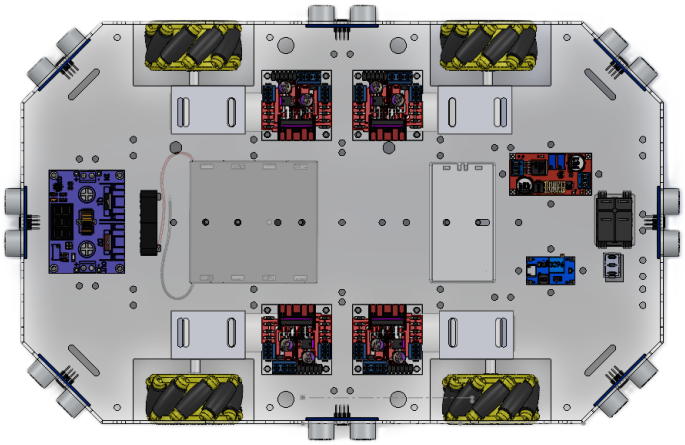


Figure 2.26: First Floor Layout: Power and Propulsion Systems

Second Floor - Control and Sensing Systems:

- **Microcontrollers**: STM32F401RCT6, ESP32, and Raspberry Pi 5 mainboards
- **Sensor Arrays**: MPU6050 gyroscope, HMC5883L compass, ultrasonic sensors, and magnetic encoders

- **Communication Modules**: CAN bus modules, Bluetooth modules, and wireless communication systems
- **Control Interfaces**: User interface components, status indicators, and control panels

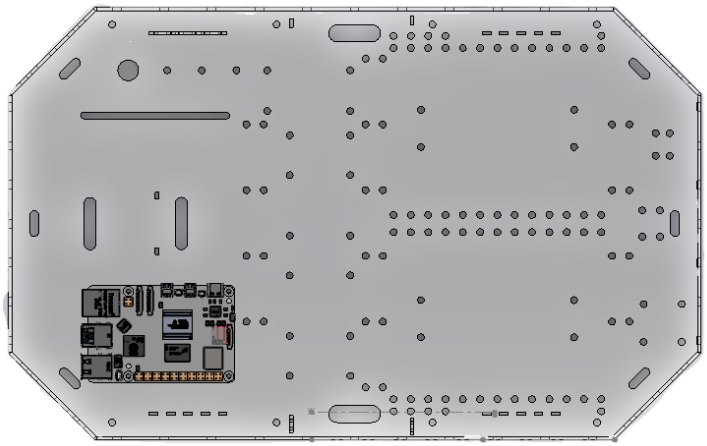


Figure 2.27: Second Floor Layout: Control and Sensing Systems

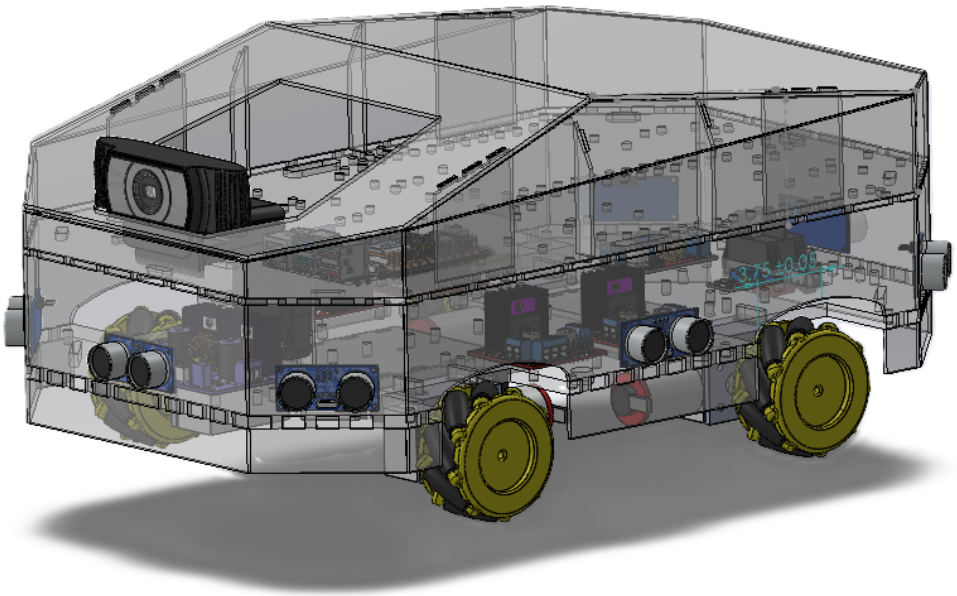


Figure 2.28: Complete Assembled Car Frame

Manufacturing Considerations

The frame design incorporates several manufacturing-friendly features:

- **Modular Assembly**: Components can be assembled in logical sub-assemblies
- **Standard Fasteners**: Use of common screw sizes and types for easy assembly and maintenance
- **Accessibility**: Strategic placement of access panels and maintenance points

- **Cable Management**: Integrated cable routing channels and mounting points
- **Protection Features**: Enclosures and covers to protect sensitive components from environmental factors

This comprehensive frame design ensures that all system components are properly housed, accessible, and optimally positioned for the ADAS system's performance requirements while maintaining the aesthetic appeal inspired by modern automotive design principles.

2.2 Software Components

2.2.1 Software Components Overview

The development of the **Advanced Driver Assistance System (ADAS)** required the use of various software tools and libraries across different hardware platforms. Each software component played a critical role in enabling real-time sensing, data processing, decision-making, and control of vehicle subsystems.

The software architecture was divided into two primary environments:

- **Bare-metal embedded systems**, such as `STM32` and `ESP32`.
- **Embedded Linux platforms**, primarily based on the `Raspberry Pi`.

These environments were chosen to best suit the performance and flexibility requirements of different ADAS modules. The bare-metal systems handled low-level, real-time control, while the embedded Linux systems were used for advanced processing tasks such as image recognition and data fusion.

2.2.2 STM32CubeMX & STM32CubeIDE

STM32CubeMX and STM32CubeIDE are official development tools provided by STMicroelectronics for STM32 microcontrollers.

- **STM32CubeMX** is a graphical configuration tool that simplifies the setup of hardware peripherals, clock trees, and middleware components. It was instrumental in configuring timers, ADCs, UART, SPI, I2C, and GPIO interfaces on the `STM32F401RCT6` microcontroller. The automatic generation of initialization code significantly accelerated our development cycle.
- **STM32CubeIDE** is an Eclipse-based integrated development environment (IDE) with built-in support for code editing, compilation using the GCC toolchain, and in-circuit debugging via ST-Link. It allowed us to develop, test, and debug our low-level control logic for sensors, actuators, and communication protocols.

These tools ensured tight integration between hardware abstraction layers (HAL) and application code, and enabled real-time performance under constrained microcontroller environments.

Figure 2.29: STM32CubeMX

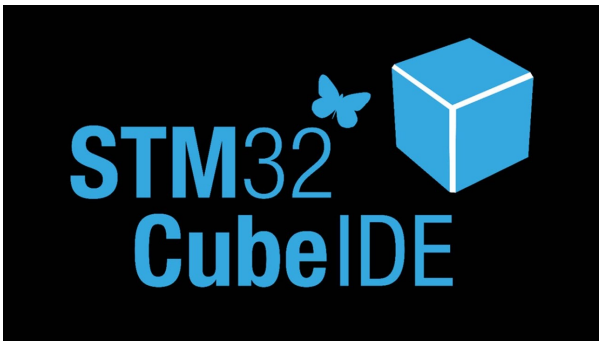


Figure 2.30: STM32CubeIDE

2.2.3 Arduino IDE

The Arduino Integrated Development Environment (IDE) was used for rapid prototyping and programming of the `ESP32` microcontroller, which played an auxiliary role in communication and control tasks. Its simplicity and extensive library ecosystem made it easy to interface with components such as Bluetooth modules, sensors, and motor drivers.

Although the Arduino IDE is lightweight, it was complemented by custom `C/C++` libraries and real-time constructs to improve timing precision and modularity, especially in tasks requiring concurrent handling of sensor data and communication with other ECUs.

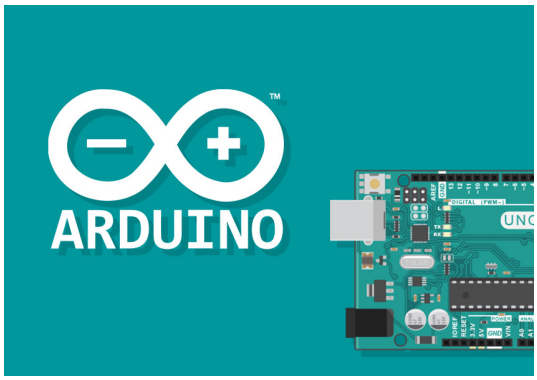


Figure 2.31: Arduino IDE

2.2.4 Raspbian OS (Raspberry Pi OS)

The `Raspberry Pi 5` served as the main processing unit for high-level computer vision tasks and the application layer. It ran **Raspbian OS**, a Debian-based Linux distribution optimized for the Raspberry Pi architecture.

Raspbian offered the following benefits:

- Support for Python-based development
- Compatibility with AI and CV libraries like `OpenCV` and `TensorFlow`
- Easy integration with external USB webcams and display interfaces
- Access to Linux utilities, package managers, and debugging tools

Using Raspbian allowed us to implement and deploy complex AI models with efficient resource utilization, while also enabling multitasking and system monitoring capabilities.

Figure 2.32: Raspbian OS

2.2.5 OpenCV (Open Source Computer Vision Library)

OpenCV is an open-source library for real-time computer vision. In our project, it was a foundational component of the **Traffic Sign Recognition** module.

Key applications included:

- Capturing video frames from the webcam
- Preprocessing images (e.g., resizing, grayscale conversion, Gaussian blurring)
- Detecting object contours, color segmentation, and applying transformations
- Displaying output frames with bounding boxes and classification labels

Its Python bindings made it convenient to integrate with machine learning frameworks and GUI libraries, providing real-time feedback during the driving simulation.

Figure 2.33: OpenCV

2.2.6 TensorFlow

TensorFlow is an end-to-end machine learning platform developed by Google. It was used to load, run, and fine-tune pre-trained deep learning models.

In our system, TensorFlow served two main purposes:

- Running object classification models for recognizing different types of traffic signs
- Providing a backend for YOLO models (when integrated via ONNX or PyTorch to TensorFlow converters)

TensorFlow's support for hardware acceleration (e.g., with `TFLite`) is especially beneficial when deploying on resource-constrained devices like the Raspberry Pi, though our implementation ran inference using the default CPU-based backend due to hardware limitations.

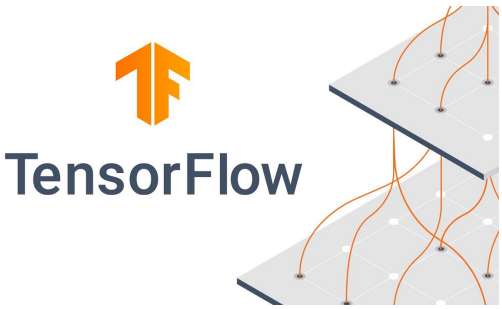


Figure 2.34: TensorFlow

2.2.7 YOLO (You Only Look Once)

YOLO is a state-of-the-art object detection algorithm known for its speed and accuracy. We used **YOLOv5**, a PyTorch-based implementation, which offers a good trade-off between detection speed and resource usage.

The YOLO module was responsible for:

- Detecting traffic signs in real time from live video feeds
- Outputting bounding box coordinates, object classes, and confidence scores
- Sending recognition results to the application logic for further processing

YOLO was selected due to its real-time performance, which is critical in ADAS applications where quick decision-making is necessary to maintain safety.

Figure 2.35: YOLOv5 Model

2.2.8 FreeRTOS (Real-Time Operating System)

FreeRTOS was integrated into both `STM32` and `ESP32` platforms to enable multi-tasking and real-time control. Its lightweight kernel allowed us to divide software functionalities into separate tasks with deterministic behavior.

Key features used:

- Task scheduling for concurrent execution (e.g., sensor reading, motor control, CAN communication)

- Software timers and delays for periodic operations
- Inter-task communication using queues and semaphores

FreeRTOS improved the reliability and scalability of our firmware, especially in modules requiring precise timing and responsiveness.

Figure 2.36: FreeRTOS

2.3 Communication Protocols

Efficient and reliable communication between components is a fundamental requirement in any embedded system. Various communication protocols are used to facilitate data exchange between microcontrollers, sensors, actuators, and peripheral devices. This section outlines and compares five widely used protocols: **UART, SPI, I2C, Bluetooth, and CAN**, explaining their operating principles, use cases, and advantages.

2.3.1 UART (Universal Asynchronous Receiver/Transmitter)

UART is a serial communication protocol that operates asynchronously, meaning it does not require a shared clock between the transmitter and receiver. Instead, both ends must agree on a common baud rate. Data is transmitted in frames containing a start bit, data bits, optional parity, and stop bits.

- **Wiring:** TX (transmit) and RX (receive).
- **Speed:** Typically up to 1 Mbps.
- **Communication Direction:** Full Duplex .

Advantages :

- Simple and widely supported.
- No clock line needed.

Limitations:

- One-to-one communication only.
- Must match baud rate on both ends.

Frame Structure :

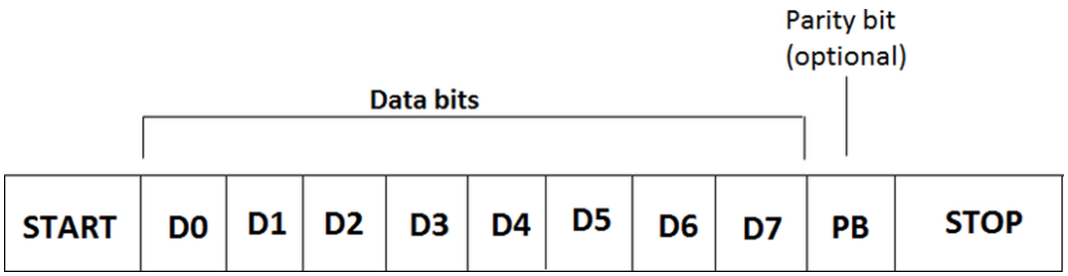


Figure 2.37: UART Message Frame

2.3.2 SPI (Serial Peripheral Interface)

SPI is a synchronous communication protocol used for high-speed data transfer. It consists of MOSI, MISO, SCLK, and SS/CS lines. The master controls the clock and initiates data transfer with the slaves.

- **Wiring:** 4 wires minimum..
- **Speed:** Up to tens of Mbps.
- **Communication Direction:** Full Duplex .

Advantages :

- High data rate.
- Simple hardware protocol.

Limitations:

- More pins required.
- Doesn't scale well with many devices.

Frame Structure :

2.3.3 I2C (Inter-Integrated Circuit)

I2C is a two-wire synchronous protocol with one clock (SCL) and one data (SDA) line. Devices are identified by addresses, supporting multiple masters and slaves.

- **Wiring:** Only 2 lines shared.
- **Speed:** Up to 3.4 Mbps.
- **Communication Direction:** Half Duplex .

Advantages :

- Simple cabling.

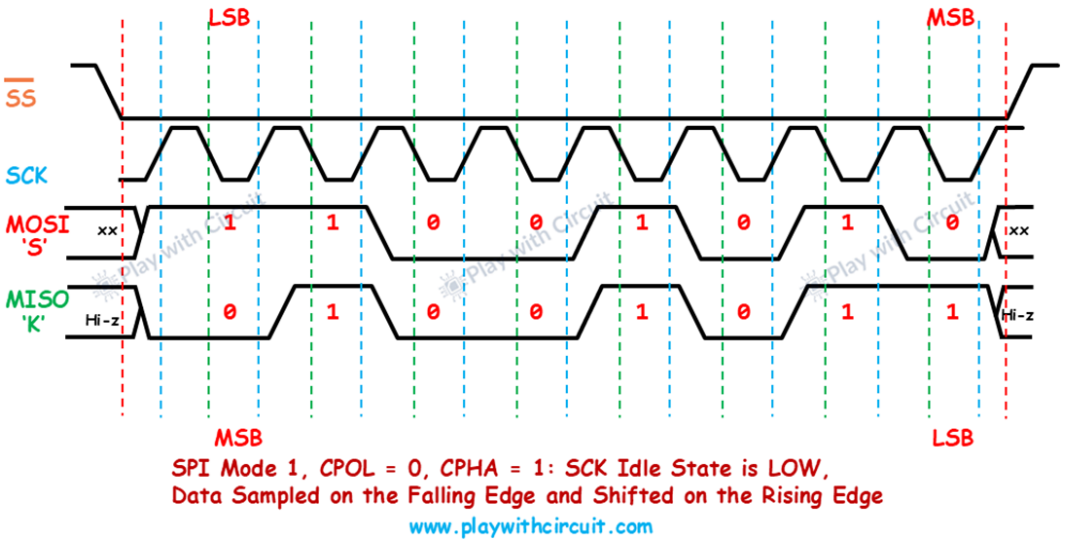


Figure 2.38: SPI Message Frame

- Easy multi-device support.

Limitations:

- Slower than SPI.
- Shorter distances.

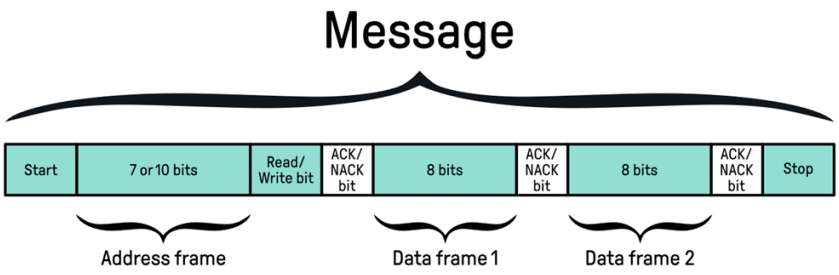


Figure 2.39: I2C Message Frame

2.3.4 CAN (Controller Area Network)

CAN is a robust multi-master communication protocol developed by Bosch, widely used in automotive and industrial applications. It enables distributed control and real-time data exchange between microcontrollers and devices.

- **Wiring:** Two wires (CAN_H, CAN_L) in a differential pair.
- **Speed:** : Up to 1 Mbps (CAN 2.0).
- **Communication Direction:** Half Duplex .

Advantages :

- High reliability and noise immunity.
- Supports multiple nodes on the same bus.
- Robust error detection and isolation

Limitations:

- Limited data payload (8 bytes in CAN 2.0).
- Slower compared to Ethernet or SPI.
- Requires CAN transceiver hardware.

CAN Node Architecture
Each CAN node generally consists of:

- Microcontroller Unit (MCU): Runs the application and interfaces with the CAN controller.
- CAN Controller: Handles data framing, arbitration, and error handling.
- CAN Transceiver: Converts logic-level signals to differential signals for the CAN bus and vice versa.

Reliable communication depends on correct hardware design and matching 120-ohm termination resistors at both ends of the bus.
Frame Structure

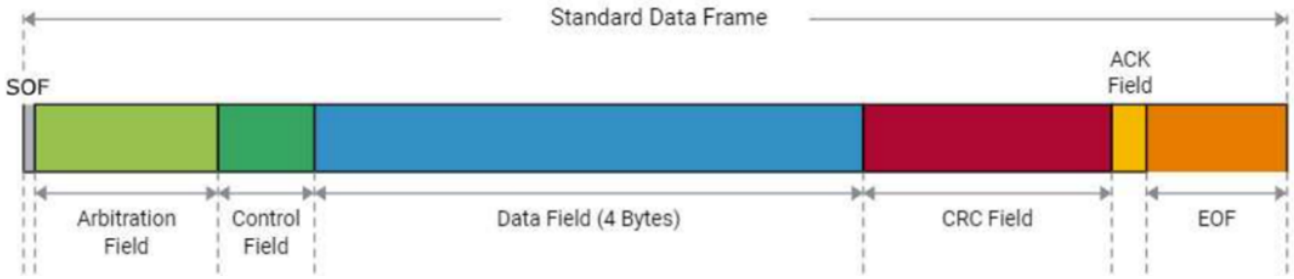


Figure 2.40: CAN Message Frame

2.3.5 Bluetooth

Bluetooth is a wireless communication protocol using the 2.4 GHz band. It enables low-power, short-range communication between devices, ideal for mobile and IoT applications.

- **Wiring:** Wireless.
- **Speed:** :: Up to 3 Mbps (Classic), 2 Mbps (BLE).
- **Range :** 10–100 meters.
- **Communication Direction:** Half Duplex .

Advantages :

- No physical connections.
- Built-in in most consumer devices.

Limitations:

- Complex pairing and security setup.
- Higher power use than wired options.

Frame Structure

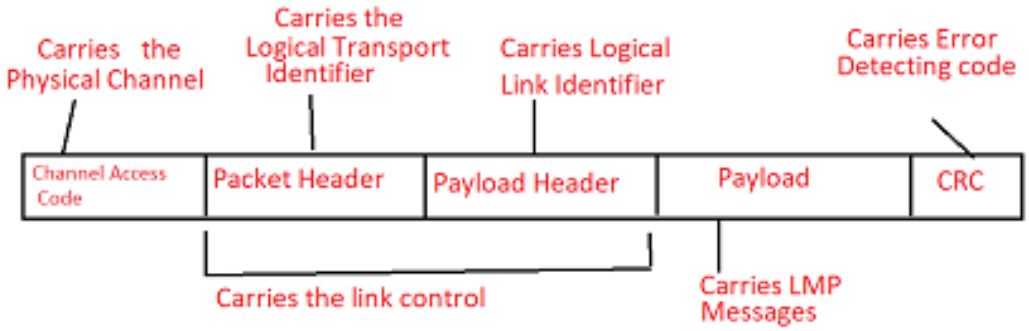


Figure 2.41: Bluetooth Frame

Protocol	Wires	Speed	Type	Direction
UART	2	1 Mbps	Asynchronous	Full-duplex
SPI	4+	Up to 50 Mbps	Synchronous	Full-duplex
I2C	2	Up to 3.4 Mbps	Synchronous	Half-duplex
Bluetooth	0	Up to 3 Mbps	Wireless	Half-duplex
CAN	2	Up to 1 Mbps	Synchronous	Half-duplex

Table 2.1: Comparison of Communication Protocols

2.4 System Architecture

2.4.1 ECUs with CAN

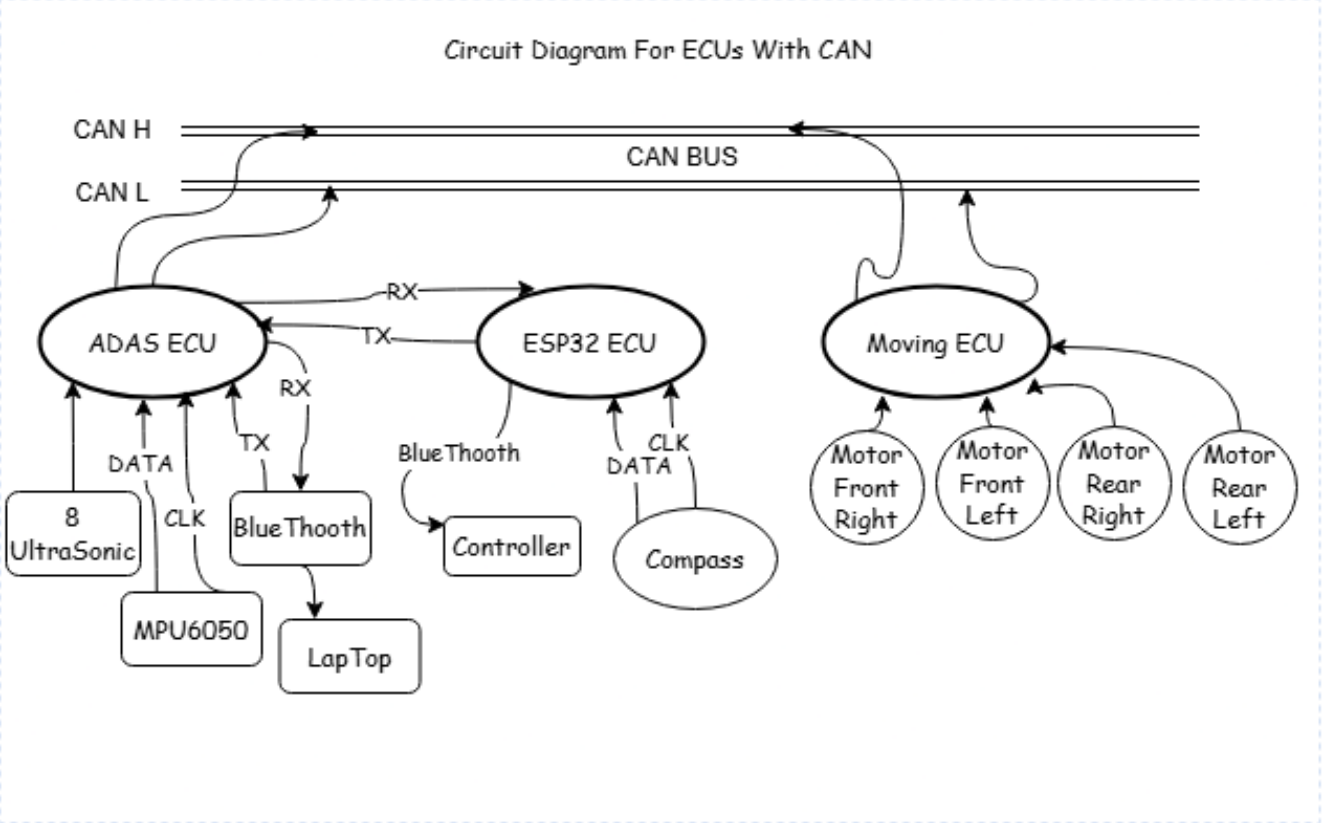


Figure 2.42: Circuit Diagram for ECUs with CAN

The diagram depicts a distributed control system where multiple ECUs communicate over a CAN bus. The primary purpose of this setup is to coordinate the operation of different subsystems, such as Advanced Driver Assistance Systems (ADAS), motor control, and sensor data processing. The system also integrates Bluetooth connectivity for external communication and uses sensors like ultrasonic sensors and an IMU (Inertial Measurement Unit) for environmental sensing.

CAN Bus

The CAN bus connects all ECUs, enabling them to share data and coordinate their operations.

ADAS and Moving ECU

Take input Connections: (8 Ultrasonic Sensors, MPU6050, Bluetooth, ESP32)

ADAS ECU sends and receives data from CAN bus with moving ECU and controls the motor according to the input.

ESP32 ECU

- Controller: Processes data and controls the overall system.
- Compass: Provides head information for navigation.
- Bluetooth: Enables wireless communication with external devices.

2.4.2 Raspberry Pi with CAN

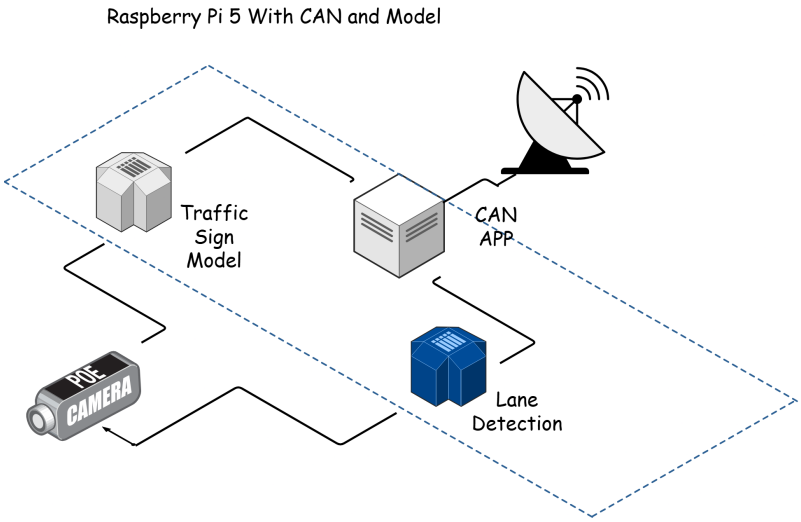


Figure 2.43: Raspberry Pi Diagram with CAN and Model

The provided diagram illustrates a system architecture centered around a Raspberry Pi 5, which is used to process data from various sensors and models for traffic monitoring and vehicle control. The system integrates components such as a camera, traffic sign detection model, lane detection model, and a CAN application, all connected via a communication network.

2.4.3 Battery System

We must first isolate all power sources. Each component should have its own dedicated power source: one for the ECU, one for the Raspberry Pi, and one for the motor. This ensures that none of them overheat or malfunction due to improper power distribution.

ECUs

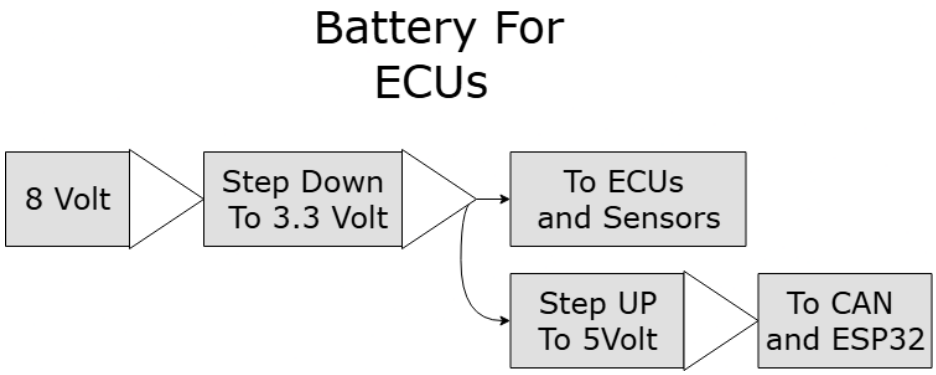


Figure 2.44: ECUs Battery System

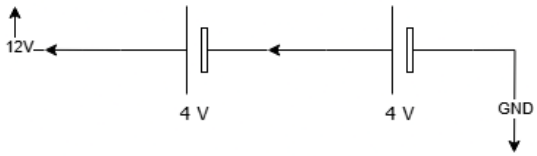


Figure 2.45: Battery Configuration for ECUs

The diagram depicts a battery-powered system where the primary voltage source is 8 volts. This voltage is then converted into two different output voltages with XL4015 for step down and MT3608 for step up:

- 3.3 Volts: Supplied to ECUs and sensors. Ensures that ECUs and sensors, which typically operate at 3.3 volts, receive the correct voltage level.
- 5 Volts: Supplied to CAN (Controller Area Network) and ESP32 modules. Supplies the required 5 volts to components like the CAN bus interface and the ESP32 module, which may require this voltage level for proper operation.

Why Different Voltages? Different electronic components require specific voltage levels for optimal performance:

- 3.3 Volts: Commonly used for modern microcontrollers, sensors, and low-power digital circuits. Operating at 3.3 volts helps reduce power consumption and heat generation.
- 5 Volts: Often required for legacy systems, communication interfaces (like CAN), and certain modules (like the ESP32 in some configurations). These components may have been designed to operate at 5 volts for compatibility or historical reasons.

Raspberry Pi

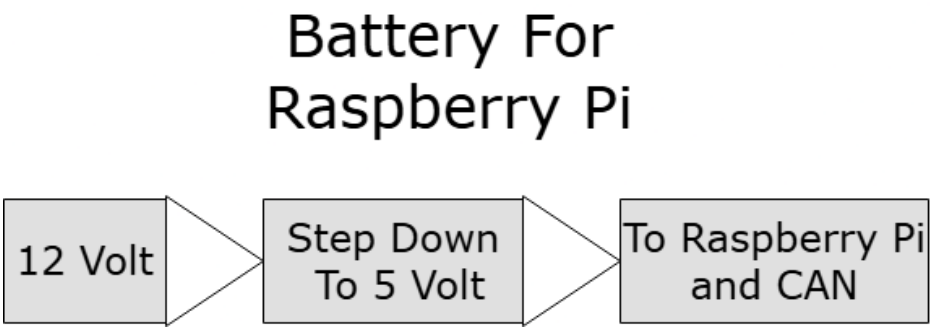


Figure 2.46: Raspberry Pi Battery System

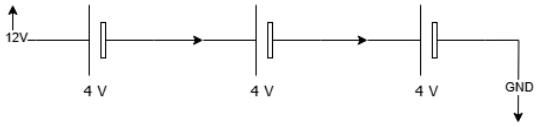


Figure 2.47: Battery Configuration for Raspberry Pi

The diagram depicts a battery-powered system where the primary voltage source is 12 volts. This voltage is converted into a lower voltage (5 volts) using a step-down converter. The 5-volt output is then supplied to both the Raspberry Pi and the CAN interface, ensuring they receive the correct voltage required for operation.

We use 3 batteries, each battery has 4 Volt; total is 12 Volt and convert to 5 Volt to the Raspberry Pi.

Why Different Voltages?

Different electronic components require specific voltage levels for optimal performance; for example, 3.3 volts is commonly used for modern microcontrollers, sensors, and low-power digital circuits as it helps reduce power consumption and heat generation, while 5 volts is often required for legacy systems, communication interfaces like CAN, and modules such as the ESP32 in certain configurations—these components are designed to operate at 5 volts for reasons of compatibility, historical standardization, and efficient operation. The Raspberry Pi and many other devices rely on 5 volts as a standard operating voltage because it ensures reliable performance across a wide range of microcontrollers, sensors, and peripheral modules, while also maintaining backward compatibility with existing hardware and providing a safe and stable power supply that prevents damage to sensitive electronics.

Motor

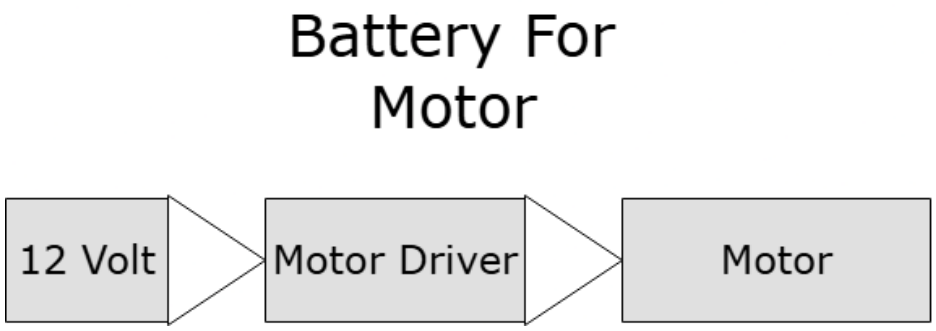


Figure 2.48: Motor Battery System

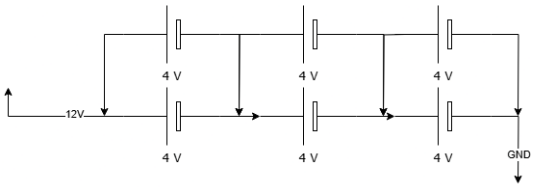


Figure 2.49: Battery Configuration for Motor

We use for motor 6 batteries, each 2 batteries in parallel and series in each of them to be in total 12 Volt but we use the parallel batteries to increase the current, each motor want in range 2A that we want in total 8A.

Chapter 3

Implemented ADAS Features

Contents

3.1 Adaptive Cruise Control

3.1.1 Definition and Meaning

Adaptive Cruise Control (**ACC**) is an advanced driver-assistance system (ADAS) that automatically adjusts a vehicle's speed to maintain a safe following distance from vehicles ahead. Unlike conventional cruise control (which only maintains a constant driver-set speed), ACC uses forward-looking sensors (radar, LiDAR, or cameras) to:

- **Monitor Traffic:** Detect the speed and distance of preceding vehicles.
- **Automate Speed Adjustments:** Intelligently control throttle and braking.
- **Enhance Safety:** Prevent rear-end collisions by maintaining safe gaps.

Key Characteristics

- **Dynamic Speed Control:** Automatically slows down or speeds up based on traffic flow.
- **Stop-and-Go Capability:** Some systems can bring the vehicle to a complete stop in heavy traffic.
- **Driver Customization:** Allows adjustable following distance (e.g., "close," "medium," "far").

Evolution from Conventional Cruise Control

Table 3.1: Comparison between Conventional and Adaptive Cruise Control

Feature	Conventional Cruise Control	Adaptive Cruise Control
Speed Maintenance	Fixed driver-set speed	Dynamic speed adjustment
Traffic Awareness	None	Monitors vehicles ahead
Collision Prevention	No	Yes
Stop Capability	Disengages at low speeds	Can handle full stops

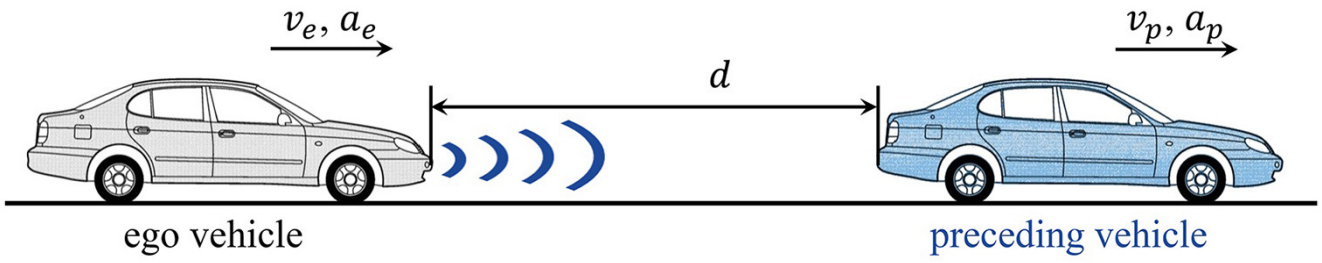


Figure 3.1: Adaptive Cruise Control System

3.1.2 How It Helps the Driver

Primary Benefits:

1. **Reduces Driver Fatigue**
   - Automates constant speed adjustments in highway/traffic conditions
   - Eliminates frequent braking/accelerating in stop-and-go traffic
2. **Enhances Safety**
   - Maintains safe following distances (reduces rear-end collision risk by up to 50%)
   - Provides smoother deceleration than human drivers in emergencies
3. **Improves Fuel Efficiency**
   - Optimizes acceleration patterns (saves 5-15% fuel in highway driving)
4. **Comfortable Driving Experience**
   - Gentle speed transitions mimic expert human driving

Typical Use Cases:

- Highway driving
- Traffic jams
- Inclement weather (fog, rain) where sensors outperform human vision

3.1.3 Implementation Methodology

Adaptive Cruise Control algorithms continuously process data from sensors (such as radar and cameras) to detect the distance and speed of vehicles ahead. The system uses control logic often based on normal level of speed based on the distance of the forwarding car or with more smoothly control we can use **PID** (Proportional-Integral-Derivative) controllers or model predictive control—to automatically adjust the motors speed, maintaining a safe following distance. Advanced algorithms can also handle stop-and-go traffic, smoothly bringing the vehicle to a halt and resuming movement as needed.

Our Implementation

Our Adaptive Cruise Control implementation operates as follows:

1. **Sensor Data Acquisition:** The main control loop periodically calls `ACC_relative_task()`, which reads distance measurements from ultrasonic sensors (e.g., `p_ACC->Front_UL`, `p_ACC->Left_UL`) to detect obstacles and measure relative speed.

2. **Setpoint Calculation:** The target following distance (setpoint) is dynamically calculated as a function of the desired speed:

$$SetPointDistance = 50.0 \times \min\left(WantedSpeed,\ MaxAllowedSpeed\right) + PID\_MIN\_SP \quad (3.1)$$

3. **PID Controller Initialization:** During system setup, `ACC_task_init()` initializes the PID controllers for both longitudinal (Vx) and lateral (Vy) control using `PID_Init()` with tuned parameters (Kp, Ki, Kd, etc.).

4. **PID Control:** The function `ACC_action_task_x()` computes the velocity adjustment by passing the setpoint and measured distance to `PID_Compute()`, which outputs the required speed correction to maintain the safe gap (acceleration or deceleration value for current distance).

$$\begin{aligned} K_\mathrm{p} = 1.5,\ K_\mathrm{d} = 21,\ K_\mathrm{i} = 0,\ N = 22.8 \\ u(t) = K_\mathrm{p} e(t) + K_\mathrm{i} \int_0^t e(\tau)\,\mathrm{d}\tau + K_\mathrm{d} \frac{\mathrm{d}e(t)}{\mathrm{d}t} \end{aligned} \quad (3.2)$$

where *e(t)* represents the error between current distance in front of the car and the set point calculated in previous step and *u(t)* is the acceleration or deceleration by which should the car update its speed.

5. **Speed Limiting:** The function `Max_speed_responsible()` updates the vehicle's maximum allowed speed based on the PID output and current driving context, ensuring the car does not exceed safe limits which determined by other features.

6. **Control Command Transmission:** If speed or direction adjustments are needed, CAN messages are sent using `CAN_send_message()` to communicate with the vehicle's actuators (e.g., `msg_robot_strafe`), and the moving MCU receive it and move the car with required speed.

7. **Continuous Monitoring:** This process repeats in a loop, allowing the system to adapt instantly to new obstacles or changes in the driving environment, and to reset speed limits when no obstacles are detected.

3.1.4 Flowchart

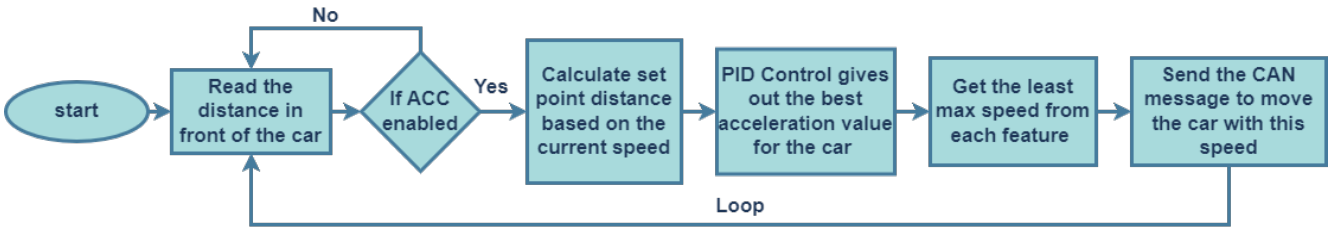


Figure 3.2: Adaptive Cruise Control System Flowchart

3.1.5 Challenges and Limitations

1. **Sensor Problem:** We used ultrasonic to read the distance in front of the car but this sensor has a lot of problems like short range and noisy readings due to surrounding echos from other ultrasonics.

2. **Motors Control:** To control the speed of the car we should control the speed of each motor because of that we implemented a PID controller for each motor to contorl it's speed.

3. **Curve Senarios:** ACC struggles on sharp curves because sensors may lose track of the lead vehicle, requiring manual driver intervention as in **Figure 3.3**.

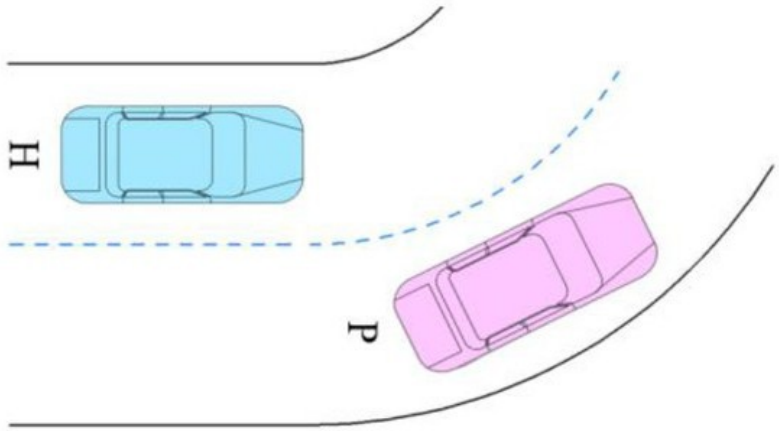


Figure 3.3: Curve Senario

3.2 Blind Spot Detection

In the dynamic and often challenging environment of modern roadways, driver awareness is paramount to preventing accidents. Despite advancements in vehicle design and mirror technology, inherent limitations in a driver's field of vision create 'blind spots' – areas around the vehicle that are obscured from direct view. These hidden zones, often located to the rear and sides of the vehicle, pose a substantial risk, particularly during maneuvers such as lane changes, where unseen vehicles can lead to dangerous collisions. To address this critical safety concern, automotive engineers have developed sophisticated Blind Spot Detection (BSD) systems. This segment will delve into the intricacies of BSD technology, explaining its operational principles, the various types of systems available, and the profound benefits they offer in enhancing driver awareness and overall road safety.

3.2.1 Definition and Meaning

Blind Spot Detection (BSD) is a safety feature in Advanced Driver Assistance Systems (ADAS) that helps drivers monitor areas not visible in their mirrors (blind spots). BSD systems use sensors to detect vehicles or objects in the blind spots and provide warnings to the driver using visual, auditory, or haptic alerts.

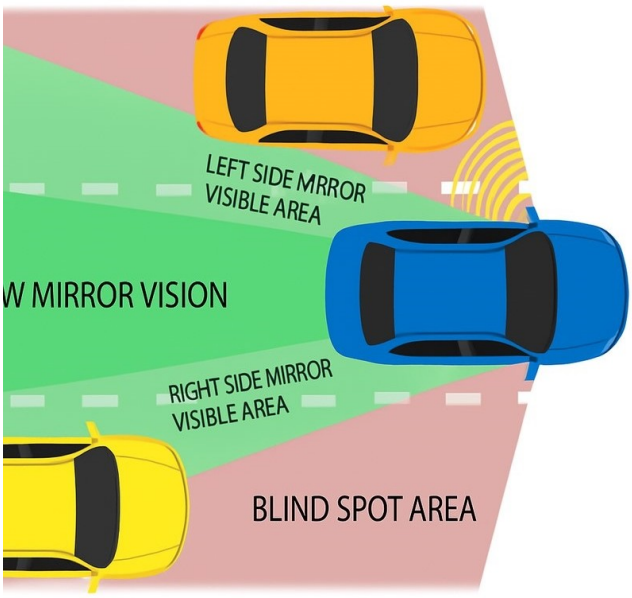


Figure 3.4: Blind Spot Detection Monitoring System

Key Objectives of BSD:

1. Enhance driver awareness by detecting objects or vehicles in blind spots
2. Reduce the risk of side collisions during lane changes or turns.
3. Improve overall road safety

3.2.2 How It Helps the Driver

Blind Spot Detection (BSD) systems are invaluable aids that significantly enhance driver awareness and safety by addressing the critical issue of blind spots. Blind spots are areas around a vehicle that cannot be seen by the driver through the rearview or side mirrors, nor through direct peripheral vision. These hidden zones, often located to the rear and sides of the vehicle, pose a substantial risk, especially during dynamic driving situations. BSD technology actively mitigates this risk by continuously monitoring these unseen areas using an array of sensors, primarily radar or ultrasonic, and in some advanced systems, cameras. When another vehicle enters a monitored blind spot, the system promptly alerts the driver, typically through visual cues (like an illuminated icon in the side mirror) and, if a lane change is initiated, audible or haptic warnings. This immediate notification allows drivers to react proactively, preventing potential collisions. For instance, during highway lane changes, where traffic moves at high speeds and blind spots are particularly dangerous, BSD provides a crucial 'second set of eyes,' alerting the driver to an unseen vehicle before they commit to the maneuver. Similarly, when merging into traffic or navigating multi-lane roads, the system helps drivers make safer decisions by confirming clear adjacent lanes. By extending the driver's perception beyond their natural field of vision, BSD systems reduce driver stress, improve overall situational awareness, and demonstrably contribute to a significant reduction in lane-change related accidents, making roads safer for everyone.

3.2.3 Implementation Methodology

The code implements a BSD system using ultrasonic sensors, LEDs, and a buzzer.

1. Overview of Components
   - **Sensors:** Ultrasonic sensors (e.g., `UL_90, UL_135`) measure distances around the vehicle.
   - **LEDs:** Indicate the presence of objects in the blind spot.
     (a) **Right LED:** Indicates Objects on the right.
     (b) **Left LED:** Indicates Objects on the left.
   - **Buzzer:** Provides an audible warning when an object is detected.
   - **Control Logic:** Determines whether to activate LEDs and buzzer based on sensor inputs.
2. **BSD Initialization**
   The BSD_init function initializes the BSD system by:
   (a) Setting up callback functions for delay, buzzer suspend, and buzzer resume.
   (b) Returning an error status if the BSD structure pointer (p_bls) is NULL.

   `app_status_t BSD_init(BSD_t p_bls , void (p_delay)(uint32_t) , void (p_suspend)(void), void (p_resume)(void))` .
3. **How does Blind Spot Detection Work**
   Periodically, FREERTOS calls the BSD job, which compares the values from the four ultrasonic sensors (UL45, UL90, UL270, and UL315) to Desired Minimum Distance
   (a) If the distances measured by UL45 or UL90 are smaller than MINDISTANCE When the right-side LED turns on, the buzzer begins to sound an alarm.
   (b) If the distances measured by UL270 or UL315 are smaller than MINDISTANCE The buzzer begins to sound an alarm when the LED on the left side is activated.
4. **BSD Task Logic:**
   The `BSD_task` function monitors the ultrasonic sensors and takes actions based on their readings.
   Core Logic:
   (a) **Sensor Input Handling:**
   If the distance from any sensor is less than the minimum safe distance , the system detects a potential object in the blind spot .
   (b) **Actions:**
   - Turn on the right LED if objects are detected on the right (`UL_90, UL_135`).
   - Turn on the left LED if objects are detected on the left (`UL_270, UL_225`).
   - Activate the buzzer for audible alerts.
   - **Safe State:**
     If no objects are detected, all LEDs and the buzzer are turned off, and the buzzer is suspended.

(c) **Buzzer Behavior**
The `BSD_buzzer_task` function manages the buzzer's alert pattern:

- Turns the buzzer on, Delays for 500 milliseconds.
- Turns the buzzer on, Delays for 250 milliseconds.
- Uses the delay callback to manage timing.

(d) **LED and Buzzer Control:**
The system uses inline functions to encapsulate the control of LEDs and the buzzer:

- `right_led_turn_on/off`
- `left_led_turn_on/off`
- `buzzer_on/off/toggle`

These functions rely on helper functions (`logic_set`, `logic_reset`, `logic_toggle`) to change the state of the respective outputs.

3.2.4 Flowchart

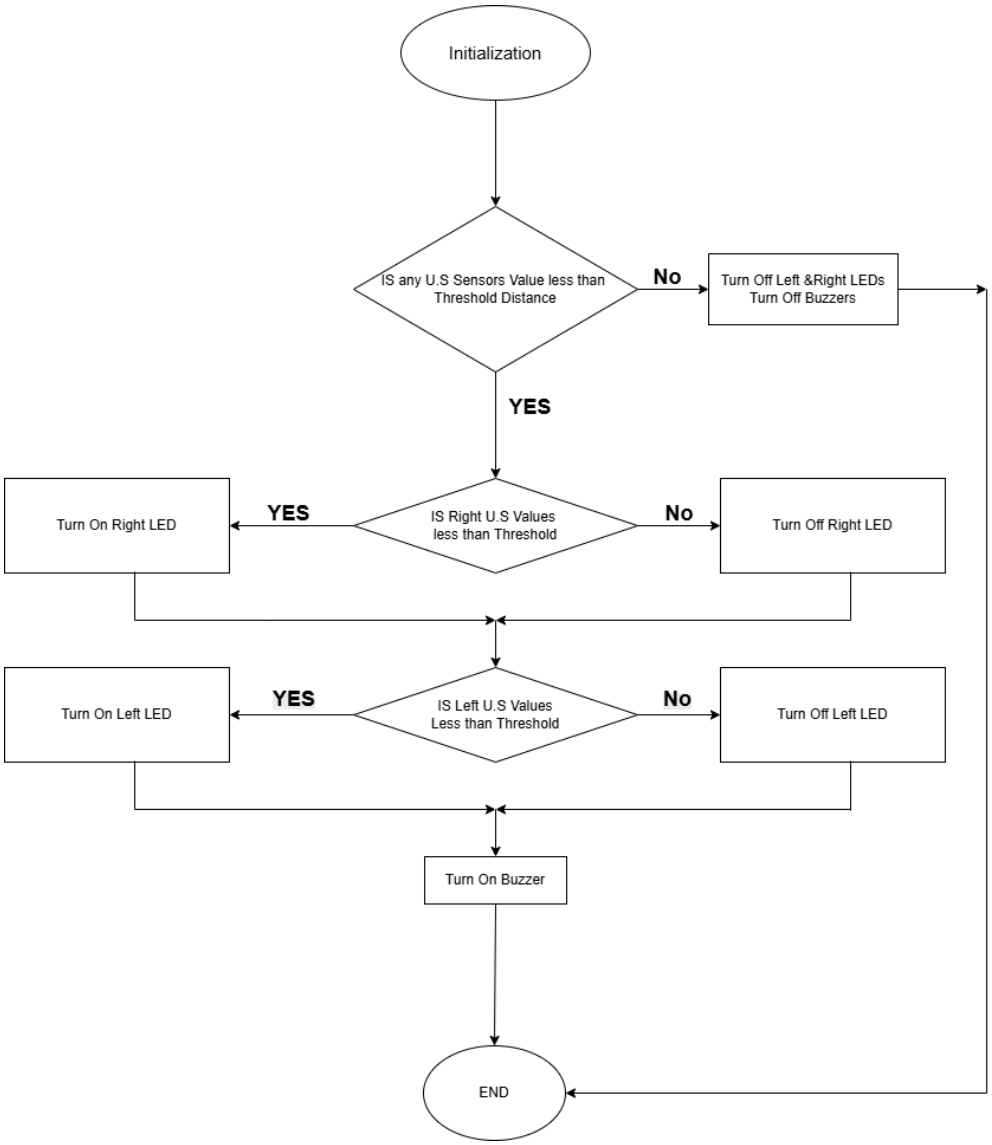


Figure 3.5: System Code Flowchart

3.2.5 Challenges and Limitations

While cost-effective and suitable for certain applications, Blind Spot Detection systems relying solely on ultrasonic sensors and processing on a microcontroller unit inherently face several limitations compared to more advanced, higher-cost components like radar or camera-based systems. Ultrasonic sensors operate by emitting sound waves and measuring the time it takes for the echo to return, which limits their effective range and can be susceptible to environmental factors. Their detection range is typically short, often only a few meters, making them less effective at detecting fast-approaching vehicles from a distance, particularly on highways where closing speeds are high. Furthermore, ultrasonic waves can be absorbed or deflected by certain materials, and their performance can be significantly degraded by adverse weather conditions such as heavy rain, snow, or even strong winds, leading to false negatives or reduced reliability. The limited processing power of a microcontroller unit, while sufficient for basic distance calculations and simple alert logic, may struggle with more complex tasks such as object classification, tracking multiple targets simultaneously, or differentiating between relevant threats and stationary roadside objects. This can result in a higher propensity for false alarms or missed detections in complex traffic scenarios, ultimately impacting the system's overall robustness and the driver's trust in its warnings. Therefore, while offering an accessible entry point into ADAS, ultrasonic-based BSD systems are best suited for low-speed maneuvers and urban environments, and drivers should be aware of their inherent limitations in more demanding driving conditions.

3.3 Auto Parking

3.3.1 Definition and meaning

Auto parking systems are one of the most significant advancements in modern vehicle technology, contributing to Advanced Driver Assistance Systems (ADAS). These systems allow vehicles to autonomously detect suitable parking spots and maneuver into them with minimal or no driver intervention. The implementation of such systems involves a combination of sensor fusion, decision-making algorithms, and precise motor control.

In this project, an auto parking feature has been developed using a robotic platform equipped with ultrasonic sensors, encoders, and a motor control system that enables autonomous detection and execution of both parallel and perpendicular parking maneuvers.

This chapter outlines the design and implementation of the auto parking system, including the underlying algorithm, sensor integration, and software logic used to achieve autonomous parking capabilities.

Types of Parking

The system supports two primary types of parking:

Parallel Parking

- Involves aligning the robot alongside a parked object and then performing a sequence of movements to move into the available space.

- Requires precise distance measurement and controlled reverse movement while adjusting the angle.

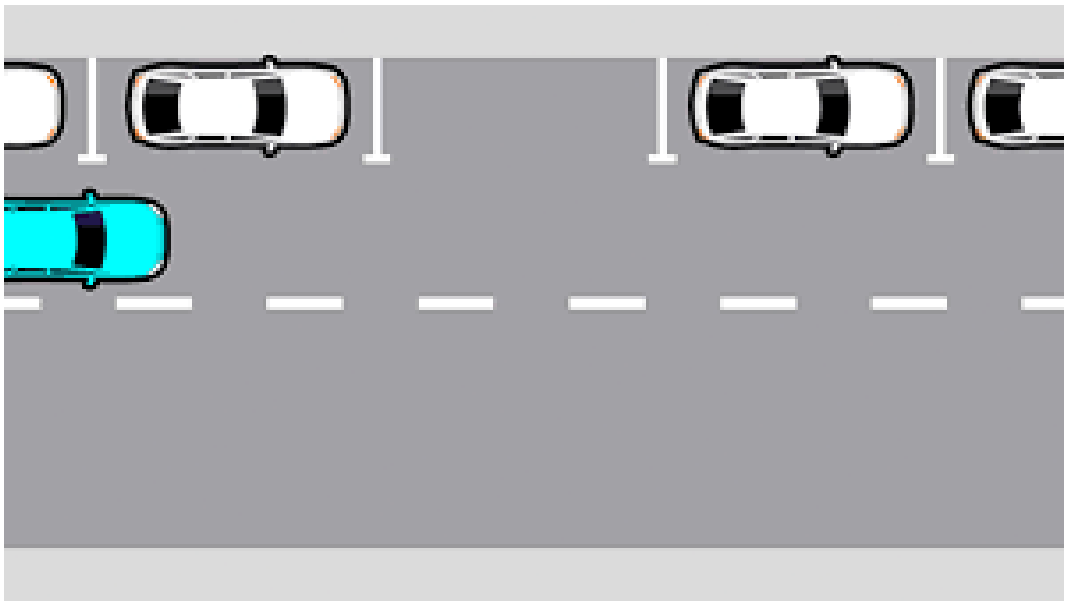


Figure 3.6: Parallel Parking

Perpendicular Parking

- Involves detecting a free area perpendicular to the direction of motion and directly moving into it.
- Requires accurate positioning and alignment to ensure the robot enters space without collisions.

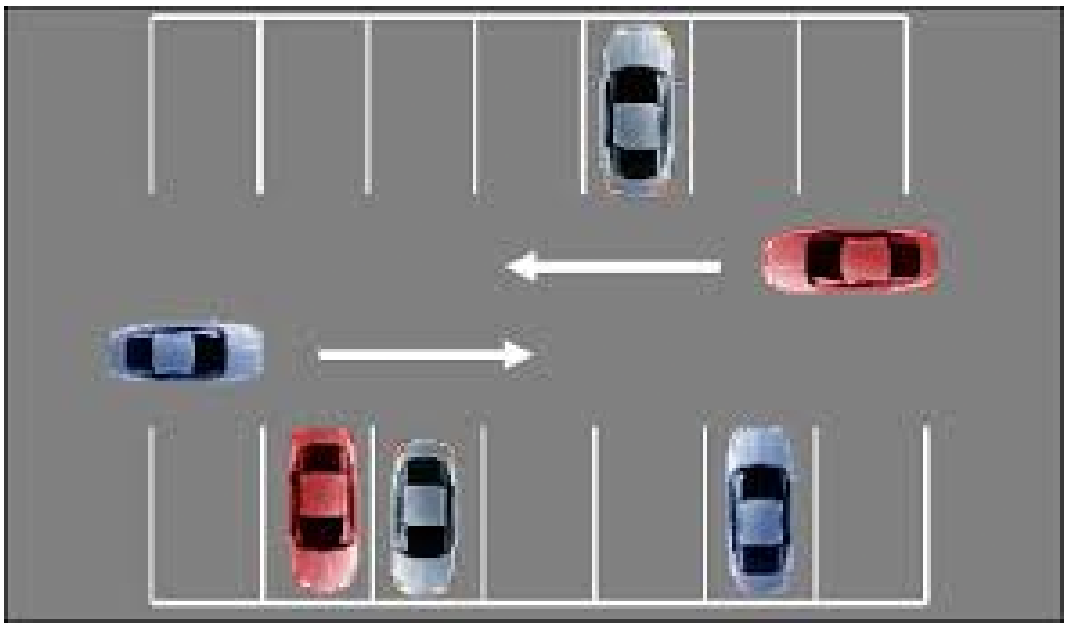


Figure 3.7: Perpendicular Parking

Both types rely on real-time data from ultrasonic sensors and encoder feedback to determine the presence of a valid parking spot and execute the appropriate maneuver.

3.3.2 How It Helps the Driver

The Auto Parking System implemented in your project is a key component of an Advanced Driver Assistance System (ADAS), designed to reduce driver effort and improve safety during parking maneuvers.

Overview Parking is one of the most challenging tasks for many drivers, especially in tight or complex environments. The auto parking system developed in this project aims to assist the driver by:

- Automatically detecting suitable parking spaces
- Selecting the appropriate type of parking (parallel or perpendicular)
- Executing the maneuver with minimal or no driver input

This not only improves convenience but also enhances safety, precision, and user experience.

1. **Reduces Driver Effort**
   - Manual parking requires precise control of steering, speed, and timing.
   - The system automates these actions, allowing the driver to simply initiate the parking process and monitor the surroundings.
   - Example: When a valid space is detected, the robot automatically performs forward alignment, rotation (if needed), and reverse entry — eliminating the need for the driver to manually steer or judge distances.
2. **Improves Safety**
   - The system uses ultrasonic sensors to detect obstacles in real-time.
   - If an object comes too close during the maneuver, the robot automatically stops, preventing collisions.
   - This is especially helpful in blind spots or situations where visibility is limited.
3. **Enhances Precision**
   - Encoder feedback ensures that each movement is executed accurately, maintaining consistent speed and distance.
   - The robot aligns itself precisely within the parking space, avoiding issues like oversteering or misjudging distances.
   - This results in smoother and more accurate parking than many human drivers can achieve consistently.
4. **Simplifies Complex Maneuvers**
   - Perpendicular parking involves multiple steps: forward motion, reverse alignment, rotation, and final backing into the space.
   - Parallel parking requires careful straight-line control.
   - The auto parking feature handles all these steps sequentially and reliably, even under dynamic conditions.

- Drivers are freed from the stress of performing complex movements, especially in high-pressure situations.

5. **Real-Time Feedback and Monitoring**
   - The system continuously monitors sensor data and encoder readings.
   - It provides real-time updates via CAN communication, which could be used to display information on a dashboard or mobile app.
   - This gives the driver confidence in the system's operation and allows them to take control if needed.
6. **Adaptable to Different Environments**
   - The system supports both parallel and perpendicular parking modes.
   - With minor adjustments to thresholds and logic, it can be extended to support angled parking or multi-space selection.
   - This adaptability makes it useful in various urban and indoor environments.
7. **Enables Hands-Free Parking**
   - Once activated, the system can execute the entire parking sequence without requiring further driver input.
   - This is particularly useful for inexperienced drivers or in congested areas where parking is stressful.
   - In future versions, integrating FOTA (Firmware Over-The-Air) will allow continuous improvements and new features without hardware changes.

3.3.3 Implementation Methodology

The auto parking system integrates several hardware and software components working together to enable autonomous behavior.

Components

- Ultrasonic Sensors
- Encoders

Software Modules

- `APK_Check_Side`
- `APK_Check_Axis`
- `APK_Task`

Algorithm Description

The auto parking algorithm follows a structured and modular approach, consisting of the following main steps:

Step 1: Check Available Parking Side

- The system uses two ultrasonic sensors placed at 90° and 270° to measure distances from surrounding objects.
- If the distance on one side exceeds a predefined threshold (`MIN_DISTANCE_PARKING_Y_AXIS`), a potential parking space is detected.
- The system determines whether parking should be performed on the left or right side.

Step 2: Check Parking Axis

- Based on the side identified, the system checks whether the parking space is aligned along the current axis or requires rotation.
- This is determined by comparing the front/rear distances with another threshold (`MIN_DISTANCE_PARKING_X_AXIS`).

Step 3: Execute Parking Maneuver Based on the type of space detected, the system performs either:

- **Perpendicular Parking**: Requires rotating the robot before entering the space.
- **Parallel Parking**: Involves direct entry into the space.

For Perpendicular Parking:

1. Move forward until the desired position is reached.
2. Reverse slightly to align with the parking space.
3. Rotate the robot by 90° (left or right).
4. Complete the maneuver by reversing into space.

For Parallel Parking:

1. Move forward until reaching the parking space.
2. Adjust directions to enter space.
3. Stop when the (left or right) of the robot clears the obstacle.

3.3.4 Flowchart

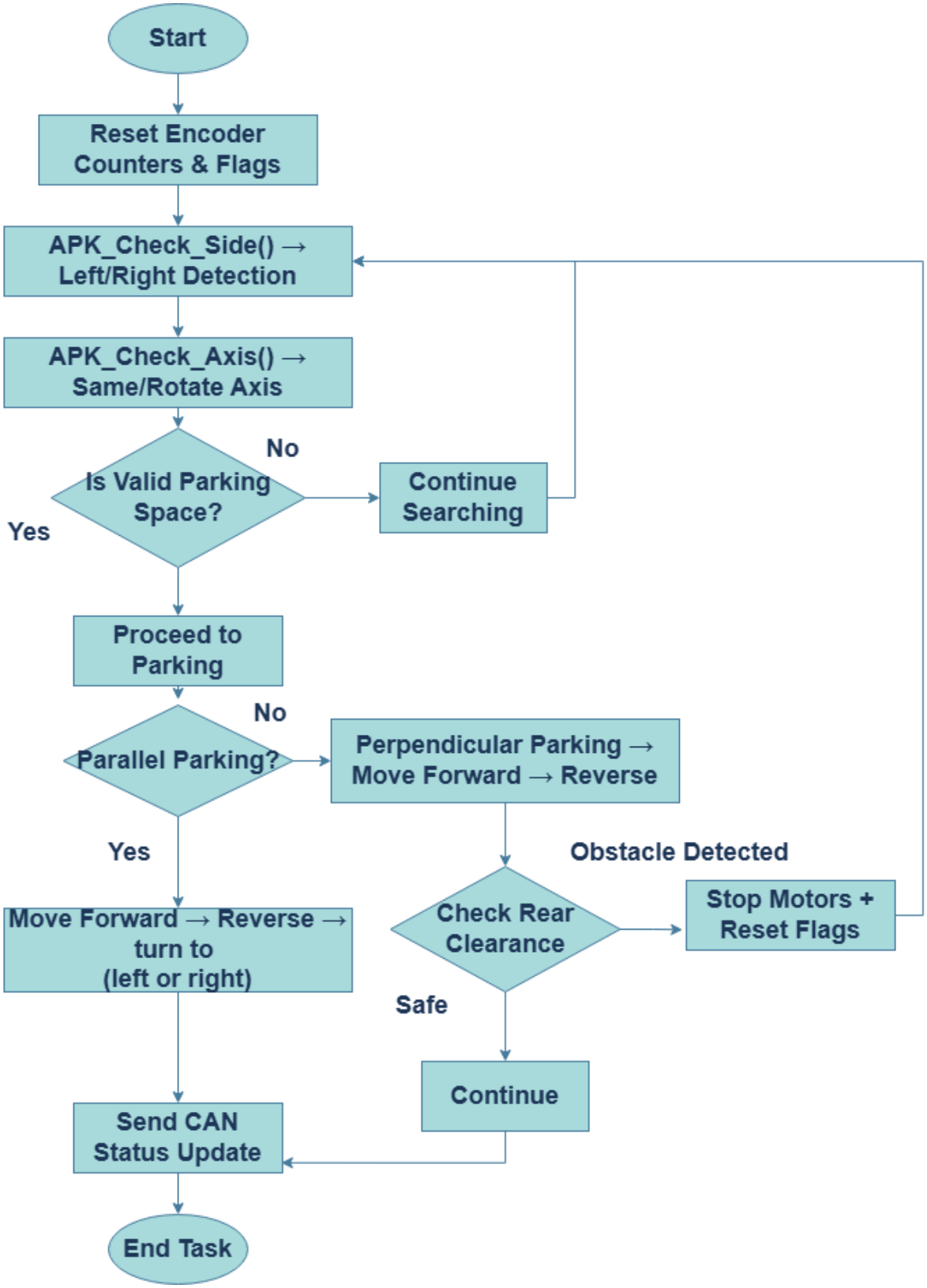


Figure 3.8: Auto Parking Flowchart

3.3.5 Challenges and Limitations

The auto parking system implemented in this project demonstrates autonomous detection and execution of parallel and perpendicular parking maneuvers. However, during development and testing, several technical challenges and system limitations were identified that impacted performance and reliability.

Below is a comprehensive breakdown of these challenges and how they were addressed or mitigated.

Sensor Accuracy and Range Limitations

1. **Challenge:**
   - The system relies on ultrasonic sensors (UL_90°, UL_270°) to detect available parking spaces.
   - These sensors have limited range and are sensitive to environmental conditions such as surface texture, angle of incidence, and temperature.
2. **Solution:**
   - Implemented software filtering to reduce noise and false readings.
   - Set minimum distance thresholds (MIN_DISTANCE_PARKING_X_AXIS, MIN_DISTANCE_PARKING_Y_AXIS) to avoid triggering false positives.
   - Future improvement: Consider integrating LiDAR or IR time-of-flight sensors for more accurate obstacle detection.

Encoder-Based Distance Estimation Errors

1. **Challenge:**
   - The robot uses wheel encoders to estimate movement distances during parking maneuvers.
   - Encoder-based estimation can suffer from slippage, cumulative error, and inaccurate calibration, leading to misalignment during parking.
2. **Solution:**
   - Periodically recalibrated encoder values at the start of each maneuver.
   - Used relative positioning rather than absolute navigation to reduce drift effects.

Limited Decision-Making Logic

1. **Challenge:**
   - The current implementation uses a rule-based algorithm without machine learning or adaptive logic.
   - This limits the robot's ability to handle complex environments, such as angled parking, multi-space selection, or dynamic obstacles.
2. **Solution:**
   - Expanded decision logic to distinguish between parallel and perpendicular spaces based on sensor input.
   - Added flags like Min_Distance_Flag and Parking_Flag to manage state transitions cleanly.
   - Future improvement: Implement vision-based systems or integrate with ROS (Robot Operating System) for intelligent path planning.

Fixed Thresholds and Hardcoded Values

1. **Challenge:**
   - The system uses fixed threshold values (e.g., MIN_DISTANCE_PARKING_Y_AXIS) to determine whether a space is valid.
   - These values may not be suitable across different environments or robot speeds.
2. **Solution:**
   - Calibrated thresholds experimentally under lab conditions.
   - Allowed manual tuning through configuration files or flash memory.
   - Future improvement: Enable dynamic threshold adjustment using AI or real-time sensor fusion.

Lack of Real-Time Obstacle Avoidance During Maneuver

1. **Challenge:**
   - Although the robot checks for obstacles before starting a maneuver, it does not actively monitor surroundings during the parking process.
   - If an object enters the robot's path mid-maneuver, the system may collide with it.
2. **Solution:**
   - Monitored rear ultrasonic sensor (UL_180) to stop the robot if an obstacle was detected during reverse entry.
   - Future improvement: Integrate real-time obstacle avoidance logic and emergency braking mechanism.

3.4 Traffic Sign Recognition

Figure 3.9: Traffic Sign Recognition System

3.4.1 Definition and Meaning

Traffic Sign Recognition (TSR) is an advanced computer vision system integrated into modern Advanced Driver Assistance Systems (ADAS) to detect, classify, and interpret traffic signs in real time. The primary goal of TSR is to enhance vehicle intelligence and driver awareness by providing timely recognition of crucial traffic signs such as speed limits, stop signs, yield signs, and various warning indicators.

TSR systems utilize forward-facing cameras mounted on the vehicle to continuously scan the road environment. The captured video frames are processed using sophisticated image processing and deep learning algorithms. Detected signs are then translated into meaningful actions such as visual alerts, dashboard notifications, or even vehicle behavior adjustments when combined with other ADAS features like adaptive cruise control or lane keeping.

In our graduation project, we implemented a real-time TSR system that operates on a `Raspberry Pi 5`. Using a live camera feed and a pre-trained `YOLOv5` deep learning model, the system can detect and recognize multiple types of traffic signs and display the results through a live visual interface. This feature can serve as a foundation for future integrations with autonomous driving functionalities.

3.4.2 How It Helps the Driver

The integration of TSR into ADAS systems plays a critical role in improving road safety, reducing cognitive load on the driver, and enhancing the vehicle's environmental awareness. Below are specific ways TSR benefits the driver:

a. Accurate Interpretation of Road Signs

- Helps the driver stay informed of speed limits, regulatory signs, and warning signs, particularly in unfamiliar regions or during long-distance driving.

b. Reduction of Human Error

- Assists in situations where the driver may be distracted or unable to see signs due to weather, lighting, or traffic congestion.

c. Improved Compliance with Traffic Laws

- Real-time recognition of signs such as "No Entry", "Stop", or "Yield" encourages safer driving and adherence to legal requirements.

d. Integration with Vehicle Behavior

- TSR output can feed into systems like Adaptive Cruise Control (ACC), where the vehicle automatically adjusts its speed upon recognizing a new speed limit.
- Can provide audible or visual alerts when the driver is violating recognized sign regulations.

3.4.3 Implementation Methodology

The development of the TSR system in our project followed a modular, embedded approach. The objective was to achieve real-time performance using cost-effective hardware and open-source tools. The following subsections explain the methodology in detail.

a. Hardware Components

- **Camera Module (USB Webcam):** A basic forward-facing webcam was mounted on the vehicle prototype to capture live video frames. It was connected directly to the Raspberry Pi via USB and interfaced using OpenCV.
- **Processing Unit – Raspberry Pi 5:** The Raspberry Pi was selected for its balance between computational power and cost. It provided sufficient resources for running Python scripts, OpenCV image processing, and TensorFlow inference at acceptable real-time speeds (10–12 FPS).

b. Software Environment

- **Operating System:** Raspberry Pi OS (Debian-based)
- **Programming Language:** Python 3.9
- **Libraries and Frameworks:**
  - OpenCV: For image capture, preprocessing, and display
  - NumPy: For efficient matrix and array operations
  - Keras: For loading and running the TensorFlow Lite model
  - TensorFlow: For model inference and processing
  - Matplotlib (Optional): For visualizing performance metrics

c. Model and Dataset

- **TensorFlow Lite Model:** A lightweight, fast object detection model based on convolutional neural networks. Selected for its suitability on embedded systems like Raspberry Pi.
- **Dataset – GTSRB (German Traffic Sign Recognition Benchmark):** The Tensorflow model was pre-trained on this dataset, which includes over 50,000 images across 43 traffic sign classes, ensuring wide coverage of commonly used signs in road environments.

d. Processing Pipeline

1. **Frame Acquisition**
   - The camera captures real-time frames at 15 FPS.
   - Frames are sent to the TSR pipeline using `cv2.VideoCapture()`.
2. **Preprocessing**
   - Images are resized to 320x320 pixels.
   - RGB color conversion and normalization are applied to match model input requirements.
3. **Traffic Sign Detection (Tensorflow Inference)**
   - The frame is passed to the tensorflow model.
   - Model outputs include bounding box coordinates, class index, and confidence score.
4. **Classification and Post-Processing**
   - Detected signs are mapped to class names (e.g., “Speed Limit 50”, “Stop”).
   - Bounding boxes and labels are drawn on the frame using OpenCV.
5. **Integration and Output**
   - The final annotated frame is displayed in real-time.
   - Recognition data can be optionally logged or transmitted to other ADAS modules for decision-making.

3.4.4 Block Diagram / Flowchart

The following diagram outlines the internal flow of the TSR system:

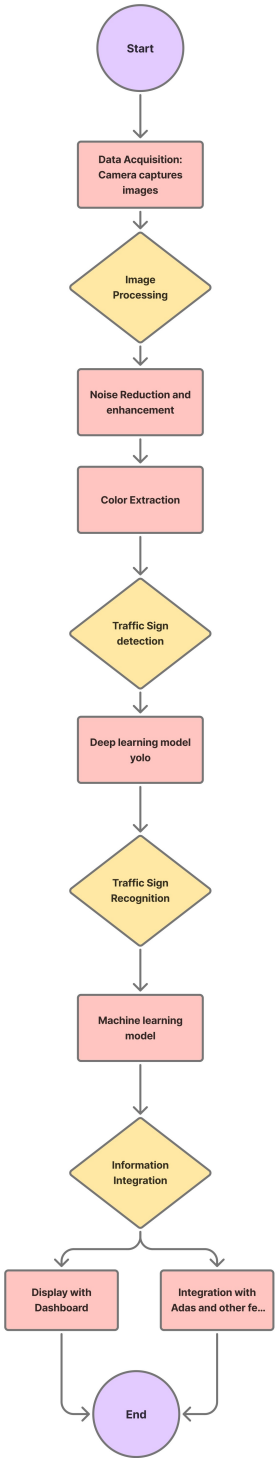


Figure 3.10: TSR System Block Diagram

Explanation:
The system starts by acquiring frames from the camera, followed by preprocessing steps such as resizing and normalization. The preprocessed frame is then passed through the YOLOv5 deep learning model for detection and classification. Recognized signs are displayed on-screen and can be integrated with other ADAS systems if needed.

3.4.5 Challenges and Limitations

Although the TSR system performed well in test environments, several real-world challenges were encountered during development and testing:

a. Environmental Conditions

- **Lighting Variability:** Overexposure, glare, and shadows can degrade sign visibility.
- **Weather Interference:** Rain or fog can obscure camera vision and reduce detection accuracy.

b. Hardware Limitations

- **Low Frame Rate:** Raspberry Pi 5's performance limits detection to around 10–12 FPS.
- **Camera Quality:** Basic webcams may lack the sharpness and dynamic range needed in all conditions.

c. Model Constraints

- **False Positives:** Misclassification of irrelevant objects as traffic signs (e.g., billboards, logos).
- **Training Dataset Bias:** GTSRB does not include non-European signs or construction/temporary signs, which can lead to missed detections.

d. Integration Limitations

- **Lack of Feedback Loop:** Currently, the system displays detection results but does not actively influence vehicle behavior (e.g., braking or steering).
- **Latency:** There is minor delay (100–150 ms) in processing and displaying detection results.

3.5 Lane Keeping and Auto Lane Change

3.5.1 Definition and Meaning

Lane Keeping Assist

The Lane Keeping Assist (LKA) feature in Advanced Driver Assistance Systems (ADAS) is a critical technology designed to enhance vehicle safety by preventing unintentional lane departures, thereby reducing the risk of collisions caused by driver inattention or fatigue. Utilizing a combination of cameras and sophisticated image-processing algorithms, the LKA system continuously monitors the vehicle's position relative to lane markings on the road. When the system detects that the vehicle is drifting out of its lane without an active turn signal, it intervenes by applying corrective motion or gently braking individual wheels to guide the car back into the center of

the lane. Some advanced implementations even incorporate machine learning and artificial intelligence to improve accuracy under varying road conditions, such as poorly marked lanes, sharp curves, or adverse weather. The system typically operates in conjunction with other ADAS functionalities like Lane Departure Warning (LDW), which provides auditory or haptic alerts before active intervention, ensuring a layered approach to safety. Modern LKA systems also integrate with adaptive cruise control and traffic sign recognition to create a more cohesive and intelligent driving experience. Despite its benefits, challenges remain, including false activations in complex urban environments, reliance on clear lane markings, and the need for driver awareness to prevent over-reliance on automation. As automotive technology evolves, LKA is expected to become more robust, with future iterations potentially leveraging vehicle-to-everything (V2X) communication and high-definition mapping for even greater precision. Ultimately, the Lane Keeping Assist feature represents a significant step toward semi-autonomous and fully autonomous driving, prioritizing safety while reducing driver workload on long journeys or in monotonous traffic conditions.

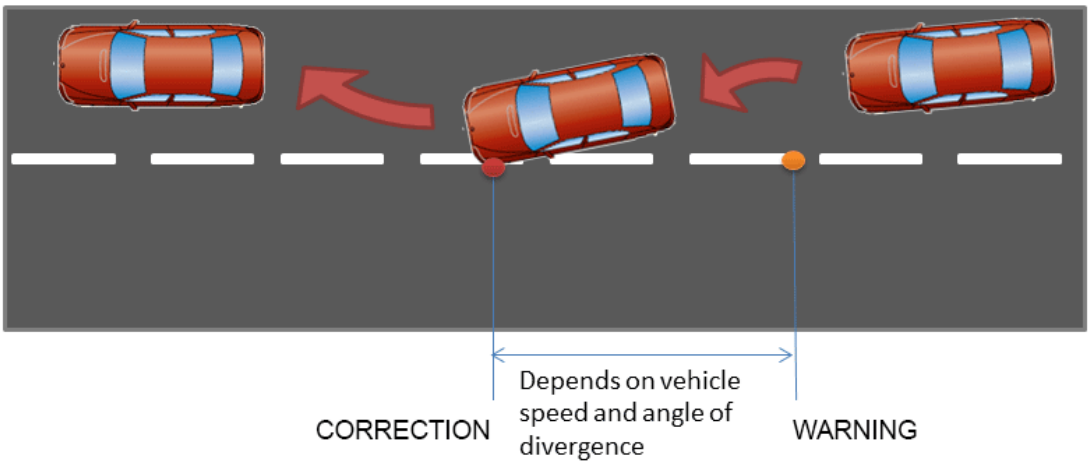


Figure 3.11: Lane Keeping Assist System

Auto Lane Change

The Auto Lane Changing feature in Advanced Driver Assistance Systems (ADAS) represents a pivotal innovation in modern automotive technology, bridging the gap between driver-assist functions and fully autonomous driving by enabling vehicles to independently assess, initiate, and execute lane changes with minimal human input. This sophisticated system relies on multi-sensor fusion architecture, incorporating high-resolution cameras and in some advanced implementations, LiDAR (Light Detection and Ranging) is used to construct a comprehensive, real-time 360-degree perception of the vehicle's surroundings. By continuously monitoring lane markings, adjacent vehicles, traffic flow, and road conditions, the system employs complex algorithms often powered by machine learning and artificial intelligence to evaluate whether a lane change is both safe and optimal. When the driver activates the turn signal (or, in higher autonomy levels, when the system autonomously determines a need to overtake a slower vehicle or prepare for an upcoming exit), the vehicle conducts a multi-stage validation process: first, it checks blind spots using Blind Spot Detection (BSD); then, it assesses the speed and trajectory of approaching vehicles via Rear Cross-Traffic Alert (RCTA) and adaptive radar tracking; and finally, it predicts potential risks using probabilistic modeling to ensure no sudden obstacles emerge during the maneuver. Once the system confirms a safe window, it seamlessly coordinates with Electric Power Steering (EPS),

Electronic Stability Control (ESC), and Adaptive Cruise Control (ACC) to execute a smooth lane transition, adjusting speed and torque with precision to avoid abrupt movements that could unsettle passengers or surprise nearby drivers. In traffic jam scenarios, some advanced systems can even perform creeping lane changes at low speeds, leveraging stop-and-go functionality to navigate congested highways.

However, despite its advanced capabilities, the auto lane-changing feature faces challenges, including sensor limitations in heavy rain or snow, ambiguous lane markings in construction zones, and unpredictable human driver behavior, which necessitate continuous refinement through over-the-air (OTA) updates and deeper integration with Vehicle-to-Everything (V2X) communication networks. Future advancements aim to incorporate predictive AI that can anticipate traffic patterns, cooperative driving algorithms allowing vehicles to negotiate lane changes with each other, and HD mapping integration for centimeter-level accuracy in complex urban environments. As the automotive industry progresses toward Level 4 and Level 5 autonomy, auto lane changing will evolve from a convenience feature into a fundamental component of fully self-driving systems, enabling safer, more efficient, and less stressful highway travel while reducing human error. Ultimately, this technology not only enhances driver comfort but also lays the groundwork for a future where interconnected, intelligent vehicles communicate seamlessly to optimize traffic flow, minimize congestion, and revolutionize the way we experience mobility.

Figure 3.12: Auto Lane Change System

3.5.2 How It Helps the Driver

Lane Keeping Assist

Imagine driving down a winding coastal highway at sunset, the ocean breeze drifting through your open window as you relax into your seat without caring about accidentally veering out of your lane. This effortless confidence is made possible by Lane Keeping Assist (LKA), a guardian angel of modern driving that blends seamlessly into the background until the moment it's needed. Unlike traditional driver aids that beep or vibrate in protest, LKA works like an invisible co-pilot, gently nudging the steering wheel with the subtlety of an experienced driver's guiding hand. It doesn't just react to lane markings—it anticipates, using real-time data to distinguish between intentional steering inputs (like avoiding a pothole) and unintended drifts (like a drowsy moment on a late-night drive). For parents, it's peace of mind when teaching teens to drive; for commuters, it transforms stop-and-go traffic from a chore into a more relaxed experience. The system even adapts to your driving style, learning when to intervene more assertively on sharp curves or ease off during creative parking maneuvers. Far from being robotic override, LKA enhances the human aspect of driving, letting you enjoy the journey while it quietly ensures the tires stay exactly where they should. In a world where split-second distractions are inevitable, this technology doesn't just protect you.it lets you reclaim the joy of driving without fear.

Auto Lane Change

Imagine you're cruising down the highway, your favorite song playing, when you notice the car ahead slowing down. Without lifting a finger, your car smoothly glides into the next lane as if reading your mind finding the perfect gap in traffic with the precision of a seasoned driver. This isn't science fiction; it's Auto Lane Changing, the ultimate driving wingman that turns highway navigation into a seamless dance. Unlike basic cruise control that just maintains speed, this system transforms your vehicle into an observant partner, constantly scanning blind spots with hawk-like attention, predicting other drivers' moves before they make them, and executing lane changes with the confidence of a Formula 1 pit crew. It's like having a chauffeur's intuition built into your car anticipating when you'll want to pass that lumbering truck before you even signal or subtly adjusting its timing when it senses an aggressive driver approaching in the fast lane. For road-trippers, it means effortless thousand-mile journeys where fatigue never compromises safety; for busy parents, it's an extra set of eyes during chaotic school-run traffic. The magic lies in its adaptability—on a packed German autobahn, it might make assertive, rapid lane changes, while in Los Angeles traffic, it adopts a more relaxed, defensive style. By handling stressful calculations of speed differentials, safe following distances, and merging angles, the technology doesn't just assist your driving it elevates it, turning the most tedious part of long journeys into an opportunity to relax. This isn't just automation; it's automotive empathy, a system that doesn't just follow commands but understands intent, proving that the future of driving isn't about replacing humans, it's about enhancing our instincts with superhuman perception.

3.5.3 Implementation Methodology

Lane Keeping Assist

To simply implement LKA a webcam running on a raspberry pi is used. The camera resolution is 1280x720 pixels. Using OpenCV each frame captured by the camera is divided into 4 smaller frames the left frame, the center left frame, the center right frame and the right frame. The car has 5 drift status drift right status, drift left status, left center status, right center status and centralized status. The algorithm depends on determining the white color percentage and yellow color in each of the 4 frames then comparing them to certain thresholds and depending on the percentages of these colors in each frame the car position is determined relative to the lane. The color is detected using HSV color ranges as the following: lower yellow threshold (15,150,20), upper yellow threshold (35,255,255), lower white threshold (0,0,150) and upper white threshold (180,70,255). When the percentage of white and yellow colors in each frame is calculated the position of the car can be determined easily according to an algorithm that will be explained later.

HSV Representation The HSV (Hue, Saturation, Value) color model is an alternative representation to the traditional RGB (Red, Green, Blue) system, designed to align more closely with how humans perceive and describe colors. Unlike RGB, which decomposes colors into additive primary components, HSV organizes color information in a cylindrical coordinate system, separating chromatic attributes into three distinct dimensions for more intuitive manipulation. Hue, the first component, defines the dominant color in terms of its position on the color wheel, expressed as an angle between 0° and 360°, where 0° corresponds to red, 120° to green, and 240° to blue, with intermediate angles representing blends between these primary colors. Saturation, the

second dimension, measures the intensity or purity of the color, ranging from 0% (a completely desaturated, grayscale tone) to 100% (a fully vivid, rich color). This allows for easy adjustments to make colors appear more muted or vibrant without altering their base hue. The third component, Value (sometimes referred to as Brightness or Lightness), determines the overall luminosity of the color, scaling from 0% (pure black, regardless of hue or saturation) to 100% (the brightest possible version of the color, depending on saturation). This separation of hue, saturation, and brightness makes HSV particularly useful in applications like image editing, where users may want to adjust color balance, enhance contrast, or isolate specific color ranges without affecting other attributes. Additionally, HSV is widely employed in computer vision tasks such as object detection, color-based segmentation, and thresholding, as it simplifies the process of distinguishing between different colors under varying lighting conditions. For example, in automated systems that detect traffic lights or skin tones, converting an image from RGB to HSV can make it easier to filter hues of interest while compensating for shadows or highlights. The model's perceptual uniformity, where changes in numerical values correspond more predictably to visual changes, also benefits artistic and design workflows, enabling precise color grading and correction. Despite its advantages, HSV does have limitations, such as its dependence on a single hue axis, which can lead to discontinuities in color transitions (e.g., red at 0° and 360°), and its less direct relationship with digital display technologies, which inherently use RGB. Nevertheless, HSV remains a cornerstone of color theory in computing, bridging the gap between technical color representation and human-centric color interaction. Its variants, such as HSL (Hue, Saturation, Lightness) and HSB (Hue, Saturation, Brightness), further refine this approach, but HSV's balance of simplicity and effectiveness ensures its continued relevance in graphics, vision, and user interface design.

Auto Lane Change

The auto lane change feature is implemented in the same script with LKA feature. Auto lane change depends on the same parameters as LKA, the white and the yellow colors percentages in the 4 given frames. However, the lane may have 4 different statuses not 5 as LKA left only, right only, left right and lane error. The left only status represents the status when only a left lane is available, the right only status represents the status when only a right lane is available, the left right status represents the status when a right lane and a left lane are available and the lane error status represents the status when the camera can't determine any lane in unmarked roads or slightly marked roads. When it is required to change the lane while driving just give the signal to the car and the car will automatically change the lane. The can controller sends an update every 0.25 seconds to the STM32 so that it can control the motors according to the lane status and the drift status.

3.5.4 Block Daigram and Flowchart

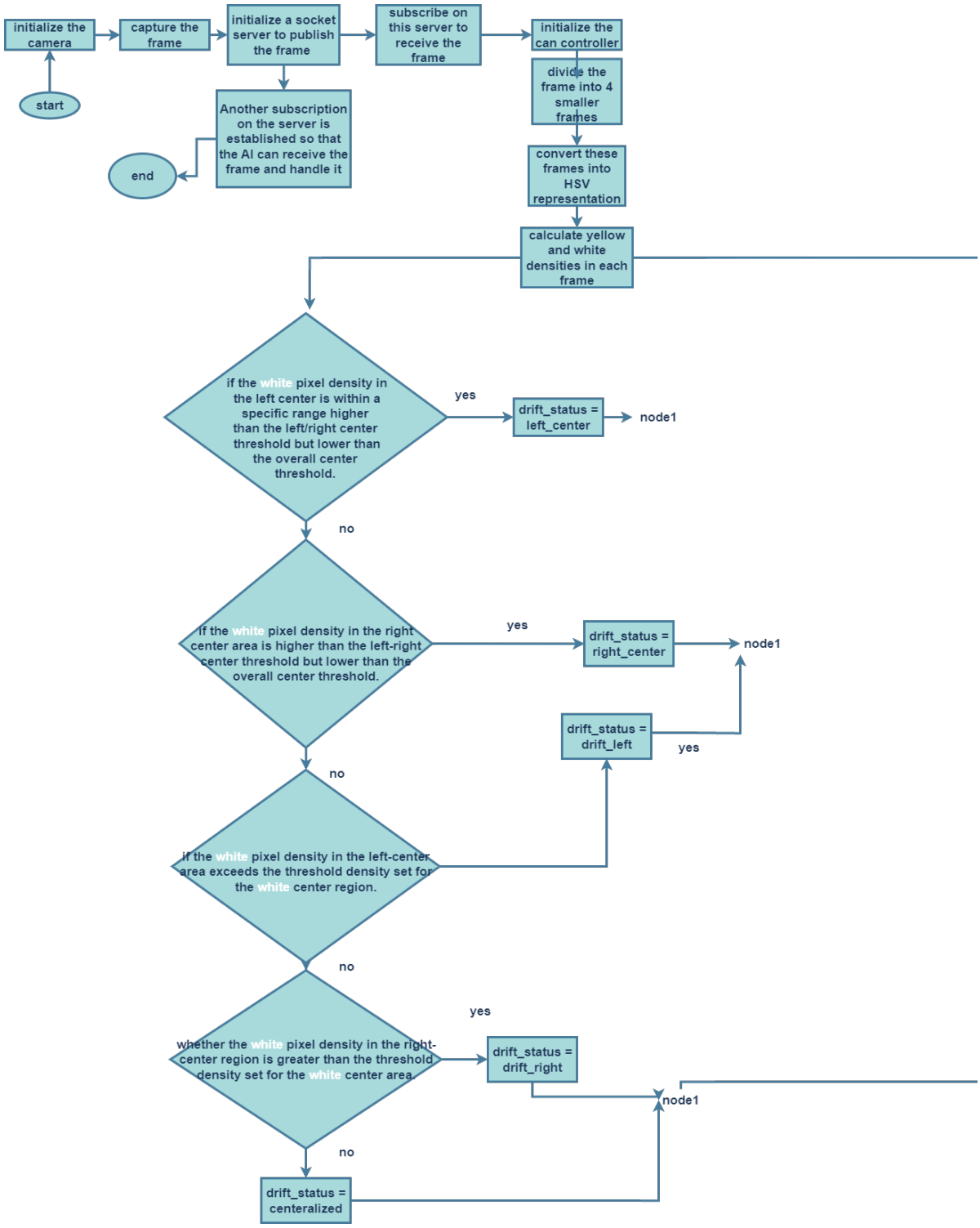
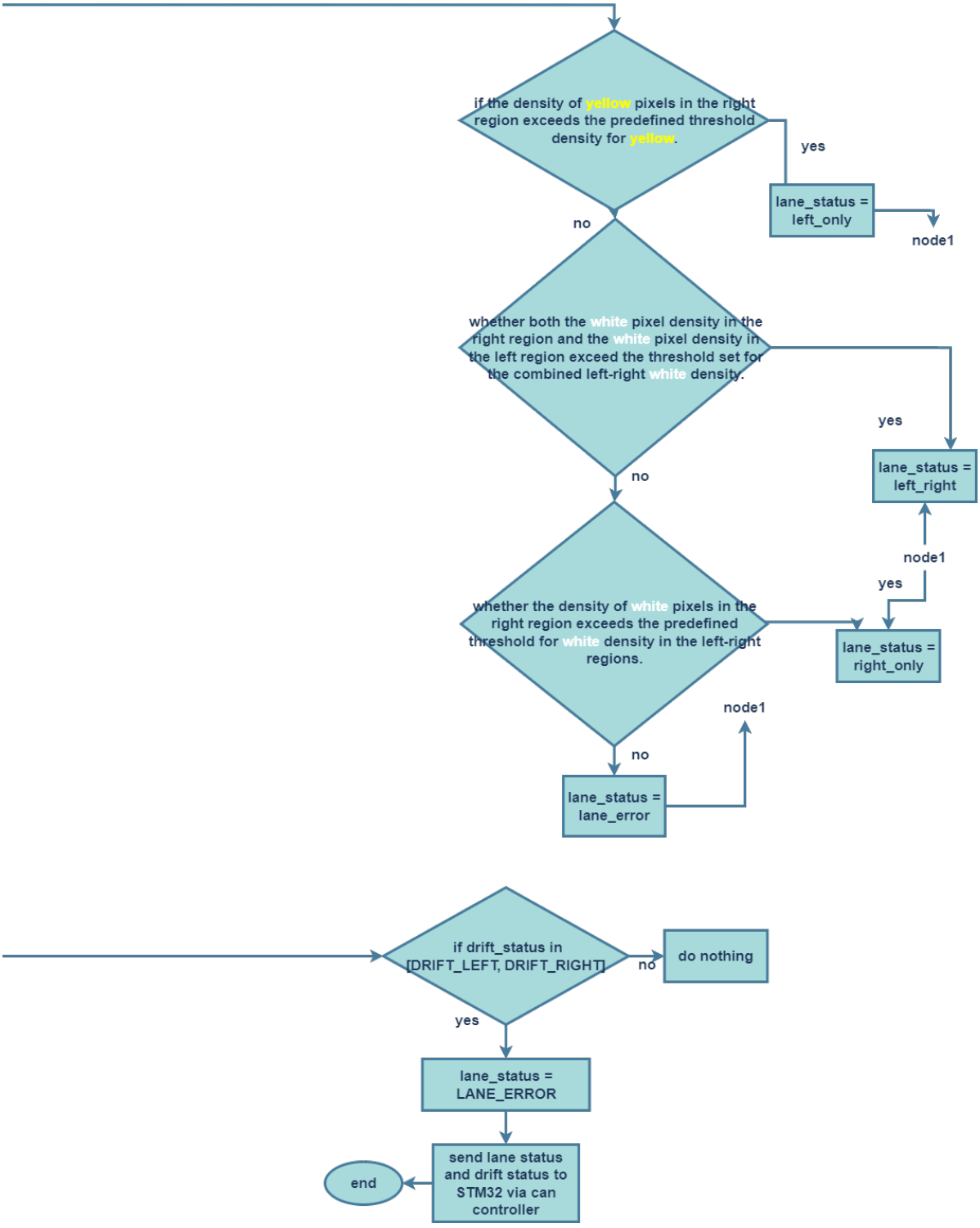


Figure 3.13: Lane Keeping Assist and Auto Lane Change Flowchart


if the density of yellow pixels in the right region exceeds the predefined threshold density for yellow.
yes
lane_status = left_only
node1
no
whether both the white pixel density in the right region and the white pixel density in the left region exceed the threshold set for the combined left-right white density.
yes
lane_status = left_right
node1
no
whether the density of white pixels in the right region exceeds the predefined threshold for white density in the left-right regions.
yes
lane_status = right_only
node1
no
lane_status = lane_error
if drift_status in [DRIFT_LEFT, DRIFT_RIGHT]
no
do nothing
yes
lane_status = LANE_ERROR
send lane status and drift status to STM32 via can controller
end

3.5.5 Challenges and Limitations

Challenges and Limitations that can oppose LKA and Auto Lane Change

While Lane Keeping Assist (LKA) and Auto Lane Changing represent remarkable advancements in vehicle automation, they are not without significant challenges and limitations that impact their reliability and widespread adoption. One of the primary hurdles for LKA is its dependence on clearly visible lane markings, faded, obscured, or missing lines due to weather, construction, or poor road maintenance can render the system ineffective or cause erratic behavior. Additionally, LKA struggles in complex urban environments with frequent intersections, merging lanes, or ambiguous traffic patterns, where human judgment remains superior. The system's steering interventions can sometimes feel intrusive or unnatural, particularly on winding roads, leading to driver discomfort or unintended overrides. Auto Lane Changing, while impressive, faces even greater challenges, including accurately predicting the behavior of surrounding vehicles, especially in aggressive or unpredictable traffic conditions where human drivers may not adhere to expected norms. Sensor limitations, such as radar being affected by heavy rain or LiDAR struggling with fog, can degrade performance, while blind spot detection may fail to account for fast-approaching vehicles or motorcycles filtering through traffic. Both systems also grapple with legal and ethical dilemmas, such as determining liability in the event of a malfunction or deciding how aggressively to execute maneuvers in edge-case scenarios (e.g., avoiding a collision at the cost of crossing solid lane markings). Furthermore, over-reliance on these features risks driver complacency, where motorists may pay less attention to the road, assuming the car will handle all situations flawlessly. Cybersecurity vulnerabilities also pose a threat, as malicious actors could potentially exploit sensors or communication systems to induce false lane changes or disable safety interventions. Finally, the lack of standardized regulations across regions means performance and safety thresholds vary, complicating global implementation. While ongoing advancements in AI, sensor fusion, and V2X (vehicle-to-everything) communication aim to address these issues, these limitations highlight that even the most sophisticated ADAS features still require an attentive, responsible driver behind the wheel at least until fully autonomous systems achieve true robustness in all driving conditions.

3.6 Driver Drowsiness Detection

3.6.1 Definition and Meaning

Driver Drowsiness Detection (DDD) is a critical component of modern Advanced Driver Assistance Systems (ADAS) designed to monitor the driver's alertness and prevent accidents caused by fatigue or inattention. Drowsy driving significantly impairs reaction time, decision making, and overall vehicle control, leading to an increased risk of collisions.

A Driver Drowsiness System utilizes various sensors (e.g., cameras, steering input monitors, or physiological sensors) combined with machine learning algorithms to detect signs of fatigue, such as:

- Eye closure duration (PERCLOS – Percentage of Eye Closure)
- Head pose and nodding movements
- Yawning frequency

- Steering pattern deviations
- Lane departure warnings

Upon detecting drowsiness, the system issues visual, auditory, or haptic alerts to prompt the driver to take corrective action, such as taking a break. In more advanced implementations, the system may integrate with autonomous emergency braking (AEB) or lane-keeping assist (LKA) to mitigate risks if the driver fails to respond.

The inclusion of drowsiness detection in ADAS enhances road safety by reducing human error related accidents, aligning with the broader goals of intelligent transportation systems and the progression toward semi-autonomous and autonomous vehicles.

Figure 3.14: Driver Drowsiness Detection System

3.6.2 How It Helps the Driver

The Driver Drowsiness Detection System plays a crucial role in enhancing road safety by actively monitoring the driver's condition and intervening when signs of fatigue are detected. Here's how it benefits the driver:

1. **Prevents Accidents Due to Fatigue**
   - Drowsiness slows reaction time and impairs judgment, increasing the risk of collisions.
   - By detecting early signs of fatigue (e.g., prolonged eye closure, yawning, or irregular steering), the system provides timely warnings, allowing the driver to take corrective action before an accident occurs.
2. **Real-Time Alerts for Immediate Awareness**
   - The system uses visual (dashboard warnings), auditory (beeps/alarms), or haptic (steering wheel vibrations) alerts to grab the driver's attention.
   - Some advanced systems may also suggest taking a break if persistent drowsiness is detected.

3. **Improves Long-Distance and Night Driving Safety**
    - Drivers on long trips or night shifts are more prone to microsleep episodes.
    - Continuous monitoring helps maintain driver alertness, especially in monotonous driving conditions.
4. **Complements Other ADAS Features**
    - Integrates with Lane Keeping Assist (LKA) to prevent unintentional lane drifting.
    - Works alongside Adaptive Cruise Control (ACC) to maintain safe following distances if the driver is slow to react.
    - In extreme cases, may trigger Autonomous Emergency Braking (AEB) if the driver is unresponsive.
5. **Encourages Safer Driving Habits**
    - By making drivers aware of their fatigue levels, the system promotes self-regulation, encouraging them to rest before continuing their journey.
    - Can log drowsiness events, helping fleet managers or individual drivers track patterns and improve driving behavior over time.
6. **Reduces Insurance and Liability Risks**
    - Vehicles equipped with drowsiness detection may qualify for lower insurance premiums due to reduced accident risks.
    - For commercial fleets, it helps companies comply with driver safety regulations, minimizing legal liabilities.

3.6.3 Implementation Methodology

The driver drowsiness detection system was designed to enhance road safety by monitoring the driver's alertness in real-time and intervening when signs of fatigue are detected. The implementation follows a structured approach:

1. **Model Training & Integration** This section describes the process of training the drowsiness detection model. It will be described in section 5.3.
2. **Real-Time Detection & Thresholds**
    - **Camera Feed Analysis:** The system continuously captures and processes the driver's face using an onboard camera.
    - **Drowsiness Metrics:**
        - Eye Closure Duration: Measures how long the driver's eyes remain closed (e.g., using PERCLOS metrics).
        - Head Pose Estimation: Detects nodding or tilted head positions.
        - Blink Frequency: Monitors abnormal blink patterns (excessive or slow blinking).
    - **Dynamic Thresholds:**

  - Alert Threshold (3 seconds): If drowsiness is detected beyond this duration, the system activates warnings.
  - Emergency Threshold (8 seconds): If the driver remains unresponsive, the system escalates to emergency protocols.

3. **Response Mechanism**

   - **Warning Phase (3–8 seconds):**
     - Audible Alarm: A loud, escalating sound alerts the driver to take action.
     - Visual Warning: A dashboard notification prompts the driver to rest.
   - **Emergency Phase (Beyond 8 seconds):**
     - Automatic Parking: The vehicle initiates a controlled stop (e.g., pulling over or parking) if safe to do so.
     - Emergency Email: The system sends the vehicle's approximate GPS coordinates to a predefined contact via email, including a Google Maps link for quick location tracking.

4. **Recovery & Safety Logic**

   - **Driver Wake-Up Detection:** If the driver wakes up during the Warning Phase, the system:
     - Resets the Timer: The 3-second alert threshold restarts.
     - Silences Alarms: Only after confirming 3 seconds of sustained attentiveness (open eyes, upright posture).
   - **Fail-Safe Design:**
     - False Positive Mitigation: Short, intermittent drowsiness (e.g., blinking) does not trigger alarms.
     - Manual Override: Drivers can dismiss warnings if awake (e.g., pressing a button).

5. **System Configuration & Adaptability**

   - **Adjustable Parameters:** Thresholds (3s/8s), alarm volume, and email recipients can be modified via a user-friendly interface.
   - **Location Services:** Uses a combination of GPS (if available) and IP-based approximation to determine the vehicle's position during emergencies.

This methodology ensures proactive fatigue detection while prioritizing driver and road safety through gradual interventions. The system minimizes false alarms while responding decisively to genuine drowsiness episodes.

3.6.4 Block Diagram and Flowchart

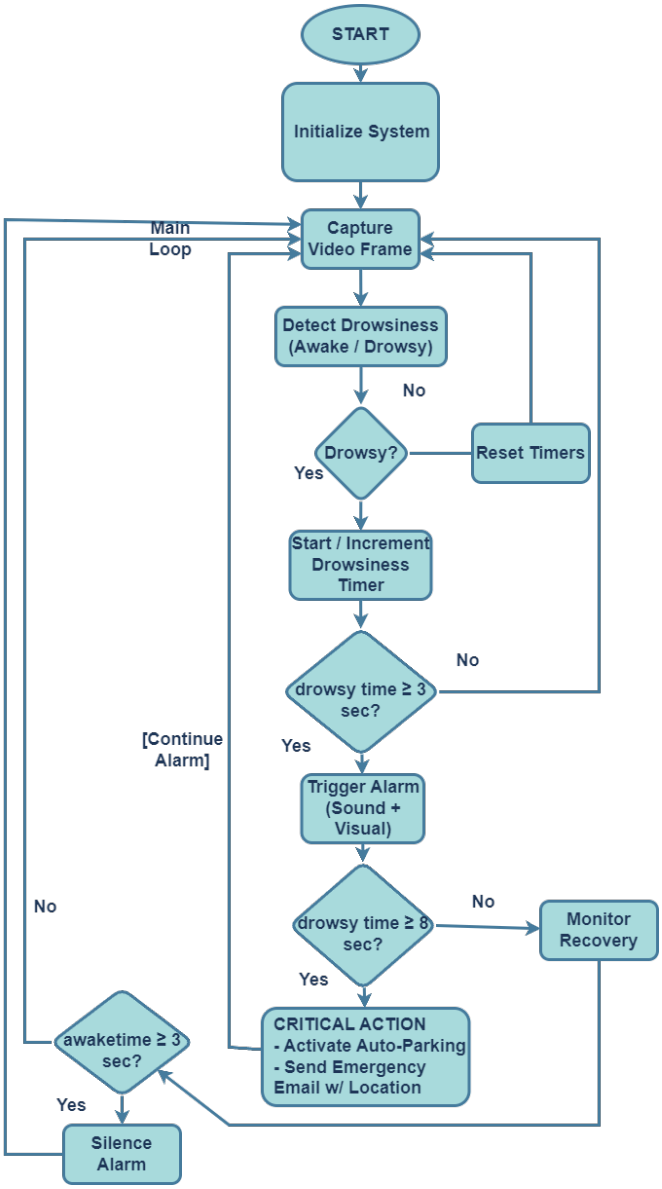


Figure 3.15: Driver Drowsiness Detection System Flowchart

3.6.5 Challenges and Limitations

1. **Eye Blink Detection False Positives**

   - **Problem:**
     - The system initially misinterpreted normal blinking as drowsiness, triggering false alarms.
     - Rapid blinks or temporary eye closures (e.g., from sunlight or dust) disrupted the logic.
   - **Solution:**
     - Implemented a blink frequency analysis within a sliding time window (e.g., 2 seconds).

  - Only flagged drowsiness if:
    * Eye closure exceeded a duration threshold (e.g., >0.3 seconds per blink).
    * Blink frequency surpassed a count threshold (e.g., ≥3 blinks in 2 seconds).

2. **SMS Notification Failure**

   - **Problem:**
     - Attempts to send emergency alerts via SMS faced hurdles due to:
       * Carrier restrictions (e.g., requiring paid APIs or phone plans).
       * Complex integration with GSM modules.
   - **Solution:**
     - Switched to email notifications via SMTP (e.g., Gmail).
     - Added GPS coordinates and Google Maps links for location tracking.
   - **Limitation:** Email delivery depends on internet connectivity, which may delay alerts in remote areas.

3. **Latency in Emergency Actions**

   - **Challenge:**
     - The 8-second emergency threshold must balance safety and false triggers.
     - System latency (camera processing + model inference) delays responses by ∼0.5–1 second.
   - **Compromise:**
     - Prioritized reliability over speed, accepting minor delays to ensure correct detection.

4. **User Adaptability**

   - **Observation:**
     - Drivers found alarms disruptive if triggered too frequently.
   - **Improvement:**
     - Added a calibration mode to personalize sensitivity thresholds based on individual blink patterns.

Chapter 4

Embedded Systems Design

Contents

4.1 Bare-Metal Implementation

4.1.1 Layer Architecture

Layered architecture is a fundamental design paradigm employed in complex software systems, including those found in embedded systems and microcontroller-based applications. It involves organizing the system into distinct, hierarchical layers, each with specific responsibilities and interfaces. This modular approach promotes separation of concerns, where each layer provides services to the layer above it and utilizes services from the layer below it. This structured decomposition simplifies development, enhances maintainability, and improves the overall robustness and scalability of the system.

Purpose and Advantages of Layered Architecture:
The primary purpose of adopting a layered architecture in embedded systems is to manage complexity and facilitate efficient development and maintenance. Embedded systems often interact directly with hardware, manage real-time constraints, and handle diverse application requirements, making their design inherently intricate. Layered architecture addresses these challenges by:

- **Modularity and Abstraction:**
  Each layer encapsulates specific functionalities, hiding the underlying complexities from higher layers. For instance, the application layer does not need to know the intricate details of how a peripheral is controlled; it simply calls a function provided by a lower layer.
- **Reusability:**
  Layers, especially lower ones like the Hardware Abstraction Layer (HAL), can be reused across different projects or hardware platforms. This significantly reduces development time and effort when porting software to new hardware.
- **Maintainability and Debugging:**
  Changes or bug fixes in one layer are less likely to affect other layers, provided the interfaces remain consistent. This isolation simplifies debugging and makes the system easier to maintain over its lifecycle.
- **Scalability:**
  New functionalities or hardware components can be integrated by adding or modifying specific layers without necessitating a complete overhaul of the system.
- **Testability:**
  Individual layers can be tested independently, which streamlines the verification and validation process, leading to more reliable software.
- **Team Collaboration:**
  Different development teams can work concurrently on separate layers with well-defined interfaces, improving development efficiency.

4.1.2 HAL Layer

The Hardware Abstraction Layer (HAL) sits directly above the Hardware Layer. Its primary role is to provide a standardized, abstract interface to the underlying hardware. The HAL shields the higher layers (like the ECU or application) from the specific details of the hardware. This means that if the underlying microcontroller or peripheral changes, only the HAL needs to be modified, while the layers above it can remain largely unchanged. The HAL typically consists of a set of functions and drivers that allow higher layers to interact with hardware components without needing to know the low-level register manipulations.

- **Responsibilities:**

  1. Abstracting hardware-specific details.
  2. Providing a consistent API for hardware access.
  3. Handling low-level driver implementations for peripherals (e.g., GPIO control, Communications Protocols, ADC readings).
  4. Managing interrupts and DMA (Direct Memory Access) operations.

- **Interaction with Hardware Layer:**
  The HAL directly interacts with the hardware by reading from and writing to hardware registers, configuring peripherals, and managing their operational states. It translates generic requests from higher layers into specific hardware commands.

4.1.3 ECU Layer

The Electronic Control Unit (ECU) Layer serves as the central interface between the embedded software and the hardware components of the system. This layer is responsible for managing the drivers of various sensors, communication modules, and other hardware interfaces, ensuring seamless data exchange and control. By abstracting hardware details, the ECU Layer enables reliable and efficient integration of all system peripherals.

Sensors

Encoder Driver Implementation

High-Level Overview

The encoder driver provides real-time motor speed and position tracking through quadrature encoder signals. Key features include:

- **Bi-directional counting** using timer midpoint (22000)
- **Precision measurement** with floating-point calculations
- **Two core metrics**:

  - Speed in RPM (Revolutions Per Minute)
  - Position in meters (odometry)
- **Hardware abstraction** through STM32 HAL
- **Safety mechanisms**:
  - NULL pointer validation
  - Timer initialization checks
  - Absolute speed conversion

Implementation Details

Data Flow

1. Timer captures encoder pulses
2. Periodic update computes:
   - Δ counts since last reading
   - Mechanical revolutions
   - Angular velocity (RPM)
   - Linear displacement
3. Results stored in encoder structure

Key Formulas

- **Revolutions**:

$$\text{Revolutions} = \frac{\text{Moved Cycles}}{\text{ENCODER\_PULSES\_NUMBER} \times 40} \tag{4.1}$$

Revolutions Calculation

- **Speed (RPM)**:

$$\text{Speed} = \frac{\text{Revolutions} \times 60}{\text{Period Time (s)}} \tag{4.2}$$

Speed Calculation

- **Position (meters)**:

$$\Delta\text{Position} = \text{Revolutions} \times 2\pi \times \text{Wheel Radius} \tag{4.3}$$

Position Calculation

Function Specifications

`encoder_init()`

```c
ecu_status_t encoder_init(encoder_t *p_Encoder)
{
    ecu_status_t l_EcuStatus = ECU_OK;
    if (p_Encoder == NULL) {
        l_EcuStatus = ECU_ERROR;
    }
    else {
        p_Encoder->Speed = 0.0f;
        p_Encoder->Position = 0.0f;
        p_Encoder->LastCount = 0.0f;
        __HAL_TIM_SET_COUNTER(p_Encoder->SelectedTimer, 22000);
        if (HAL_TIM_Encoder_Start(p_Encoder->SelectedTimer,
                                  TIM_CHANNEL_ALL) != HAL_OK) {
            l_EcuStatus = ECU_ERROR;
        }
    }
    return l_EcuStatus;
}
```

Code Section 4.1: Encoder Initialization Function

`encoder_periodic_update()`

```c
ecu_status_t encoder_periodic_update(encoder_t *p_Encoder,
                                     float_t p_PeriodTime)
{
    ecu_status_t l_EcuStatus = ECU_OK;
    if (p_Encoder == NULL) {
        l_EcuStatus = ECU_ERROR;
    }
    else {
        uint32_t l_CurrentCount = __HAL_TIM_GET_COUNTER(p_Encoder->SelectedTimer);
        __HAL_TIM_SET_COUNTER(p_Encoder->SelectedTimer, 22000);

        float_t l_MovedCycles = (float_t)((float_t)l_CurrentCount - 22000.0);
        float_t l_Revolutions = l_MovedCycles / (ENCODER_PULSES_NUMBER * 40.0);

        p_Encoder->Speed = fabsf((l_Revolutions * 60) / (p_PeriodTime / 1000.0));
        p_Encoder->Position += l_Revolutions * 2 * M_PI * p_Encoder->WheelRadius;
    }
    return l_EcuStatus;
}
```

Code Section 4.2: Encoder Periodic Update Function

Design Considerations

Table 4.1: Encoder Driver Parameters

Parameter	Type	Description
SelectedTimer	TIM_HandleTypeDef*	Hardware timer handle
WheelRadius	float	Wheel radius in meters
Speed	float	Output RPM (always positive)
Position	float	Cumulative position (meters)

Usage Guidelines

1. **Initialization**

```
encoder_t enc;
enc.SelectedTimer = &htim2;
enc.WheelRadius = 0.05f; // 50mm wheel
encoder_init(&enc);
```

Code Section 4.3: Encoder Initialization Example

2. **Periodic Update**

```
// Call every 10ms (100Hz update rate)
encoder_periodic_update(&enc, 10.0f);
```

Code Section 4.4: Encoder Periodic Update Example

3. **Data Access**

   - Current speed: `enc.Speed` (RPM)
   - Traveled distance: `enc.Position` (meters)

Ultrasonic Driver Implementation

High-Level Overview

The ultrasonic driver measures real-time distance to nearby objects using time-of-flight from ultrasonic pulses. Key features include:

- **Multi-sensor support** up to 8 ultrasonic sensors
- **Accurate distance calculation** using timer input capture
- **Overflow correction** for extended timing range
- **Hardware abstraction** using STM32 HAL
- **Safe design principles**:
  - NULL pointer validation
  - Callback registration via HAL
  - Dynamic triggering of selected sensors

Implementation Details

Data Flow

1. `Ultrasonic_Init` registers timers, starts input capture and base timer
2. `Ultrasonic_ReadDistance` triggers ultrasonic sensors
3. `USER_TIM_IC_CALLBACK` handles capture events
4. `USER_TIM_OVERFLOW_CALLBACK` tracks timer overflow
5. Distance values are updated in sensor structure pointers

Key Formula

$$\text{Distance} = (\text{CaptureTime} \times \text{Tick Duration}) \times \frac{v_{\text{sound}}}{2} \tag{4.4}$$

- In this driver, the constant 0.017 is derived from prescaler, clock, and sound speed.

Function Specifications

`Ultrasonic_Init()`

```
ecu_status_t Ultrasonic_Init(int p_NumSensors, ...)
{
    ecu_status_t l_EcuStatus = ECU_OK;
    va_list l_Args;
    va_start(l_Args, p_NumSensors);

    for (int i = 0; i < p_NumSensors; i++) {
        UltrasonicSensor* sensor = va_arg(l_Args, UltrasonicSensor*);
        if (NULL == sensor) {
            l_EcuStatus = ECU_ERROR;
            break;
        }
        HAL_TIM_RegisterCallback(sensor->htim, HAL_TIM_IC_CAPTURE_CB_ID,
            USER_TIM_IC_CALLBACK);
        HAL_TIM_RegisterCallback(sensor->htim, HAL_TIM_PERIOD_ELAPSED_CB_ID,
            USER_TIM_OVERFLOW_CALLBACK);
        HAL_TIM_IC_Start_IT(sensor->htim, sensor->Channel);
        HAL_TIM_Base_Start_IT(sensor->htim);
        Distance[i] = sensor->Distance;
    }

    va_end(l_Args);
    return l_EcuStatus;
}
```

Code Section 4.5: Ultrasonic Sensor Initialization Function

Ultrasonic_ReadDistance()

```
ecu_status_t Ultrasonic_ReadDistance(int p_NumSensors, int index, ...)
{
    ecu_status_t l_EcuStatus = ECU_OK;
    va_list l_Args;
    va_start(l_Args, p_NumSensors);
    SensorsToGetDistance = p_NumSensors;
    int i = index - 1;

    for (; i < (index - 1 + p_NumSensors); i++) {
        Sensors[i] = va_arg(l_Args, UltrasonicSensor*);
        if (NULL == Sensors[i]) {
            l_EcuStatus = ECU_ERROR;
            break;
        }
    }
    va_end(l_Args);

    if (l_EcuStatus != ECU_ERROR) {
        for (i = index - 1; i < (index - 1 + p_NumSensors); i++) {
            HAL_GPIO_WritePin(Sensors[i]->TRIG_PORT, Sensors[i]->TRIG_PIN, GPIO_PIN_SET);
        }

        delay_us(Sensors[index - 1]->htim, 15);

        for (i = index - 1; i < (index - 1 + p_NumSensors); i++) {
            HAL_GPIO_WritePin(Sensors[i]->TRIG_PORT, Sensors[i]->TRIG_PIN,
                GPIO_PIN_RESET);
        }
    }

    return l_EcuStatus;
}
```

Code Section 4.6: Ultrasonic Distance Reading Function

USER_TIM_IC_CALLBACK()

```
void USER_TIM_IC_CALLBACK(TIM_HandleTypeDef *htim)
{
    for (uint8_t i = 0; i < TOTOAL_NUMBER_OF_ULTRASONIC; i++) {
        if ((Sensors[i]->htim) == htim &&
            (Sensors[i]->Channel == htim->Channel)) {
            if (INITIAL == FirstVal[i]) {
                OverFlow[i] = 0;
                FirstVal[i] = (float)HAL_TIM_ReadCapturedValue(htim,
                    Sensors[i]->Channel);
            } else {
                SecondVal[i] = (float)HAL_TIM_ReadCapturedValue(htim,
                    Sensors[i]->Channel);
                *(Distance[i]) = (OverFlow[i] * htim->Init.Period +
                                  (SecondVal[i] - FirstVal[i])) * 0.017;
```

```
                FirstVal[i] = INITIAL;
                OverFlow[i] = INITIAL;
            }
        }
    }
}
```

Code Section 4.7: Timer Input Capture Callback Function

`USER_TIM_OVERFLOW_CALLBACK()`

```
void USER_TIM_OVERFLOW_CALLBACK(TIM_HandleTypeDef *htim)
{
    for (uint8_t i = 0; i < TOTOAL_NUMBER_OF_ULTRASONIC; i++) {
        if (Sensors[i]->htim->Instance == htim->Instance &&
            OverFlow[i] != INITIAL) {
            OverFlow[i]++;
        }
    }
}
```

Code Section 4.8: Timer Overflow Callback Function

Design Considerations

Table 4.2: Ultrasonic Driver Parameters

Parameter	Type	Description
TRIG_PORT	`GPIO_TypeDef*`	GPIO port for trigger pin
TRIG_PIN	`uint16_t`	GPIO pin number for trigger
htim	`TIM_HandleTypeDef*`	Timer used for ECHO timing
Channel	`uint8_t`	Timer input capture channel
Distance	`float*`	Output distance in meters

1. **Initialization**

```
UltrasonicSensor sensor1 = {GPIOA, GPIO_PIN_1, &htim2, TIM_CHANNEL_1, &distance1};
UltrasonicSensor sensor2 = {GPIOA, GPIO_PIN_2, &htim3, TIM_CHANNEL_2, &distance2};
Ultrasonic_Init(2, &sensor1, &sensor2);
```

2. **Distance Reading**

```
// Read distance from both sensors
Ultrasonic_ReadDistance(2, 1, &sensor1, &sensor2);
```

3. **Data Access**

   - Real-time distance: `*sensor1.Distance` (meters)
   - Supports multiple calls with varying sensors and indices

MPU6050 Driver Implementation

High-Level Overview

The MPU6050 driver communicates with a 6-axis motion tracking sensor using I2C to read raw accelerometer and gyroscope data. Key features include:

- **I2C-based communication** with STM32 HAL
- **3-axis motion tracking** (acceleration and angular velocity)
- **Register-level configuration**
- **Safe design practices**:
  - NULL pointer validation
  - Status code feedback
  - Physical unit conversion

Implementation Details

Data Flow

1. `MPU6050_Init` configures internal registers and verifies the device
2. `MPU6050_ReadSensorData` reads and converts motion data
3. Raw data is parsed, scaled, and stored in the MPU handle

Key Formulas

$$\text{Acceleration } (\text{m/s}^2) = \frac{\text{RawAccel}}{16384.0} \times 9.81 \tag{4.5}$$

$$\text{Gyro } (\text{õ0b0/s}) = \frac{\text{RawGyro}}{131.0} \tag{4.6}$$

MPU6050 Acceleration Formula

Function Specifications

`MPU6050_Init()`

```
MPU_StatusTypeDef MPU6050_Init(MPU6050_HandleTypeDef* mpu)
{
    if (mpu == NULL || mpu->hi2c == NULL) return MPU_ERROR;

    uint8_t check, data;

    HAL_I2C_Mem_Read(mpu->hi2c, mpu->Address, WHO_AM_I, 1, &check, 1, 1000);
    if (check != 0x68) return MPU_ERROR;
```

```
    data = 0;
    HAL_I2C_Mem_Write(mpu->hi2c, mpu->Address, PWR_MGMT_1, 1, &data, 1, 1000);

    data = 7;
    HAL_I2C_Mem_Write(mpu->hi2c, mpu->Address, SMPLRT_DIV, 1, &data, 1, 1000);

    data = 0x00;
    HAL_I2C_Mem_Write(mpu->hi2c, mpu->Address, GYRO_CONFIG, 1, &data, 1, 1000);
    HAL_I2C_Mem_Write(mpu->hi2c, mpu->Address, ACCEL_CONFIG, 1, &data, 1, 1000);

    return MPU_OK;
}
```

MPU6050_ReadSensorData()

```
MPU_StatusTypeDef MPU6050_ReadSensorData(MPU6050_HandleTypeDef* mpu)
{
    if (mpu == NULL || mpu->hi2c == NULL) return MPU_ERROR;

    uint8_t buffer[14];
    HAL_I2C_Mem_Read(mpu->hi2c, mpu->Address, ACCEL_XOUT_H, 1, buffer, 14, 1000);

    int16_t rawAx = (int16_t)(buffer[0] << 8 | buffer[1]);
    int16_t rawAy = (int16_t)(buffer[2] << 8 | buffer[3]);
    int16_t rawAz = (int16_t)(buffer[4] << 8 | buffer[5]);

    int16_t rawGx = (int16_t)(buffer[8] << 8 | buffer[9]);
    int16_t rawGy = (int16_t)(buffer[10] << 8 | buffer[11]);
    int16_t rawGz = (int16_t)(buffer[12] << 8 | buffer[13]);

    mpu->Ax = (float)rawAx / 16384.0f * 9.81f;
    mpu->Ay = (float)rawAy / 16384.0f * 9.81f;
    mpu->Az = (float)rawAz / 16384.0f * 9.81f;

    mpu->Gx = (float)rawGx / 131.0f;
    mpu->Gy = (float)rawGy / 131.0f;
    mpu->Gz = (float)rawGz / 131.0f;

    return MPU_OK;
}
```

Design Considerations

Table 4.3: MPU6050 Handle Structure

Field	Type	Description
hi2c	`I2C_HandleTypeDef*`	Pointer to I2C peripheral
Address	`uint8_t`	Sensor I2C address (0xD0 default)
Ax, Ay, Az	`float`	Acceleration values (m/s^2)
Gx, Gy, Gz	`float`	Angular velocity values (rad/s)

Usage Guidelines

Initialization

```
MPU6050_HandleTypeDef mpu;
mpu.hi2c = &hi2c1;
mpu.Address = 0xD0;

if (MPU6050_Init(&mpu) != MPU_OK) {
    // Error handling
}
```

Code Section 4.9: MPU6050 Initialization Example

Sensor Reading

```
MPU6050_ReadSensorData(&mpu);

float ax = mpu.Ax;
float gz = mpu.Gz;
```

Code Section 4.10: MPU6050 Sensor Reading Example

Communication Modules

The drivers for communication modules provide the necessary software interface to enable reliable data exchange between the microcontroller and external devices. They handle protocol implementation, data transmission, and reception for modules such as CAN and Bluetooth.

1- MCP2515-CAN

This part documents the implementation of the MCP2515 CAN controller driver in the ECU (Electronic Control Unit) layer. The MCP2515 is a stand-alone CAN controller that implements the CAN specification, version 2.0B, supporting both standard and extended data frames. The driver provides an interface between the microcontroller (STM32F4 in this case) and the MCP2515 over SPI.

Driver Architecture

The driver is implemented across two main components:

1. **Low-level MCP2515 interface (MCP2515.h/c)**
   - Direct register access and SPI communication
   - Basic command set implementation
2. **Higher-level CAN interface (CANSPI.h/c)**
   - Message handling and filtering
   - Error detection and handling
   - Mode configuration

Key Features

1. **SPI Communication**
   - Full-duplex SPI interface implementation
   - Hardware CS (Chip Select) control
   - Timeout handling for robust communication
2. **CAN Functionality**
   - Supports both standard (11-bit) and extended (29-bit) identifiers
   - Multiple baud rate configurations (1000kbps down to 100kbps)
   - Three transmit buffers with prioritization
   - Two receive buffers with message filtering
3. **Error Handling**
   - Bus-off state detection
   - Error passive state monitoring
   - Receive/transmit error counters
4. **Power Management**
   - Configurable sleep mode with wake-up on CAN activity

SPI Interface Layer

The low-level SPI interface provides the basic building blocks for MCP2515 communication. These functions handle the actual SPI transactions with proper CS line control and error checking.

```
static ecu_status_t SPI_Tx(SPI_HandleTypeDef *p_UsedSPI, uint8_t data);
static ecu_status_t SPI_TxBuffer(SPI_HandleTypeDef *p_UsedSPI, uint8_t *buffer, uint8_t
    length);
static ecu_status_t SPI_Rx(SPI_HandleTypeDef *p_UsedSPI, uint8_t *p_Buffer);
static ecu_status_t SPI_RxBuffer(SPI_HandleTypeDef *p_UsedSPI, uint8_t *buffer, uint8_t
    length);
```

Code Section 4.11: SPI Interface Layer for MCP2515

MCP2515 Command Set

The driver implements all essential MCP2515 commands.

```
ecu_status_t MCP2515_Initialize(SPI_HandleTypeDef *p_UsedSPI);
ecu_status_t MCP2515_SetConfigMode(SPI_HandleTypeDef *p_UsedSPI);
ecu_status_t MCP2515_SetNormalMode(SPI_HandleTypeDef *p_UsedSPI);
ecu_status_t MCP2515_SetSleepMode(SPI_HandleTypeDef *p_UsedSPI);
ecu_status_t MCP2515_Reset(SPI_HandleTypeDef *p_UsedSPI);
ecu_status_t MCP2515_ReadByte (SPI_HandleTypeDef *p_UsedSPI,uint8_t address, uint8_t
    *buffer);
ecu_status_t MCP2515_ReadRxSequence(SPI_HandleTypeDef *p_UsedSPI, uint8_t instruction,
    uint8_t *data, uint8_t length);
ecu_status_t MCP2515_WriteByte(SPI_HandleTypeDef *p_UsedSPI, uint8_t address, uint8_t
    data);
```

```
ecu_status_t MCP2515_WriteByteSequence(SPI_HandleTypeDef *p_UsedSPI, uint8_t
    startAddress, uint8_t endAddress, uint8_t *data);
ecu_status_t MCP2515_LoadTxSequence(SPI_HandleTypeDef *p_UsedSPI, uint8_t instruction,
    uint8_t *idReg, uint8_t dlc, uint8_t *data);
ecu_status_t MCP2515_LoadTxBuffer(SPI_HandleTypeDef *p_UsedSPI, uint8_t instruction,
    uint8_t data);
ecu_status_t MCP2515_RequestToSend(SPI_HandleTypeDef *p_UsedSPI, uint8_t instruction);
ecu_status_t MCP2515_ReadStatus(SPI_HandleTypeDef *p_UsedSPI, uint8_t *p_Buffer);
ecu_status_t MCP2515_GetRxStatus(SPI_HandleTypeDef *p_UsedSPI, uint8_t *p_Buffer);
ecu_status_t MCP2515_BitModify(SPI_HandleTypeDef *p_UsedSPI, uint8_t address, uint8_t
    mask, uint8_t data);
```

Code Section 4.12: MCP2515 Command Set

```
ecu_status_t CANSPI_Initialize(Can_t *p_CAN);
ecu_status_t CANSPI_Sleep(Can_t *p_CAN);
ecu_status_t CANSPI_Transmit(Can_t *p_CAN, uCAN_MSG *tempCanMsg);
ecu_status_t CANSPI_Receive(Can_t *p_CAN, uCAN_MSG *tempCanMsg);
ecu_status_t CANSPI_messagesInBuffer(Can_t *p_CAN, uint8_t *count);
ecu_status_t CANSPI_isBussOff(Can_t *p_CAN);
ecu_status_t CANSPI_isRxErrorPassive(Can_t *p_CAN);
ecu_status_t CANSPI_isTxErrorPassive(Can_t *p_CAN);
```

Code Section 4.13: CAN Interface Layer

Data Structures

The driver uses a flexible data structure system that can handle any type of data for transmission. Here are the key components:

1- Data Container Union

This union allows treating with data as CAN message which easies the transmission and reception through MCP2515.

```
typedef union
{
    struct
    {
        uint8_t idType;
        uint32_t id;
        uint8_t dlc;
        uint8_t data[8];
    } frame;
    uint8_t array[14];
} uCAN_MSG;
```

Code Section 4.14: CAN Message

Configuration and Initialization

The initialization sequence configures the MCP2515 for operation:

1. Reset the controller

2. Enter configuration mode
3. Set up acceptance filters and masks
4. Configure bit timing for the desired baud rate
5. Enable interrupts
6. Switch to normal mode

Message Transmission

The transmission process:

1. Check available transmit buffers
2. Convert CAN ID to register format
3. Load message data into selected buffer
4. Initiate transmission

```
if (ctrlStatus.TXB0REQ != 1)
{
    /* convert CAN ID for register */
    l_EcuStatus |= convertCANid2Reg(tempCanMsg->frame.id, tempCanMsg->frame.idType,
        &idReg);

    /* Load data to Tx Buffer */
    l_EcuStatus |= MCP2515_LoadTxSequence(p_CAN->UsedSPI, MCP2515_LOAD_TXB0SIDH,
        &(idReg.tempSIDH), tempCanMsg->frame.dlc, &(tempCanMsg->frame.data[0]));

    /* Request to transmit */
    l_EcuStatus |= MCP2515_RequestToSend(p_CAN->UsedSPI, MCP2515_RTS_TX0);
}
```

Code Section 4.15: Message Transmission Process

Message Reception

The reception process:

1. Check receive buffer status
2. Read message from appropriate buffer
3. Convert register format to CAN ID
4. Clear interrupt flags (if using interrupts)

```
l_EcuStatus |= MCP2515_GetRxStatus(p_CAN->UsedSPI, &rxStatus.ctrl_rx_status);

/* Check receive buffer */
if (rxStatus.rxBuffer != 0)
{
    /* finding buffer which has a message */
    if ((rxStatus.rxBuffer == MSG_IN_RXB0) | (rxStatus.rxBuffer == MSG_IN_BOTH_BUFFERS))
    {
        l_EcuStatus |= MCP2515_ReadRxSequence(p_CAN->UsedSPI, MCP2515_READ_RXB0SIDH,
            rxReg.rx_reg_array, sizeof(rxReg.rx_reg_array));
        #if CAN_RX_INTERRUPT == CAN_RX_INTERRUP_ENABLE
        l_EcuStatus |= MCP2515_BitModify(p_CAN->UsedSPI, MCP2515_CANINTF, 0xFF, 0x00);
        #endif
    }
```

Code Section 4.16: Check Receive Buffer Status

```
/* if the message is extended CAN type */
if (rxStatus.msgType == dEXTENDED_CAN_MSG_ID_2_0B)
{
    tempCanMsg->frame.idType = (uint8_t)dEXTENDED_CAN_MSG_ID_2_0B;
    l_EcuStatus |= convertReg2ExtendedCANid(rxReg.RXBnEID8, rxReg.RXBnEID0,
        rxReg.RXBnSIDH, rxReg.RXBnSIDL, &tempCanMsg->frame.id);
}
else
{
    /* Standard type */
    tempCanMsg->frame.idType = (uint8_t)dSTANDARD_CAN_MSG_ID_2_0B;
    l_EcuStatus |= convertReg2StandardCANid(rxReg.RXBnSIDH, rxReg.RXBnSIDL,
        &tempCanMsg->frame.id);
}
tempCanMsg->frame.dlc = rxReg.RXBnDLC;
tempCanMsg->frame.data[0] = rxReg.RXBnD0;
tempCanMsg->frame.data[1] = rxReg.RXBnD1;
tempCanMsg->frame.data[2] = rxReg.RXBnD2;
tempCanMsg->frame.data[3] = rxReg.RXBnD3;
tempCanMsg->frame.data[4] = rxReg.RXBnD4;
tempCanMsg->frame.data[5] = rxReg.RXBnD5;
tempCanMsg->frame.data[6] = rxReg.RXBnD6;
tempCanMsg->frame.data[7] = rxReg.RXBnD7;
```

Code Section 4.17: Convert Register Format to CAN ID

Error Handling

The driver implements comprehensive error detection:

```
ecu_status_t CANSPI_isBussOff(Can_t *p_CAN)
{
    ecu_status_t l_EcuStatus = ECU_OK;
    if (NULL == p_CAN)
    {
        l_EcuStatus = ECU_ERROR;
```

```
    }
    else
    {
        l_EcuStatus |= MCP2515_ReadByte(p_CAN->UsedSPI, MCP2515_EFLG,
            &errorStatus.error_flag_reg);

        if (errorStatus.TXBO == 1)
        {
            l_EcuStatus = ECU_ERROR;
        }
    }
    return l_EcuStatus;
}
```

Code Section 4.18: CAN Error HandlingD

Conclusion

The MCP2515 driver provides a robust interface for CAN communication in the ECU layer. Its layered architecture separates low-level SPI communication from higher-level CAN functionality, making it both flexible and maintainable. The implementation supports all critical CAN features while providing comprehensive error detection and recovery mechanisms.

Key strengths of this implementation include:

- Support for both standard and extended CAN frames
- Multiple baud rate configurations
- Efficient message handling with three transmit and two receive buffers
- Comprehensive error detection and reporting
- Power management through sleep mode

This driver forms a solid foundation for CAN-based communication in automotive and industrial applications.

2- HC-05 Bluetooth Module

We want to debug the car while it is on road so we have to monitor the system so the following part documents the implementation of a monitoring driver using the HC-05 Bluetooth module. The driver provides a flexible interface for sending data from an STM32 microcontroller to a remote monitoring system via Bluetooth, similar to the UART monitoring implementation but adapted for wireless communication.

Driver Architecture

The driver is implemented across two main components:

1. **HC-05 interface (monitoring.h/c)**
    - Bluetooth communication setup
    - Data transmission handling

- Connection management

2. **Data Conversion Layer**
   - Struct-to-bytes conversion for easy transmission
   - Callback mechanism for data updates

Data Structures

The driver uses a flexible data structure system that can handle any type of data for transmission. Here are the key components:

1- Data Container Union

This union allows treating any data structure as an array of bytes for transmission while maintaining the original structure for normal program use.

```
typedef union
{
    void *OriginalData;
    uint8_t *SendData;
}monitoring_data_t;
```

Code Section 4.19: Data Container Union for Monitoring

2- Monitoring Configuration Structure

This structure defines the configuration for monitoring, including data type, size, and update callbacks.

```
typedef struct
{
    UART_HandleTypeDef *UsedUART;
    void (*MonitorUpdateData_CALLBACK)(void);
    monitoring_data_t Data;
    uint8_t Size;
}monitoring_t;
```

Code Section 4.20: Monitoring Configuration Structure

Data Transmission Sequence

1. Check for pointer
2. Updating data through Callback function if available
3. Transmiting data through UART to HC-05

```
ecu_status_t monitoring_send_data(monitoring_t *p_MonitorOBJ)
{
    ecu_status_t l_EcuStatus = ECU_OK;
    if ((NULL == p_MonitorOBJ)              ||
        (NULL == p_MonitorOBJ->UsedUART))
    {
        l_EcuStatus = ECU_ERROR;
```

```
    }
    else
    {
        if(p_MonitorOBJ->MonitorUpdateData_CALLBACK != NULL)
        {
            p_MonitorOBJ->MonitorUpdateData_CALLBACK();
        }
        /* Send the data */
        l_EcuStatus |= HAL_UART_Transmit(p_MonitorOBJ->UsedUART,
            p_MonitorOBJ->Data.SendData, p_MonitorOBJ->Size, HAL_MAX_DELAY);
    }
    return l_EcuStatus;
}
```

Code Section 4.21: Monitoring Sending Data Implementation

Conclusion

The HC-05 Bluetooth monitoring driver provides a robust solution for wireless data transmission from an STM32 microcontroller. Key features include:

- Flexible data structure support through byte-level conversion
- Connection status monitoring
- Callback mechanism for data updates
- Error handling and recovery

3- Car Control

This part documents the implementation of a car control system that receives commands via UART from a ESP32 controller. The system supports joystick input for movement control, button inputs for discrete commands, and compass data for navigation.

System Architecture

The control system consists of:

1- Command Reception Layer

- UART interrupt-based data reception
- Command parsing and validation

2- Command Processing Layer

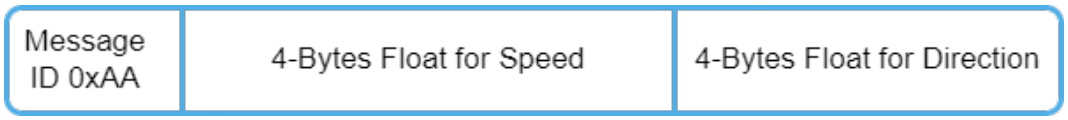
- Joystick movement interpretation
- Button press handling
- Compass angle processing

3- Command Reception Layer

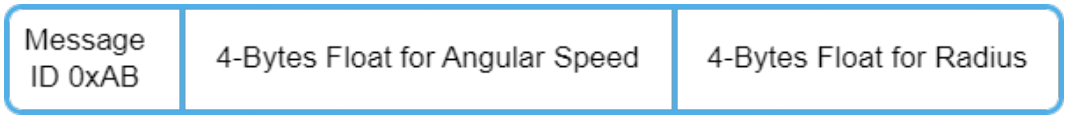
- Data structures for command representation
- Status feedback mechanism

Messages Frames

We desgined ***four*** types of messages to handle control and orientation of the car:



(a) Strafe Message Structure



(b) Rotate Message Structure

(c) Buttons Message Structure

(d) Compass Angle Message Structure

Figure 4.1: Message Frame Structures for Car Control System

Data Structure

These data sturctures allow us to convert from individual received bytes into messages frames based on the message ID received in first byte:

```
typedef union
{
    buttons_frame frame;
    uint8_t uart_data[9];

}Push_Button_Joy_Stick_Data;
```

Code Section 4.22: Buttons Data Frame

```
typedef struct
{
    uint8_t Address;
    uint8_t up;
    uint8_t down;
    uint8_t left;
    uint8_t right;
    uint8_t select;
    uint8_t start;
    uint8_t left_stick;
    uint8_t right_stick;
}buttons_frame;
```

Code Section 4.23: Buttons Frame

```c
typedef union
{
    Joy_Stick_frame frame;
    uint8_t uart_data[9];
}Joy_Stick_Data;
```

Code Section 4.24: Normal Data Frame

```c
typedef struct
{
    uint8_t Address;
    float_t Mag;
    float_t Ang;
}Joy_Stick_frame;
```

Code Section 4.25: Normal Frame

Receiving Sequence

1. Waiting for 9 bytes though specific RX pin on UART
2. After Receiving the 9 bytes it will generate and interrupt which jumps to a callback function
3. Storing bytes in normal data frame is done in callback function

```c
ecu_status_t control_receive_data(control_t *p_UsedController)
{
    ecu_status_t l_EcuStatus = ECU_OK;
    if (NULL == p_UsedController)
    {
        l_EcuStatus = ECU_ERROR;
    }
    else
    {
        l_EcuStatus |= HAL_UART_Receive_IT(p_UsedController->UsedUART ,
            p_UsedController->Data , 9);
    }
    return l_EcuStatus;
}
```

Code Section 4.26: Receving Data Callback Function

Motors and Drivers

Motor Driver

Introduction to DC Motors A DC (Direct Current) motor is an electromechanical device that converts electrical energy into mechanical energy using direct current as its power source. It is one of the most used types of electric motors due to its simplicity, reliability, and ease of

control. DC motors are widely used in various applications ranging from small electronic devices to industrial machinery and robotics.

The basic principle behind the operation of a DC motor is based on the interaction between a magnetic field and an electric current. When a current-carrying conductor is placed in a magnetic field, it experiences a force that causes it to rotate. This rotational motion is harnessed to perform useful work such as driving wheels, fans, pumps, or any other mechanical load.

One of the main advantages of DC motors is their simple speed and direction control. By varying the voltage supplied to the motor, the speed can be adjusted, and by reversing the polarity of the applied voltage, the direction of rotation can be changed. This makes them ideal for applications requiring variable speed and bidirectional movement, such as in robotics, electric vehicles, conveyor systems, and automation equipment.

What is a Motor Driver? A motor driver is an electronic device or circuit that acts as an intermediary between a control system (e.g., a microcontroller like the Raspberry Pi) and a motor. Its primary function is to regulate and control the flow of electrical power to the motor based on the commands received from the control system. Motor drivers are designed to handle the high current and voltage requirements of motors, which are typically much higher than what a microcontroller can directly provide.

Key components of a motor driver include:

- **Power Transistors/MOSFETs**: These handle the high currents required by the motor.
- **Protection Circuits**: Include features like overcurrent protection, overvoltage protection, and thermal shutdown to prevent damage.
- **Control Inputs**: Allow the motor driver to receive signals from a microcontroller to control the motor's speed, direction, and other parameters.

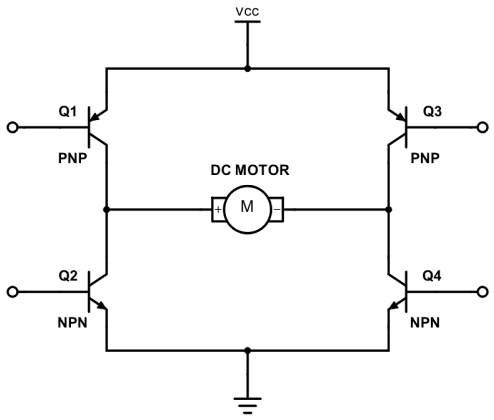


Figure 4.2: H Bridge Transistor

Operation of an H-Bridge An H-bridge is a fundamental electronic circuit used to control the direction and speed of DC motors. It is called an "H-bridge" because its circuit diagram resembles the letter "H." The H-bridge allows for bidirectional control of motors, enabling them to rotate in both forward and reverse directions. This makes it an essential component in applications such as robotics, electric vehicles, and any system requiring precise motor control.

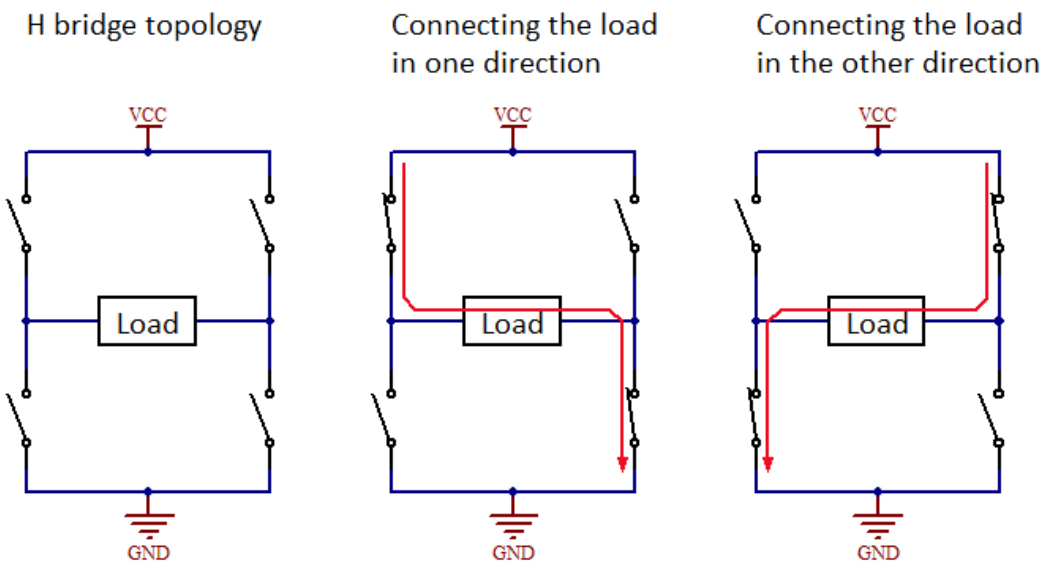


Figure 4.3: H Bridge

- **Forward Rotation**:
  - Turn on the top-left switch (high-side) and the bottom-right switch (low-side).
  - This creates a closed loop that allows current to flow through the motor in one direction, causing it to rotate forward.
- **Reverse Rotation**:
  - Turn on the top-right switch (high-side) and the bottom-left switch (low-side).
  - This reverses the direction of current flow through the motor, causing it to rotate in the opposite direction.
- **Stopping the Motor**:
  - Turn off all four switches.
  - This breaks the current path through the motor, stopping its rotation.
- **Braking the Motor**:
  - Turn on both switches on one side of the bridge (e.g., both top switches or both bottom switches).
  - This shorts the motor terminals, creating a braking effect by dissipating the motor's kinetic energy as heat.

Speed Control Using PWM The H-bridge can also control the speed of the motor using Pulse Width Modulation (PWM):

- **PWM Principle**: The motor is rapidly switched on and off at a high frequency. The percentage of time the motor is "on" (duty cycle) determines its average power input and, consequently, its speed.
- **Example**: A 50% duty cycle means the motor is powered for half the time, resulting in reduced speed compared to a 100% duty cycle.

Duty cycle is a term used in electronics and signal processing to describe the proportion of time during which a signal is active (ON) compared to the total period of the signal. It is commonly used with Pulse Width Modulation (PWM) signals, especially for controlling the speed of motors, brightness of LEDs, or power delivered to various devices.

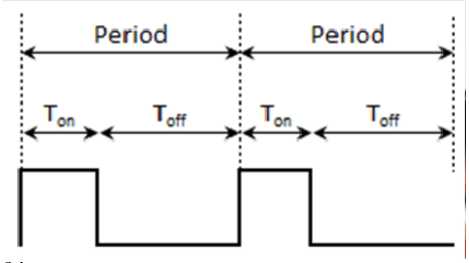


Figure 4.4: Duty Cycle

It is expressed as a percentage, calculated using this formula:

$$\text{Duty Cycle (\%)} = \left(\frac{\text{ON Time}}{\text{Total Period}}\right) \times 100 \tag{4.7}$$

Duty Cycle Formula

Why Use a Motor Driver? Using a motor driver is essential for several reasons:

- **Current Handling Capability**:
  - **Motors Require High Current**: Motors, especially when starting or under load, draw significantly more current than what a microcontroller can safely supply. For example, a small DC motor might require 1 A–2 A, while a microcontroller's GPIO pins can typically only source a few milliamps (mA).
  - **Motor Drivers Handle High Currents**: Motor drivers are designed to manage these high currents without damaging the microcontroller.
- **Voltage Regulation**:
  - **Motors Need Specific Voltages**: The voltage required to drive a motor is often higher than the operating voltage of the microcontroller (e.g., 5 V or 3.3 V). Motor drivers step up or regulate the voltage to match the motor's requirements.
  - **Prevents Overvoltage Damage**: By isolating the motor's power supply from the microcontroller, motor drivers protect the microcontroller from voltage spikes or surges.
- **Direction Control**:
  - **Bidirectional Operation**: Many motors (e.g., DC motors) need to rotate in both forward and reverse directions. Motor drivers allow you to control the direction of rotation by reversing the polarity of the applied voltage.
  - **Simplified Control**: Instead of manually switching connections, the motor driver handles direction changes through digital inputs from the microcontroller.
- **Speed Control**:
  - **PWM-Based Speed Regulation**: Motor drivers often use Pulse Width Modulation (PWM) to control the speed of the motor. By varying the duty cycle of the PWM signal, the average voltage applied to the motor can be adjusted, thereby controlling its speed.
  - **Smooth Operation**: Motor drivers ensure smooth speed transitions and precise control, which is critical for applications requiring fine motor control.

- **Protection**:
  - **Overcurrent Protection**: Motor drivers include circuits that detect and limit excessive current, preventing damage to the motor or the power supply during stalls or overload conditions.
  - **Thermal Shutdown**: If the motor driver overheats, it can automatically shut down to prevent permanent damage.
  - **Reverse Polarity Protection**: Some motor drivers protect against accidental reverse connection of the power supply.
- **Isolation**:
  - **Electrical Isolation**: Motor drivers can isolate the high-power motor circuit from the low-power control circuit (e.g., microcontroller), reducing the risk of noise interference and ensuring safer operation.

Case Example: Inputs to an H-Bridge or Motor Driver
Let's assume we're working with a typical dual H-bridge motor driver (e.g., L298N) that controls a DC motor using two inputs per motor:

- Input A (IN1)
- Input B (IN2)

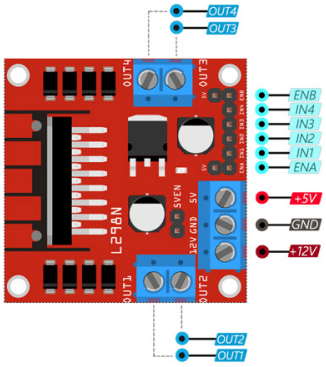


Figure 4.5: L298N Pinout

Table 4.4: Input Output Motor Driver

IN1	IN2	Spinning Direction
Low	Low	Motor OFF
Low	High	Forward
High	Low	Backward
High	High	Motor Brake

Detailed Explanation for Each Case

1. **IN1 = HIGH, IN2 = LOW → Forward Rotation**:
   - This turns on one side of the H-bridge.
   - Current flows through the motor in one direction.
   - The motor spins forward.
2. **IN1 = LOW, IN2 = HIGH → Reverse Rotation**:
   - The opposite side of the H-bridge is activated.
   - Current flows in the reverse direction.
   - The motor spins backward.

3. **IN1 = HIGH, IN2 = HIGH → Motor Brake**:
   - Both high-side or both low-side transistors are turned on.
   - This shorts the motor terminals.
   - The motor stops quickly due to internal resistance and back EMF – called dynamic braking.
4. **IN1 = LOW, IN2 = LOW → Coast/Free Stop**:
   - All switches in the H-bridge are off.
   - No current flows through the motor.
   - The motor slows down gradually due to friction – this is called coasting.

Speed Control: Use PWM signals on the ENA and ENB pins to control the speed of the motors.

If you're using a 12V power supply and applying PWM to control a device like a motor or LED, the duty cycle determines the average voltage delivered to that device.

Let's break down what each percentage represents in terms of average voltage output:

Table 4.5: PWM Duty Cycle Effects

Duty Cycle	Explanation	Average Voltage (if Vmax = 12V)
0%	The signal is always OFF. No voltage is applied.	0 V
25%	The signal is ON for 25% of the time and OFF for 75%. Delivers low power.	3 V
50%	The signal is ON half the time and OFF the other half. Average power delivery.	6 V
75%	The signal is ON for most of the time (75%) and OFF for 25%. High power delivery.	9 V
100%	The signal is always ON. Full power is delivered.	12 V

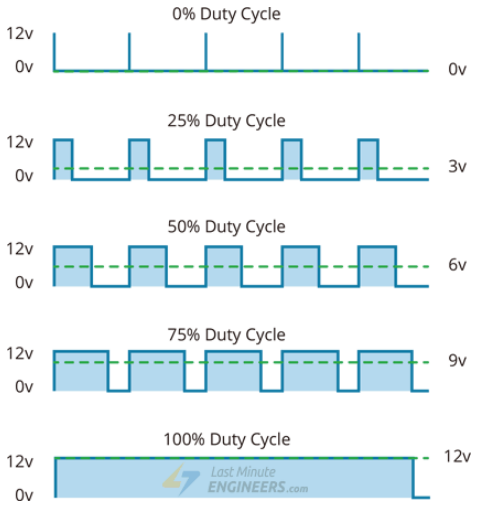


Figure 4.6: PWM Duty Cycle

Motor Code The motor_t Structure:

```
typedef struct
{
    GPIO_TypeDef *GpioxMotor[2];
    uint16_t GpioPinMotor[2];
    TIM_HandleTypeDef *SelectedTimer;
    uint32_t SelectedChannel;
}motor_t;
```

Code Section 4.27: motor_t Structure

This structure represents a DC motor connected to:

- Two GPIO pins (used for direction control, e.g., IN1 and IN2).
- A PWM timer channel (to control speed via PWM).

Example Use: You might configure:

- `GpioxMotor[0] = GPIOA, GpioPinMotor[0] = GPIO_PIN_0` → `IN1`
- `GpioxMotor[1] = GPIOA, GpioPinMotor[1] = GPIO_PIN_1` → `IN2`
- `SelectedTimer = &htim2, SelectedChannel = TIM_CHANNEL_1` → `For PWM output`

```
ecu_status_t motor_init(motor_t *p_Motor);
ecu_status_t motor_move_forward(motor_t *p_Motor , float_t p_Speed);
ecu_status_t motor_move_backward(motor_t *p_Motor , float_t p_Speed);
ecu_status_t motor_stop(motor_t *p_Motor);
ecu_status_t motor_change_speed(motor_t *p_Motor , float_t p_Speed);
ecu_status_t motor_calibrate(float_t *p_MaxSpeed);
```

Code Section 4.28: Motor Functions

- **`ecu_status_t motor_init(motor_t *p_Motor)`**
  - **Purpose**: Initializes the motor by setting up its GPIOs and PWM timer.
  - **Input**: `p_Motor`: A pointer to a motor_t structure already configured with GPIO and timer info
- **`ecu_status_t motor_move_forward(motor_t *p_Motor, float_t p_Speed)`**
  - **Purpose**: Moves the motor in the forward direction at a specified speed.
  - **Inputs**:
    - `p_Motor`: Motor to move
    - `p_Speed`: Speed as a float in m/s
  - **Implementation Tip**:
    - Sets one GPIO high and the other low.
    - Applies PWM signal to enable pin or directly to one input.

- **`ecu_status_t motor_move_backward(motor_t *p_Motor, float_t p_Speed)`**
  - **Purpose**: Moves the motor in the reverse direction at a specified speed.
  - **Inputs**: Same as above.
  - **Implementation Tip**:
    - Reverses the GPIO states compared to forward motion.
- **`ecu_status_t motor_stop(motor_t *p_Motor)`**
  - **Purpose**: Stops the motor.
  - **Inputs**: `p_Motor`: Motor to stop.
  - **Possible Actions**:
    - Sets both GPIOs to low (coast)
    - Or sets both GPIOs to high (brake), depending on design.
- **`ecu_status_t motor_change_speed(motor_t *p_Motor, float_t p_Speed)`**
  - **Purpose**: Changes the speed of a running motor without changing its direction.
  - **Inputs**:
    - `p_Motor`: Motor whose speed is being adjusted
    - `p_Speed`: New speed value in m/s
  - **How It Works**:
    - Adjusts the duty cycle of the PWM signal applied via the selected timer.
- **`ecu_status_t motor_calibrate(float_t *p_MaxSpeed)`**
  - **Purpose**: Used to calibrate the maximum motor speed, possibly based on sensor feedback or system constraints.
  - **Inputs**: `p_MaxSpeed`: A pointer to a float where the function stores the calibrated max speed.
  - **Use Case**:
    - Ensures all motors run at consistent speeds (important for robots, vehicles).
    - May be used during startup or setup phase.

Robot

Mecanum wheels Mecanum wheel. Also known as iron wheels It is a conventional wheel with a series of rollers attached to its circumference, these rollers having an axis of rotation at 45° to the plane of the wheel in a plane parallel to the axis of rotation of the wheel. Depending on each individual wheel direction and speed, the resulting combination of all these forces produce a total force vector in any desired direction thus allowing the platform to move freely in the direction of the resulting force vector, without changing of the wheels themselves. It is perfect for tight space.

Figure 4.7: APP Wheel

Characteristic : The four mecanum wheels are each connected to a motor for independent control. The robot can move forward, reverse and spin just like four regular wheels. The configuration of rollers at 45° also allows the robot to translate sideways and through a combination of these, in any direction (even while spinning!). We splits the force into two vectors, one forward/backward and one right/left. When the wheels on one side are spun in opposite directions, the forward and backward vectors cancel out while both sideways vectors add up. Doing the reverse with the other two wheels results in four added sideways vectors.

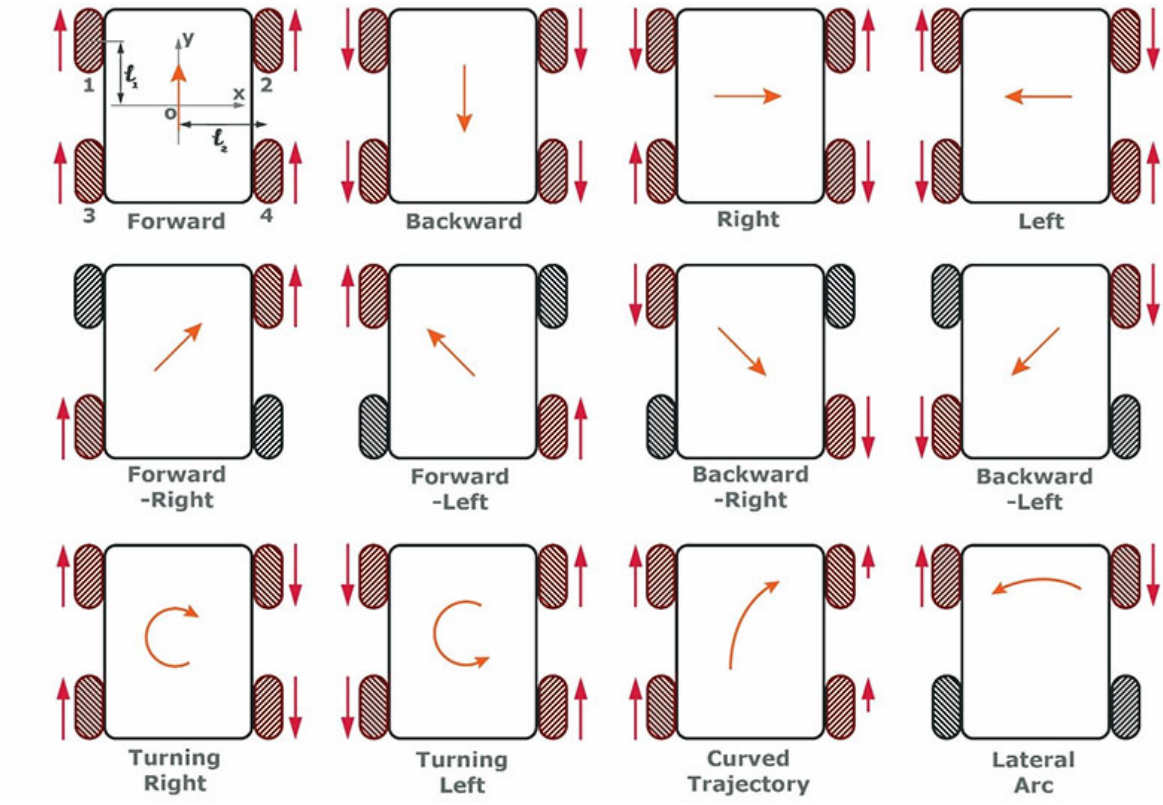


Figure 4.8: Directions Of Robot

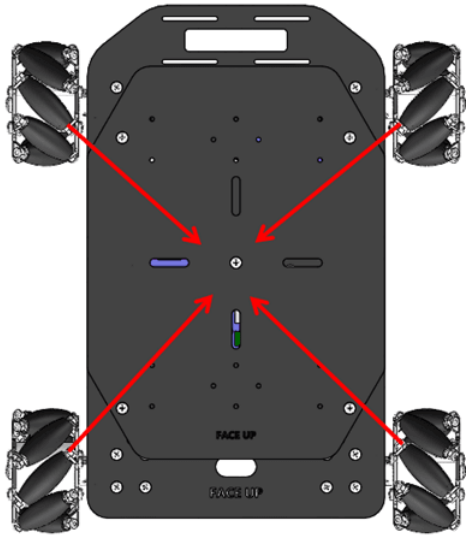
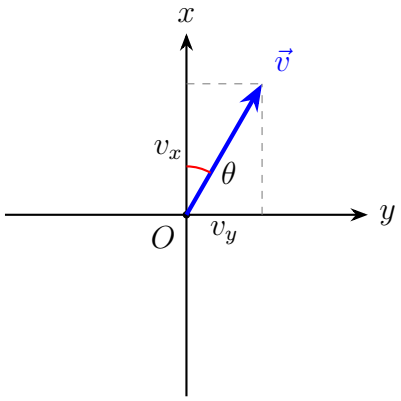


Figure 4.9: Installation of the Wheels

We want to make a car move in all directions (forward, backward, left, right, curve). We must take the information to move the car from ADAS ECU from CAN bus in (Speed and angle) (V - θ).

The system receives the speed v and the angle θ input from the user. These values are then decomposed into their respective v_x, v_y:

$$v_x = v \cdot \cos\theta$$
$$v_y = v \cdot \sin\theta$$



The system applies the appropriate kinematic equations to calculate the required speed for each wheel.

Kinematics

Forward kinematics refers to the use of the kinematic equations of a robot to compute the position of the end-effector from specified values for the joint parameters. In our case, the forward kinematics allow us to compute the global velocity of the robots base when given the angular velocities of the individual wheels.

The reverse process that computes the joint parameters that achieve a specified position of the end-effector is known as inverse kinematics. The inverse kinematic equations allow us, in our case, to compute the individual wheel velocities needed to achieve a given base velocity.

Inverse kinematics

The inverse kinematic equations allow us to compute the individual wheel velocities when we want to achieve an overall base velocity.

$$\begin{bmatrix} \omega_{fl} \\ \omega_{fr} \\ \omega_{rl} \\ \omega_{rr} \end{bmatrix} = \frac{1}{r} \begin{bmatrix} 1 & -1 & -(l_x + l_y) \\ 1 & 1 & (l_x + l_y) \\ 1 & 1 & -(l_x + l_y) \\ 1 & -1 & (l_x + l_y) \end{bmatrix} \begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} \tag{4.8}$$

Wheel speed calculation from vehicle dynamics

where:

- ω_{fl}, ω_{fr}, ω_{rl}, ω_{rr} represent the angular velocities for the front left, front right, rear left and rear right wheel respectively.
- v_x, v_y represent the robot's base linear velocity in the x and y direction respectively. The x direction is in front of the robot.
- ω_x is the angular velocity of the robot's base around the z-axis.
- l_x, l_y represent the distance from the robot's center to the wheels projected on the x and y axis respectively.
- r represent the radius of mecanum wheel.

Forward Kinematics The forward kinematic equations allow us to compute the robot's base velocity when given the individual wheel velocities. This is usefull to compute the robot's odometry using the motor's embedded quadrature encoders.

The forward kinematics for mecanum wheels can be expressed in matrix form as:

$$\begin{bmatrix} v_x \\ v_y \\ \omega_z \end{bmatrix} = \frac{r}{4} \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & 1 & 1 & -1 \\ -\frac{1}{l_x+l_y} & \frac{1}{l_x+l_y} & -\frac{1}{l_x+l_y} & \frac{1}{l_x+l_y} \end{bmatrix} \begin{bmatrix} \omega_{fl} \\ \omega_{fr} \\ \omega_{rl} \\ \omega_{rr} \end{bmatrix} \tag{4.9}$$

Forward kinematics for mecanum wheels

where:

- v_x, v_y represent the robot's base linear velocity in the x and y direction respectively
- ω_z is the angular velocity of the robot's base around the z-axis
- ω_{fl}, ω_{fr}, ω_{rl}, ω_{rr} represent the angular velocities for the front left, front right, rear left and rear right wheel respectively
- r represents the radius of the mecanum wheel
- l_x, l_y represent the distance from the robot's center to the wheels projected on the x and y axis respectively

Example: If we want to let the robot move diagonally at 0.22 m/s in the x direction and 0.11 m/s in the y direction. At what speed should we set the motors of each wheel? The robot is 25 cm in width and 40 cm in length. The wheels are placed at extremities and have a diameter of 60 mm.

Given:

- $v_x = 0.22$ m/s
- $v_y = 0.11$ m/s
- $\omega_z = 0$ (no rotation)
- Robot width: $l_y = 25/2 = 0.125$ m
- Robot length: $l_x = 40/2 = 0.20$ m
- Wheel diameter: 0.06 m $\Rightarrow r = 0.03$ m

Step by step: Calculate $l_x + l_y = 0.20 + 0.125 = 0.325$ m

The transformation matrix simplifies since $\omega_z = 0$

$$\begin{pmatrix} \omega_{fl} \\ \omega_{fr} \\ \omega_{rl} \\ \omega_{rr} \end{pmatrix} = \frac{1}{0.03} \begin{pmatrix} 1 & -1 \\ 1 & 1 \\ 1 & 1 \\ 1 & -1 \end{pmatrix} \begin{pmatrix} 0.22 \\ 0.11 \end{pmatrix}$$

Now multiply:

$$\omega_{fl} = \frac{1}{0.03}(0.22 - 0.11) = \frac{0.11}{0.03} = 3.67 \text{ rad/s}$$
$$\omega_{fr} = \frac{1}{0.03}(0.22 + 0.11) = \frac{0.33}{0.03} = 11.00 \text{ rad/s}$$
$$\omega_{rl} = \frac{1}{0.03}(0.22 + 0.11) = 11.00 \text{ rad/s}$$
$$\omega_{rr} = \frac{1}{0.03}(0.22 - 0.11) = 3.67 \text{ rad/s}$$

Final Answer:

- $\omega_{fl} = 3.67$ rad/s
- $\omega_{fr} = 11.00$ rad/s
- $\omega_{rl} = 11.00$ rad/s
- $\omega_{rr} = 3.67$ rad/s

```c
ecu_status_t robot_move(robot_t *p_Robot , float_t p_Angle , float_t p_Speed);
ecu_status_t robot_rotate(robot_t *p_Robot , float_t p_Radius , float_t p_AngularSpeed);
ecu_status_t robot_stop(robot_t *p_Robot);
ecu_status_t robot_init(robot_t *p_Robot, float_t p_TimeStep);
ecu_status_t robot_calibrate(robot_t *p_Robot);
ecu_status_t robot_PID(robot_t *p_Robot, float_t p_TimeStep);
```

Code Section 4.29: Robot Functions

```c
typedef struct
{
    wheel_t FL;
    wheel_t FR;
    wheel_t RL;
    wheel_t RR;
    PID_Controller PID_FL;
    PID_Controller PID_FR;
    PID_Controller PID_RL;
    PID_Controller PID_RR;
}robot_t;
```

Code Section 4.30: robot_t Structure

```c
typedef struct
{
    motor_t Motor;
    float_t Speed;
    direction_t Direction;
    encoder_t Encoder;
}wheel_t;
```

Code Section 4.31: wheel_t Structure

1. **robot_move(robot_t *p_Robot, float_t p_Angle, float_t p_Speed)**
   - **Purpose**: Controls the robot's movement based on a given speed and angle.
   - **Process**:
     - Converts the input speed and angle into x (Vx) and y (Vy) components.
     - Calculates angular velocities for each wheel using the kinematic equations.
     - Sets motor directions (forward/backward).
     - Calls appropriate motor functions to move the wheels.
   - **Inputs**:
     - `p_Robot`: Pointer to the robot object containing all four motors and encoders.
     - `p_Angle`: Direction of movement (in degrees).
     - `p_Speed`: Desired speed (e.g., 0.5 m/s).
2. **robot_rotate(robot_t *p_Robot, float_t p_Radius, float_t p_AngularSpeed)**
   - **Purpose**: Moves the robot in a circular path with a defined radius and angular speed.
   - **Process**:

  - Converts angular speed from RPM to RPS.
  - Calculates linear velocity based on radius and angular speed.
  - Computes individual wheel speeds for rotation.
  - Applies movement to each motor accordingly.
- **Inputs**:
  - `p_Radius`: Radius of the circular path.
  - `p_AngularSpeed`: Rotational speed in RPM.

3. **`robot_stop(robot_t *p_Robot)`**
   - **Purpose**: Stops all motors and resets their state.
   - **Process**:
     - Stops each motor using motor_stop().
     - Resets speed and direction values.
     - Clears encoder speed data.

4. **`robot_init(robot_t *p_Robot, float_t p_TimeStep)`**
   - **Purpose**: Initializes all motors, encoders, and PID controllers.
   - **Process**:
     - Initializes each motor and encoder.
     - Loads default PID constants.
     - Initializes PID controllers with specified time step.
   - **Inputs**:
     - `p_Robot`: Robot object to be initialized.
     - `p_TimeStep`: Time interval between PID updates (in milliseconds).

5. **`robot_calibrate(robot_t *p_Robot)`**
   - **Purpose**: Calibrates motors and stores PID constants in flash memory.
   - **Process**:
     - Performs motor calibration to find max speed.
     - Updates PID gains.
     - Stores calibrated values in Flash memory.

6. **`robot_PID(robot_t *p_Robot, float_t p_TimeStep)`**
   - **Purpose**: Implements closed-loop PID control for precise speed regulation.
   - **Process**:
     - Reads encoder values periodically.
     - Filters encoder readings using a low-pass filter.
     - Computes PID output for each motor.
     - Maps PID output to actual motor speed.
     - Updates motor speed using motor_change_speed().

Data Structures

- **robot_t**: Represents the robot and contains:
  - Four motor objects (FL, FR, RL, RR)
  - Encoder objects for each motor
  - PID controllers for each motor

The robot.c module serves as the core component for robot motion control. It accepts user-defined inputs – speed and direction – and translates them into individual motor commands for each of the four wheels. By decomposing the desired motion into linear and angular velocity components, the system calculates the required rotational speed for each wheel using inverse kinematics. Additionally, it implements PID-based closed-loop control using encoder feedback to maintain consistent and accurate motor speeds. This module enables the robot to perform complex maneuvers such as diagonal movement, strafing, and circular rotation.

Electronics

We are using LEDs and a buzzer as part of the robot's feedback and safety system.

- We have two LEDs:
  - One LED indicates an object detected on the left side of the robot.
  - The other LED indicates an object detected on the right side of the robot.
- The buzzer is used to alert the user when there is a dangerous situation, such as a very close obstacle or an unexpected detection near the robot.

The LEDs help determine the direction of the detected object — whether it is on the left or right side of the robot — while the buzzer serves as an emergency alarm to draw attention to critical situations.

```
ecu_status_t logic_set(logic_t *p_Logic)
{
    ecu_status_t l_EcuStatus = ECU_OK;
    if (NULL == p_Logic)
    {
        l_EcuStatus = ECU_ERROR;
    }
    else
    {
        HAL_GPIO_WritePin(p_Logic->logic_Port , p_Logic->logic_pin , GPIO_PIN_SET);
    }
    return l_EcuStatus;
}
```

Code Section 4.32: LED and Buzzer Control Code

4.1.4 DSP and Controller

PID

1- What is PID?
A Proportional-Integral-Derivative (PID) controller is a widely used feedback control algorithm in industrial and embedded systems. It continuously calculates an error value as the difference between a desired setpoint and a measured process variable, and applies a correction based on proportional, integral, and derivative terms, hence the name.

2- How PID Helps Us
In our project, the PID controller helps maintain the desired speed or position of the vehicle by automatically adjusting the control input (such as motor speed) to minimize the error. This results in smoother, more accurate, and stable system performance, especially in the presence of disturbances or changing conditions.

3- Mathematical Analysis
The PID control law can be expressed in both analog (continuous) and discrete forms:

Analog (Continuous) Form:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)\,d\tau + K_d \frac{de(t)}{dt} \tag{4.10}$$

where:

- $u(t)$ is the control output
- $e(t)$ is the error (setpoint − measured value)
- K_p is the proportional gain
- K_i is the integral gain
- K_d is the derivative gain

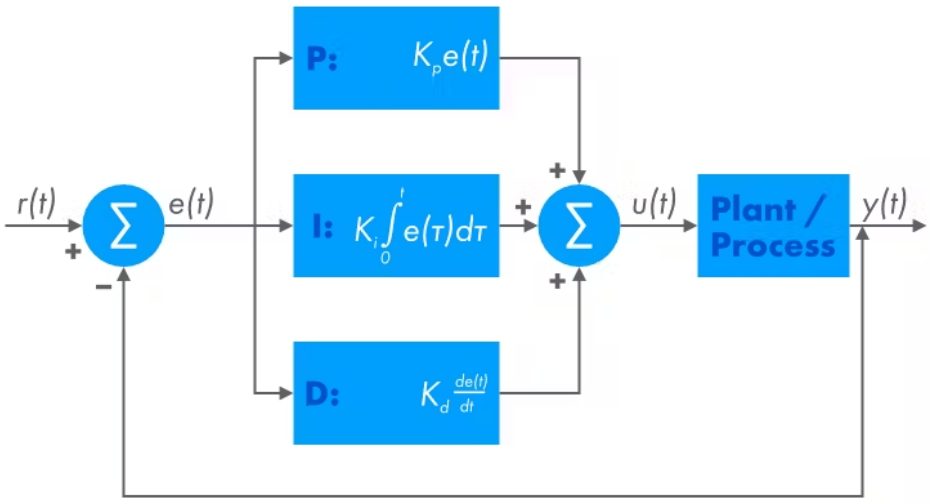


Figure 4.10: PID Controller Block Diagram

Table 4.6: Effects of Increasing and Decreasing PID Gains

Gain	*Increase*	*Decrease*
Kp	Faster response, More overshoot, Less steady-state error	Slower response, Less overshoot, More steady-state error
Ki	Eliminates steady-state error, May cause oscillation	Increases steady-state error, Less oscillation
Kd	Reduces overshoot, Improves stability, Slower response	More overshoot, Less stability, Faster response

Discrete (Digital) Form:

$$u[k] = K_p \left(e[k] + \frac{T}{T_i} \sum_{j=0}^{k} e[j] + \frac{T_d}{T} (e[k] - e[k-1]) \right) \tag{4.11}$$

where:

- $u[k]$ is the control output at step k
- $e[k]$ is the error at step k
- T is the sampling period
- K_p is the proportional gain
- T_i is the integral time constant
- T_d is the derivative time constant

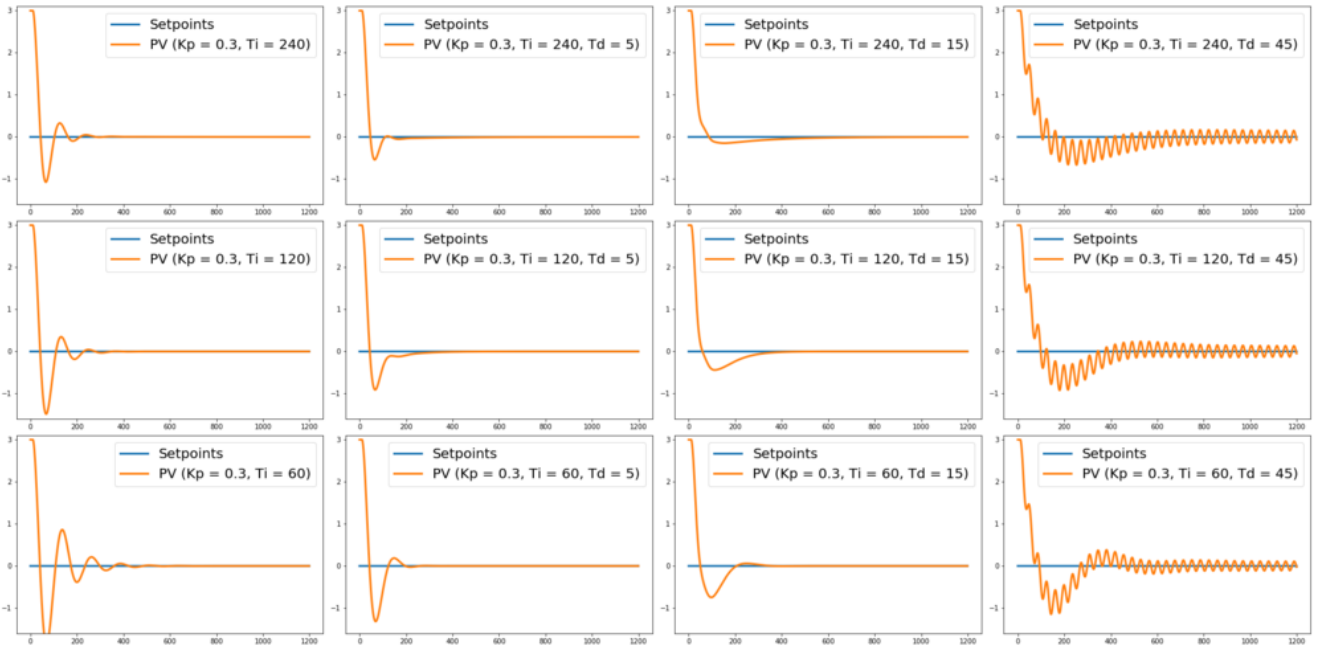


Figure 4.11: Effect of T_i and T_d on PID controller response

Note: T_i decreases from top to bottom and T_d increases from left to right.

Each term has a specific role:

- **Proportional:** Reduces the present error.
- **Integral:** Eliminates steady-state error by considering the accumulation of past errors.
- **Derivative:** Predicts future error based on its rate of change, improving stability and response.

4- Manual Tuning Steps

Manual tuning of a PID controller typically involves:

1. Set $K_i = 0$ and $K_d = 0$. Increase K_p until the system output oscillates steadily.
2. Increase K_i until the steady-state error is corrected in sufficient time.
3. Increase K_d to reduce overshoot and improve stability.
4. Adjust all three gains as needed to achieve the desired response (minimal overshoot, fast settling, no steady-state error).

5- C Implementation

The following figure shows a sample implementation of a PID controller in C:

```c
float_t PID_Compute(PID_Controller *pid, float_t setpoint, float_t measuredValue) {
    // Calculate error
    float_t error = setpoint - measuredValue;
    // Proportional term
    float_t Pout = pid->Kp * error;
    // Integral term
    pid->integral += error * pid->dt;
    float_t Iout = pid->Ki * pid->integral;
    // Derivative term with filtering
    float_t derivative = (error - pid->prevError) / pid->dt;
    float_t Dout = pid->Kd * ((pid->N * derivative - pid->prevD) / (1.0f + pid->N *
        pid->dt));
    // Update previous values
    pid->prevError = error;
    pid->prevD = Dout;
    // Total output
    float_t output = Pout + Iout + Dout;
    // Apply output limits
    if (output > pid->outputMax) {output = pid->outputMax; }
    else if (output < pid->outputMin) {output = pid->outputMin;}
    // Anti-windup: Adjust integral term if output is saturated
    if (output == pid->outputMax && error > 0) {pid->integral -= error * pid->dt;}
    else if (output == pid->outputMin && error < 0) {pid->integral -= error * pid->dt;}
    return output;
}
```

Code Section 4.33: PID Controller Implementation in C

6- PID Controllers

Following table shows the controllers we implement for each part in system:

	Motor Speed Control	Car Orientation Control	Adaptive Cruise Control
Purpose	Control the car speed and directions. Each mecanum wheel needs a specific speed to determine the car's overall speed and direction, requiring a PID controller for each motor.	Make the car rotate relative to its center to a specific angle by controlling angular speed and stopping at the desired angle (uses feedback from Kalman Filter, see 4.1.4).	As mentioned in 3.1, we use a PID controller to maintain a safe following distance from vehicles ahead.
Input	Error between set point speed and current motor speed (from encoder readings).	Error between set point angle and current angle (from Kalman Filter).	Error between set point distance and current distance (from ultrasonic sensor).
Output	PWM duty cycle to be applied to the motor to achieve desired speed.	Angular speed needed to reach the set point angle.	Acceleration or deceleration required to maintain fixed following distance.
Kp	0.85	-0.018	1.5
Ki	9.5	0.5	0
Kd	0.07	0	21
N	0.8	0	22.8

Table 4.8: PID Controllers Used in System

Kalman Filter

1. Purpose and Compatibility with PID
The Kalman filter estimates internal system states (e.g., vehicle angle and gyroscope bias) by optimally fusing a drifting inertial sensor with noisy absolute angle measurements. The smoothed estimates improve control performance when fed into PID loops (e.g., for orientation or stabilization), offering more robustness compared to using raw or filtered signals alone.

2. State-Space Model
We model the system state and measurements as:

$$\mathbf{x}_k = \begin{bmatrix} \theta_k \\ b_k \end{bmatrix}, \quad u_k = \omega_k \text{ (gyro rate)}, \quad z_k = \theta_k^{\text{meas}}. \tag{4.12}$$

Kalman Filter State-Space Model

State transition and measurement matrices:

$$F = \begin{bmatrix} 1 & -T \\ 0 & 1 \end{bmatrix}, \quad B = \begin{bmatrix} T \\ 0 \end{bmatrix}, \quad H = [1\ 0], \tag{4.13}$$

Kalman Filter State Transition and Measurement

with process noise covariance

$$Q = \text{diag}(Q_{\text{angle}}, Q_{\text{bias}}) \quad \text{and measurement noise } R. \tag{4.14}$$

Kalman Filter Process Noise Covariance

3. Discrete Kalman Equations
Predict Step:

$$\begin{aligned} \hat{\mathbf{x}}_{k|k-1} &= F\hat{\mathbf{x}}_{k-1|k-1} + Bu_k \\ P_{k|k-1} &= FP_{k-1|k-1}F^\top + Q \end{aligned} \tag{4.15}$$

Kalman Filter Predict Step

Update Step:

$$\begin{aligned} y_k &= z_k - H\hat{\mathbf{x}}_{k|k-1} \\ S_k &= HP_{k|k-1}H^\top + R \\ K_k &= P_{k|k-1}H^\top S_k^{-1} \\ \hat{\mathbf{x}}_{k|k} &= \hat{\mathbf{x}}_{k|k-1} + K_k y_k \\ P_{k|k} &= (I - K_k H)P_{k|k-1} \end{aligned} \tag{4.16}$$

Kalman Filter Update Step

where:

- $\hat{\mathbf{x}}_{k|k-1}$: Predicted state estimate at time k given observations up to $k-1$
- $\hat{\mathbf{x}}_{k|k}$: Updated state estimate at time k after measurement
- F: State transition matrix
- B: Control input matrix
- u_k: Control input at time k (e.g., gyro rate)
- $P_{k|k-1}$: Predicted error covariance
- $P_{k|k}$: Updated error covariance
- Q: Process noise covariance matrix
- z_k: Measurement at time k (e.g., measured angle)
- H: Measurement matrix
- y_k: Innovation or measurement residual
- S_k: Innovation (residual) covariance
- R: Measurement noise covariance
- K_k: Kalman gain
- I: Identity matrix

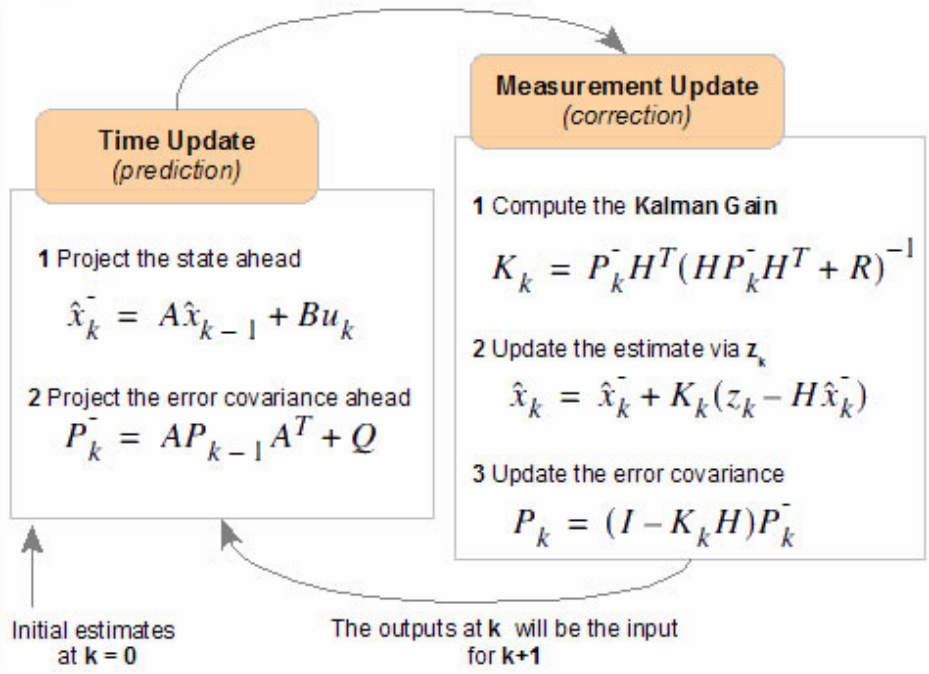


Figure 4.12: Kalman Filter Flow Diagram

4. C Implementation

```c
float Kalman_Update(Kalman *kf, float z, float w, float T) {
    // Predict
    float rate = w - kf->bias;
    kf->theta += rate * T;

    // Covariance predict
    kf->P00 += T*(T*kf->P11 - kf->P01 - kf->P10 + kf->Q_angle);
    kf->P01 -= T*kf->P11;
    kf->P10 -= T*kf->P11;
    kf->P11 += kf->Q_bias * T;

    // Measurement update
    float y = z - kf->theta;
    float S = kf->P00 + kf->R;
    float K0 = kf->P00 / S;
    float K1 = kf->P10 / S;

    kf->theta += K0 * y;
    kf->bias  += K1 * y;

    // Covariance update
    float P00 = kf->P00;
    float P01 = kf->P01;
    kf->P00 -= K0 * P00;
    kf->P01 -= K0 * P01;
    kf->P10 -= K1 * P00;
    kf->P11 -= K1 * P01;

    return kf->theta;
}
```

Code Section 4.34: Kalman_Update_Function in C

5. Performance and Tuning

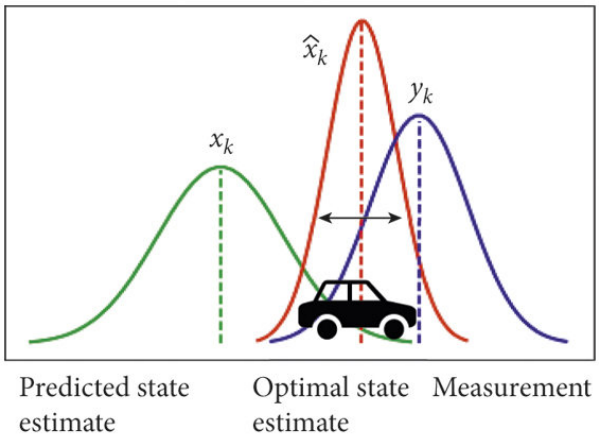
- **Observability:** Ensure the measurement matrix H covers all observable states; in this case, angle and bias are observable.
- **Stability:** Select small Q for slowly varying states (e.g., bias), and larger R for noisier sensors.
- **Convergence:** Initialize P large to reflect uncertainty; it will stabilize over time to a steady-state Riccati solution.
- **Computational Cost:** $O(n^2)$ per step; for $n = 2$, it is trivial for real-time execution on microcontrollers.
- **Numerical Stability:** Normalize angles to $[-\pi, \pi]$; avoid covariance underflow or overflow via proper bounding.

6. Comparison with Complementary Filter

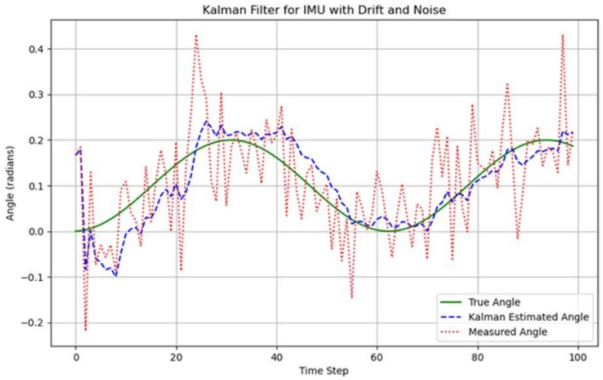
Feature	Kalman Filter	Complementary Filter
Accuracy	Optimal (Gaussian assumption)	Approximate
Bias Estimation	Yes (e.g., gyro bias)	No
Sensor Fusion	Multi-sensor capable	Limited
Tuning	Moderate (Q, R matrices)	Simple (gains)
Computation	Higher	Very low
Adaptability	Robust to drift/noise	Less adaptive
Use Cases	Robotics, aerospace, vehicles	Hobby drones, embedded devices

Table 4.9: Kalman vs. Complementary Filter

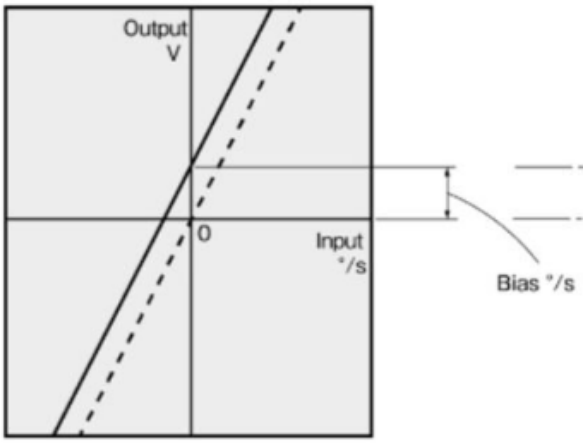
7. Visualization



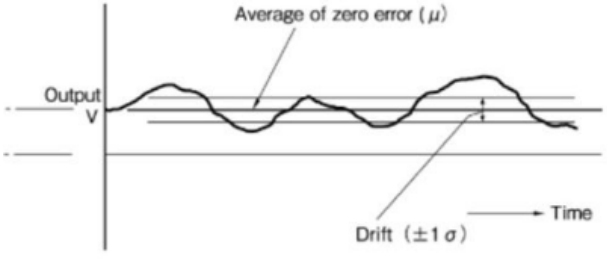
(a) Gaussian interpretation: prior, measurement, posterior.



(b) True vs. measured vs. Kalman estimate over time.



(a) Gyro bias effect on raw output.



(b) Raw signal drift over time.

8. Practical Applications

- **Autonomous Vehicles:** Sensor fusion (e.g., Compass + IMU) for localization.
- **Drones and Robotics:** Attitude estimation and stabilization.
- **Medical Devices:** Filtering noisy physiological data (e.g., ECG).
- **Finance:** Estimating trends and filtering market noise.
- **Consumer Devices:** Smartphone orientation and motion tracking.

9. Common Pitfalls

- **Mismatched Sampling Rate:** Ensure time step T is used consistently in all equations.
- **Improper Noise Tuning:** Incorrect Q and R values can lead to divergence or instability.
- **Violating Assumptions:** Kalman assumes linear-Gaussian systems; use EKF/UKF if not.
- **Initialization Errors:** Poor initial P or $\hat{x}$ values can delay convergence.
- **Angle Wraparound:** Always normalize angles to prevent estimation discontinuities.

10. Best Practices

- Match sampling rate T in both prediction and update steps.
- Monitor innovation y_k to detect sensor anomalies or abrupt events.
- Extend $\mathbf{x}$, H, and Q matrices appropriately for multiple sensors.
- Use fixed-point arithmetic where needed for embedded efficiency.
- Validate with test data and visualize convergence behavior.

4.1.5 ESP32

ESP32 Overview

The ESP32 is a series of low-cost, low-power system on a chip (SoC) microcontrollers with integrated Wi-Fi and dual-mode Bluetooth. Developed by Espressif Systems, it is a successor to the ESP8266. Its powerful capabilities and rich set of peripherals make it an ideal choice for a wide range of IoT applications, including smart home devices, wearables, and, in this project's context, smart car systems.

Key Features of ESP32

The ESP32 boasts several features that contribute to its versatility and performance:

- **Dual-Mode Bluetooth:** Includes both Bluetooth Classic (BT) and Bluetooth Low Energy (BLE). Bluetooth Classic is suitable for high-throughput data transfer, while BLE is optimized for low-power applications. In the smart car system, Bluetooth is primarily used for receiving commands from a control application, offering a robust and convenient wireless communication channel.
- **High Performance:** Equipped with a Tensilica Xtensa LX6 dual-core processor, the ESP32 can operate at clock frequencies up to 240 MHz. This processing power allows it to handle complex tasks, such as real-time data processing from sensors and simultaneous communication over multiple interfaces, without significant latency.
- **Rich Peripheral Set:** The ESP32 integrates a variety of peripherals, including:
  - **UART (Universal Asynchronous Receiver/Transmitter):** Essential for serial communication with other microcontrollers or modules. In this smart car system, UART is utilized for communication between the ESP32 and the car's motor control unit, sending commands for movement and steering.
  - **I2C (Inter-Integrated Circuit):** A two-wire serial communication protocol commonly used for connecting low-speed peripheral ICs to processors and microcontrollers. It is particularly useful for interfacing with sensors like the HMC5883L compass module, which relies on I2C for data exchange.
  - **SPI (Serial Peripheral Interface):** Another synchronous serial communication interface that can be used for high-speed data transfer with peripherals.
  - **GPIO (General-Purpose Input/Output):** Numerous GPIO pins allow for flexible interaction with external components, such as controlling LEDs, reading button states, or interfacing with various sensors and actuators.
  - **ADC (Analog-to-Digital Converter) and DAC (Digital-to-Analog Converter):** Enable the ESP32 to interact with analog signals, converting them to digital for processing or vice-versa.
- **Multitasking Capabilities:** The dual-core architecture of the ESP32 allows it to perform multiple tasks concurrently. For instance, one core can manage Wi-Fi/Bluetooth communication while the other handles sensor data processing and motor control logic. This parallel processing capability ensures efficient and responsive operation of the smart car system.

ESP32 as a Controller in a Smart Car System

In the context of a smart car project, the ESP32 serves as the central processing unit, orchestrating various functionalities to enable autonomous and remote-controlled operation. Its integrated communication modules and processing power make it an ideal choice for this role. The ESP32 acts as an intermediary, receiving high-level commands from a user interface (e.g., a smartphone application) via Bluetooth and translating these into low-level instructions for the car's motor controller.

Specifically, the ESP32's role encompasses:

- **Command Reception:** It continuously listens for incoming commands over Bluetooth. These commands can range from basic movement instructions (e.g., forward, backward, turn) to more complex operational modes (e.g., steering, rotation).
- **Sensor Data Acquisition:** The ESP32 interfaces with various sensors, such as the HMC5883L compass module, to gather real-time environmental and positional data. This data is crucial for navigation, orientation, and potentially for implementing autonomous driving features.
- **Data Processing and Logic Execution:** Upon receiving commands or sensor data, the ESP32 processes this information according to the car's control logic. This involves parsing commands, performing calculations (e.g., heading angle from compass data), and making decisions based on the current operational mode.
- **Communication with Car Controller:** After processing, the ESP32 communicates the necessary control signals to the car's motor controller, typically over UART. This serial communication ensures reliable and efficient transmission of commands that dictate the car's speed, direction, and steering angle.
- **Feedback and Status Reporting:** The ESP32 can also send feedback or status updates back to the user interface via Bluetooth, providing real-time information about the car's status, sensor readings, or operational mode. This creates a closed-loop control system, enhancing user experience and system reliability.

In summary, the ESP32's robust feature set, particularly its wireless communication capabilities and multitasking support, positions it as an indispensable component in the smart car system, enabling seamless interaction between the user, the car's control mechanisms, and its sensory inputs.

Code Explanation: Car Control

The car control module is responsible for interpreting commands received via Bluetooth and translating them into actionable signals for the car's motor controller, which communicates over UART. This section delves into the logic behind receiving, parsing, and transmitting these commands, focusing on the `processBluetooth()` function and the data transmission utilities.

Bluetooth Command Reception and Parsing

The `processBluetooth()` function continuously checks for incoming data from the Bluetooth serial port (`SerialBT`). When data is available, it reads the incoming string until a newline character (`\n`) is encountered, then trims any leading or trailing whitespace. The received string represents a command from the control application.

```
void processBluetooth() {
  if (SerialBT.available()) {
    String command = SerialBT.readStringUntil('\n');
    command.trim();
    Serial.println("Received: " + command);
    // ... command parsing logic ...
  }
}
```

Code Section 4.35: Bluetooth Command Processing Function

The system supports several types of commands, each with a distinct prefix, allowing the ESP32 to parse and act upon them accordingly:

- **Mode Selection Commands (`MODE:STEERING`, `MODE:ROTATION`):** These commands switch the car's operational mode between `STEERING` and `ROTATION`. The `currentMode` enum variable tracks the active mode, influencing how subsequent control commands are interpreted.

```
if (command == "MODE:STEERING") {
  currentMode = STEERING;
  Serial.println("Mode set to Steering");
}
else if (command == "MODE:ROTATION") {
  currentMode = ROTATION;
  Serial.println("Mode set to Rotation");
}
```

Code Section 4.36: Mode Selection Command Processing

- **Button State Command (`BUTTONS:`):** This command transmits the states of multiple virtual buttons from the control application. The format is `BUTTONS:s1,s2,s3,...,s8`, where `sX` is either '0' or '1' representing the state of each button. The `processBluetooth()` function parses this comma-separated string, converting each state to an integer and storing it in the `custom_button_states` array. These states are then immediately sent to the car controller via the `sendButtonStates()` function.

```
else if (command.startsWith("BUTTONS:")) {
  // Parse button states command "BUTTONS:1,0,1,0,0,0,1,0"
  int colonPos = command.indexOf(':');
  String statesStr = command.substring(colonPos + 1);

  int startIndex = 0;
  int endIndex = statesStr.indexOf(',');

  for (int i = 0; i < 8; i++) {
    if (endIndex == -1) endIndex = statesStr.length();

```

```
    String stateStr = statesStr.substring(startIndex, endIndex);
    custom_button_states[i] = stateStr.toInt();

    startIndex = endIndex + 1;
    endIndex = statesStr.indexOf(',', startIndex);
  }

  sendButtonStates();
  // ... Serial print for debugging ...
}
```

Code Section 4.37: Button States Command Processing

- **Steering Command (`STEER:`):** This command is used when the car is in `STEERING` mode. It expects three colon-separated float or integer values: `angle`, `speed`, and `direction`. The format is `STEER:angle:speed:direction`. The `processBluetooth()` function extracts these values, converts them to their respective data types, and applies constraints to ensure they fall within acceptable operational ranges. The `angle` is constrained between -90 and 90 degrees, and `speed` between 0 and 100. The `direction` (1 for forward, -1 for backward) adjusts the `angle` for reverse driving.

```
else if (command.startsWith("STEER:")) {
  // ... parsing logic for angle, speed, direction ...
  current_angle = -1 * constrain(current_angle, -90, 90);
  current_speed = constrain(current_speed, 0, 100);
  if (current_direction == 1)
  {
    if (current_angle < 0)  current_angle += 360;
  }
  else if (current_direction == -1)
  {
    current_angle += 180;
  }

  sendIntegerByteByByte(currentMode == STEERING ? LEFT_STICK_CMD : 0X00);
  sendFloatByteByByte(current_speed);
  sendFloatByteByByte(current_angle);
  // ... Serial print for debugging ...
}
```

Code Section 4.38: Steering Command Processing

- **Rotation Command (`ROTATE:`):** This command is used when the car is in `ROTATION` mode. It also expects three colon-separated float or integer values: `radius`, `angular_speed`, and `direction`. The format is `ROTATE:radius:angular_speed:direction`. Similar to the `STEER` command, values are extracted, converted, and constrained (`radius` between -100 and 100, `angular_speed` between 0 and 100). The `direction` (-1 for reverse rotation) adjusts the `angular_speed`.

```
else if (command.startsWith("ROTATE:")) {
  // ... parsing logic for radius, angular_speed, direction ...
  current_radius = constrain(current_radius, -100, 100);
```

```
  current_angular_speed = constrain(current_angular_speed, 0, 100);

  if (current_direction == -1)
  {
    current_angular_speed *= -1;
  }

  sendIntegerByteByByte(currentMode == ROTATION ? RIGHT_STICK_CMD : 0X00);
  sendFloatByteByByte(current_angular_speed);
  sendFloatByteByByte(current_radius);
  // ... Serial print for debugging ...
}
```

Code Section 4.39: Rotation Command Processing

Data Transmission via UART

After parsing and constraining the command values, the ESP32 transmits them to the car controller via UART. This is achieved using specific command identifiers and byte-by-byte transmission functions to ensure reliable communication.

- **Command Identifiers:** Each type of command is prefixed with a unique identifier byte to allow the receiving motor controller to correctly interpret the incoming data stream:
  - `0xAA` (`LEFT_STICK_CMD`): Used for steering commands when in `STEERING` mode.
  - `0xAB` (`RIGHT_STICK_CMD`): Used for rotation commands when in `ROTATION` mode.
  - `0xAC` (`BUTTON_CMD`): Used for transmitting button states.
- **`sendIntegerByteByByte(byte num)`:** This function sends a single byte (integer) over the UART port. It is used to transmit the command identifier.

```
void sendIntegerByteByByte(byte num) {
  UART_PORT.write(num);
}
```

Code Section 4.40: Integer Byte Transmission Function

- **`sendFloatByteByByte(float value)`:** This crucial function handles the transmission of floating-point numbers (like speed, angle, radius, angular speed) over UART. Since UART typically transmits byte by byte, a `union` is employed to access the individual bytes of a float. A `union` allows different data types to share the same memory location. By assigning a float value to the `floatUnion.x` member, its underlying 4 bytes can be accessed through `floatUnion.data[i]`, which are then sent sequentially over UART.

```
void sendFloatByteByByte(float value) {
  union {
    float x;
    uint8_t data[4];
  } floatUnion;

  floatUnion.x = value;
  for (int i = 0; i < 4; i++) {
```

```
    UART_PORT.write(floatUnion.data[i]);
  }
}
```

Code Section 4.41: Float Byte Transmission Function

- **sendButtonStates():** This function specifically sends the `BUTTON_CMD` (0xAC) followed by the 8 bytes representing the `custom_button_states` array. This allows the car controller to know the real-time status of the virtual buttons.

```
void sendButtonStates() {
  UART_PORT.write(BUTTON_CMD);
  for (int i = 0; i < 8; i++) {
    UART_PORT.write(custom_button_states[i]);
  }
}
```

Code Section 4.42: Button States Transmission Function

Driving Modes and Command Interpretation

The `currentMode` variable plays a critical role in how the ESP32 interprets incoming commands. When a `STEER:` command is received, it is only processed if `currentMode` is `STEERING`. Similarly, `ROTATE:` commands are only processed if `currentMode` is `ROTATION`. If a command is received that does not match the current mode, the corresponding `sendIntegerByteByByte` call will send `0x00` as the command identifier, effectively ignoring the command at the motor controller side. This mechanism ensures that the car responds only to commands relevant to its current operational state, preventing erroneous movements and enhancing control precision.

Code Explanation: Compass Module

The compass module is a critical component for providing the smart car with a sense of direction and orientation. It utilizes the HMC5883L magnetometer to measure the Earth's magnetic field and determine the car's heading. This section explains the initialization, data acquisition, and processing of the compass data.

HMC5883L Compass Sensor Initialization

The `setup()` function is responsible for initializing the HMC5883L compass sensor. This process involves several key steps to ensure accurate and reliable readings:

1. **Begin Communication:** The `compass.begin()` function initiates communication with the sensor over the I2C bus. The code includes a loop that continuously tries to connect to the sensor, providing a message if the sensor is not found.

2. **Configuration Settings:** Once the connection is established, several parameters are configured to optimize the sensor's performance for this specific application:

   - `setRange(HMC5883L_RANGE_1_3GA)`: Sets the measurement range of the sensor. A smaller range provides higher resolution, and ±1.3 Gauss is suitable for measuring the Earth's magnetic field.

- `setMeasurementMode(HMC5883L_CONTINOUS)`: Configures the sensor to be in continuous measurement mode, meaning it will constantly take readings.
- `setDataRate(HMC5883L_DATARATE_30HZ)`: Sets the data output rate to 30 Hz, providing a good balance between update frequency and power consumption.
- `setSamples(HMC5883L_SAMPLES_8)`: Configures the sensor to average 8 samples for each reading, which helps to reduce noise and improve the stability of the output.

3. **Calibration:** The `compass.setOffset()` function applies pre-determined calibration offsets. Magnetic sensors are susceptible to interference from nearby metallic objects and electronic components (hard-iron and soft-iron distortions). These offset values are typically determined through a separate calibration process (e.g., using the `HMC5883L_calibration.ino` sketch mentioned in the code comments) and are crucial for correcting these distortions to obtain an accurate heading.

```
// Set calibration offset. See HMC5883L_calibration.ino
compass.setOffset(-122, -138, -103, 0.97, 0.94, 1.11);
```

Code Section 4.43: Compass Calibration Offset Setting

4. **Initial Heading Reference:** After initialization, the system establishes an initial heading reference (`angleCompassStartPoint`). It takes five initial readings from the `compass_read()` function, averages them, and stores this value as the starting orientation. This reference point is then used to calculate all subsequent relative angle changes.

```
for (uint8_t i = 0; i < 5; i++) {
  angleCompassStartPoint += compass_read();
}
angleCompassStartPoint /= 5;
```

Code Section 4.44: Initial Heading Reference Calculation

Compass Reading and Heading Calculation The `compass_read()` function is responsible for obtaining a single, filtered heading reading from the sensor.

1. **Data Acquisition and Averaging:** The function reads the sensor 10 times in a loop (`COMPASS_AVG`). In each iteration, `compass.readNormalize()` fetches the calibrated and normalized magnetic field vector readings for the X and Y axes.

2. **Heading Calculation with `atan2`:** The heading angle is calculated using the `atan2(norm.YAxis, norm.XAxis)` function. `atan2` is used instead of a simple `atan(y/x)` because it correctly handles all four quadrants, providing a result in the range of $-\pi$ to $+\pi$ radians (-180°to +180°), which avoids ambiguity in the angle.

3. **Magnetic Declination Correction:** The calculated heading is then corrected for magnetic declination. Magnetic declination is the angle between magnetic north (which the compass points to) and true north. This value depends on the geographic location. The code applies a fixed declination angle corresponding to a specific location (`4°49'`). This correction is necessary for applications requiring navigation relative to true geographic coordinates.

```
float declinationAngle = (4.0 + (49.0 / 60.0)) / (180 / M_PI);
heading += declinationAngle;
```

Code Section 4.45: Magnetic Declination Correction

4. **Normalization and Conversion to Degrees:** The heading is normalized to be within the 0 to 2π range (0°to 360°) and then converted from radians to degrees. The sum of the 10 readings is then averaged to produce the final, stable heading value for that function call.

```
    headingDegrees /= COMPASS_AVG;
    return headingDegrees;
```

Angle Change Calculation and Transmission The `processCompass()` function, called continuously in the main `loop()`, is responsible for calculating the change in the car's orientation and transmitting this information.

1. **Relative Azimuth Calculation:** It first gets the current heading from `compass_read()` and calculates the azimuth relative to the initial reference point (`angleCompassStartPoint`). The result is normalized to be within the 0-360 degree range.

```
    float azimuth_read = compass_read();
    float azimuth = angleCompassStartPoint - azimuth_read;
    if (azimuth < 0) azimuth += 360;
```

2. **Difference Calculation and Wrap-Around Correction:** The function then calculates the difference between the current `azimuth` and the `previousAzimuth`. A critical step here is to handle the wrap-around issue that occurs when crossing the 360°/0°boundary. For example, a small turn from 359°to 1°would result in a raw difference of -358°, when the actual change was +2°. The code corrects for this by adding or subtracting 360°if the difference is greater than 180°or less than -180°, ensuring the smallest angle of change is correctly identified.

```
    float difference = azimuth - previousAzimuth;
    if (difference > 180) difference -= 360;
    else if (difference < -180) difference += 360;
```

3. **Accumulating Change:** The calculated `difference` is added to `accumulatedChange`, which tracks the total net rotation of the car since the system started. The `previousAzimuth` is then updated for the next iteration.

4. **Data Transmission:** If there has been a change in angle (`difference != 0`), the `sendCompassData()` function is called to transmit the `accumulatedChange` value to the motor controller via UART. This function works similarly to `sendFloatByteByByte`, using a `union` to send the float value byte by byte. It prefixes the data with the `COMPASS_CMD` identifier (`0xAD`) so the receiver can distinguish it from other data streams. The function also sends four additional zero bytes, likely as padding or to match a specific protocol expected by the receiver.

```
    void sendCompassData(float compass_value) {
      union {
        float angle;
        uint8_t data[4];
      } compassUnion;

      compassUnion.angle = compass_value;
      UART_PORT.write(COMPASS_CMD);
```

```
      for (int i = 0; i < 4; i++) {
        UART_PORT.write(compassUnion.data[i]);
      }
      for (int i = 0; i < 4; i++) {
        UART_PORT.write(0);
      }
    }
```

System Integration

The ESP32 serves as the central hub in the smart car system, seamlessly integrating various inputs and outputs to enable real-time control and autonomous capabilities. Its ability to manage multiple communication protocols concurrently is fundamental to the system's overall functionality. The integration can be understood by examining the flow of information and control signals between the key components:

- **Bluetooth Input (User Commands):** The system initiates with user commands transmitted from a control application (e.g., a smartphone app) to the ESP32 via Bluetooth. These commands, such as `STEER:`, `ROTATE:`, and `BUTTONS:`, represent high-level instructions for the car's behavior. The ESP32's `processBluetooth()` function is dedicated to receiving and parsing these commands, translating them into specific control parameters (e.g., speed, angle, radius).
- **Compass Readings (Environmental Feedback):** Simultaneously, the ESP32 continuously acquires orientation data from the HMC5883L compass module via the I2C interface. The `processCompass()` function handles the reading, calibration, and calculation of the car's heading and accumulated angle changes. This real-time feedback on the car's orientation is crucial for precise navigation, especially in scenarios requiring accurate turns or maintaining a specific direction.
- **UART Output (Control Signals to Main Robot MCU):** After processing both user commands and compass data, the ESP32 generates appropriate control signals for the main robot microcontroller (MCU), which is responsible for directly controlling the car's motors and actuators. This communication occurs over the UART serial interface. The ESP32 sends command identifiers (e.g., `0xAA` for steering, `0xAB` for rotation, `0xAC` for buttons, `0xAD` for compass data) followed by the corresponding data values (e.g., speed, angle, accumulated compass change). The use of byte-by-byte transmission functions (`sendIntegerByteByByte()`, `sendFloatByteByByte()`) ensures reliable data transfer.

Real-Time System Operation The ESP32's dual-core architecture and efficient task scheduling allow it to manage these diverse inputs and outputs in real-time. The `loop()` function continuously calls `processCompass()` and `processBluetooth()`, ensuring that both sensor data is constantly updated and new user commands are promptly processed. This concurrent operation is vital for a responsive and accurate control system:

- **Responsiveness to User Input:** New Bluetooth commands are immediately parsed and translated into motor control signals, allowing for agile remote control of the car.

- **Adaptive Control with Sensor Feedback:** The continuous compass readings enable the car to adjust its movements based on its current orientation. For instance, if the car deviates from its intended path during a turn, the compass data can be used by the main robot MCU to correct the steering angle, ensuring precise execution of maneuvers.

- **Decoupled Control Logic:** By having the ESP32 handle the high-level command interpretation and sensor data processing, and then transmitting simplified control parameters to the main robot MCU, the system achieves a modular design. This decoupling simplifies the programming of the main robot MCU, as it only needs to interpret a predefined set of commands and execute motor actions, rather than handling complex communication protocols or sensor fusion.

This integrated approach leverages the ESP32's strengths as a communication and processing hub, creating a robust and intelligent smart car system capable of responding to user commands while adapting to its environment. The block diagram below illustrates the flow of information within this integrated system.

4.1.6 FreeRTOS

FreeRTOS is a popular, open-source, real-time operating system (RTOS) for embedded systems. It provides a kernel with:

- Task scheduling (preemptive and cooperative)
- Memory management
- Inter-task communication (queues, semaphores, mutexes)
- Timers
- Low power support

Designed to be small and simple, FreeRTOS is particularly well-suited for microcontroller-based applications where resources are limited. It's widely used in automotive, industrial, and IoT applications due to its reliability and real-time performance guarantees.

Why We Used FreeRTOS in Our ADAS Project

We chose FreeRTOS for our Advanced Driver Assistance System (ADAS) project because:

1. **Real-Time Requirements**: ADAS systems require deterministic behavior and timely response to sensor inputs. FreeRTOS provides preemptive scheduling to ensure high-priority tasks (like collision detection) get immediate CPU attention.

2. **Concurrent Processing**: Our system has multiple independent functions (ACC, BSD, TSR, etc.) that need to run simultaneously. FreeRTOS allows us to implement these as separate tasks.

3. **Resource Efficiency**: With limited resources on the STM32 microcontroller, we needed a lightweight RTOS. FreeRTOS has a small memory footprint (can run in under 10KB of RAM).

4. **Reliability**: The priority-based scheduling and inter-task communication mechanisms help prevent race conditions and ensure predictable behavior.

5. **Community Support**: As one of the most popular RTOSes, FreeRTOS has extensive documentation and community support, which was valuable for our development.

6. **Hardware Abstraction**: FreeRTOS provides a hardware abstraction layer that made it easier to port our application to different STM32 variants if needed.

How We Used FreeRTOS in Our Implementation

Task Organization We structured our ADAS system into multiple FreeRTOS tasks as we will discuss in ***Application Layer***, each with specific responsibilities:

- **Sensor Tasks**:
  - `MPU_task`: Handles IMU data processing (128 bytes stack)
  - `Ultrasonic_task`: Manages ultrasonic sensor readings (128 bytes stack)
- **Control Tasks**:
  - `CONTROL_task`: Main control logic (128 bytes stack)
  - `YawKalman_task`: Kalman filtering for orientation (128 bytes stack)
  - `YawPID_task`: PID control for yaw (128 bytes stack)
- **Feature Tasks**:
  - `ACC_Task`: Adaptive Cruise Control (256 bytes stack)
  - `BSD_task`: Blind Spot Detection (128 bytes stack)
  - `TSR_Task`: Traffic Sign Recognition (128 bytes stack)
  - `APK_Task`: Automatic Parking (512 bytes stack)
- **Communication Tasks**:
  - `CAN_task`: Handles CAN bus communication (512 bytes stack)
  - `MONITORING_task`: System monitoring (128 bytes stack)

Priority Management
We assigned priorities based on criticality:

- Most tasks use `osPriorityRealtime`
- Critical control tasks like `YawPID_task` use `osPriorityRealtime1` (higher priority)

Inter-Task Communication
We implemented several synchronization mechanisms:

- **Semaphores**:
  - `MPU_sema`: Signals new IMU data
  - `CAN_sema`: Signals incoming CAN messages
  - `Orientation_sema`: For orientation data ready
  - `KalmanReady_sema`/`YawPIDReady_sema`: For initialization synchronization
- **Task Control**:
  - Tasks can suspend/resume each other (e.g., `Yaw_PID_suspend()`/`Yaw_PID_resume()`)
  - Feature tasks start suspended and are activated by button presses

Timing Control

- Used `osDelay()` for periodic task execution
- Implemented a timer (`Timer_testHandle`) for time-based operations
- Ultrasonic sensors have specific timing requirements handled by delays

Resource Management

- Carefully allocated stack sizes based on each task's needs
- Used suspend/resume to conserve resources when features aren't active
- Implemented error handling through `app_status_t` return values

Feature Activation Features like ACC, BSD, and TSR are toggled via button callbacks that:

1. Update status flags (`ACC_Flag`, `BSD_Flag`, etc.)
2. Suspend/resume the corresponding task
3. Initialize or clean up feature states

This design allows our ADAS system to efficiently manage multiple concurrent functions while ensuring real-time performance for critical operations. FreeRTOS provided the necessary infrastructure to make this complex system manageable and reliable on our STM32 hardware platform.

STM32CubeMX FreeRTOS Support

STM32CubeMX provided essential tools for integrating FreeRTOS into our project:

- **Visual Task Configuration**: Created tasks with customizable stack sizes and priorities through a GUI interface
- **Automatic Code Generation**: Generated ready-to-use task initialization code in `freertos.c` with proper CMSIS-RTOS wrappers
- **Synchronization Primitives**: Simplified creation of semaphores and mutexes with automatic handle generation
- **Memory Management**: Calculated and allocated the required heap memory for FreeRTOS kernel
- **System Tick Configuration**: Automatically configured the SysTick timer for RTOS scheduling
- **HAL Integration**: Ensured proper interaction between FreeRTOS and STM32 HAL drivers

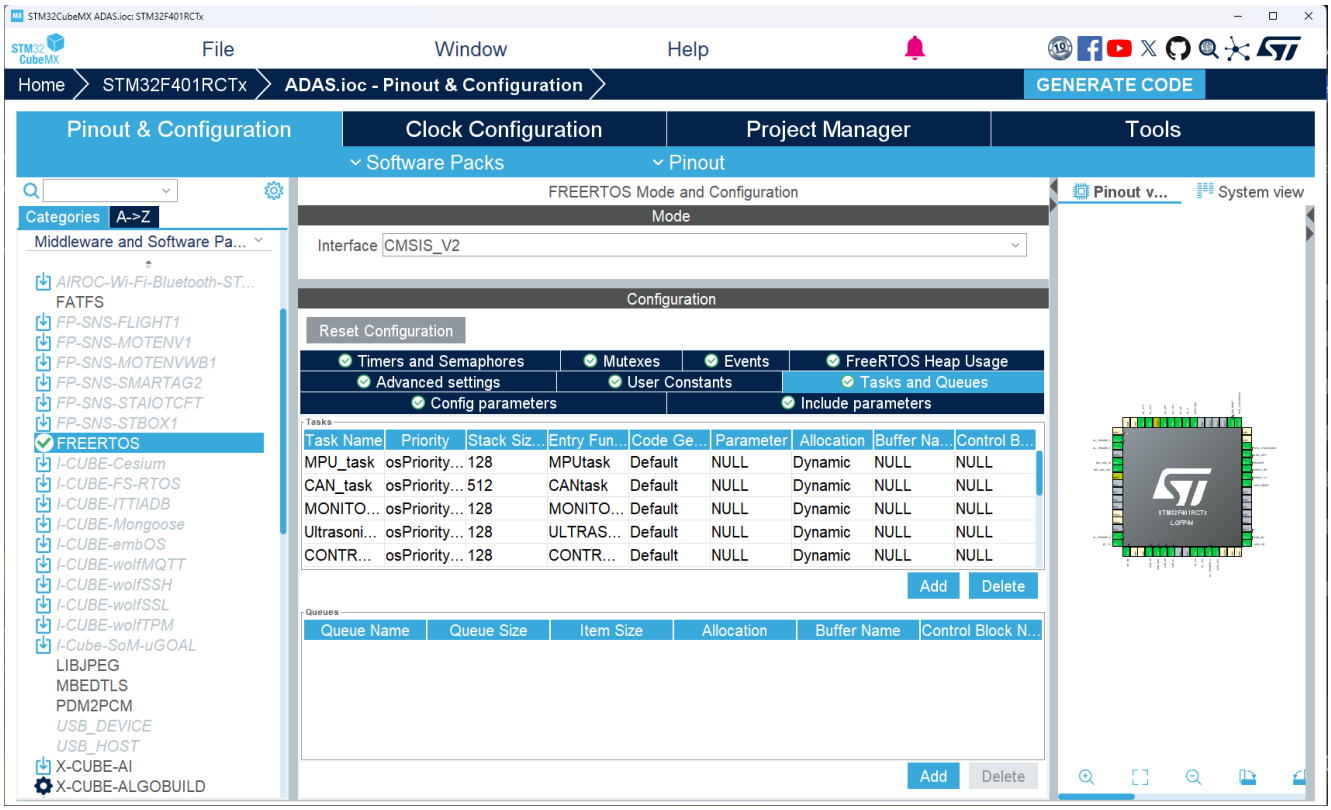


Figure 4.15: STM32CubeMX GUI for FreeRTOS Configuration

The tool significantly accelerated our development by handling the low-level RTOS setup while allowing focus on application logic implementation.

4.1.7 Application Layer

Ultrasonic Sensor Task Implementation

High-Level Overview
The ultrasonic task system provides comprehensive distance measurement around a vehicle using eight strategically placed sensors (0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°). Key features include:

- **Multi-sensor management** with grouped update tasks
- **Outlier detection** using sliding window median filtering
- **Four update groups**:
  - X-axis (0°-180°)
  - Y-axis (90°-270°)
  - U-group (45°-225°)
  - V-group (135°-315°)
- **Data validation** through threshold comparison
- **Error handling** for sensor failures

Implementation Details

Data Structures

- `ultrasonics_t` - Container for all sensor handles
- `Last_N_Readings_*` - Circular buffers for each sensor (size = `OUTLIER_WINDOW_SIZE`)

Core Algorithms

- **Sliding Window**:

$$\text{Median} = \frac{\sum_{i=0}^{N-1} \text{Buffer}[i]}{N} \tag{4.17}$$

Sliding Window Median Calculation

- **Outlier Detection**:

$$\text{Valid Reading} = \begin{cases} \text{Median} & \text{if } |\text{NewReading} - \text{Median}| > \text{THRESHOLD} \\ \text{NewReading} & \text{otherwise} \end{cases} \tag{4.18}$$

Outlier Detection Logic

Function Specifications

```
app_status_t ultrasonics_task_init(ultrasonics_t *p_AllUltrasonics)
{
    app_status_t l_AppStatus = APP_OK;
    if (NULL == p_AllUltrasonics) {
        l_AppStatus = APP_ERROR;
    }
    else {
        ecu_status_t l_EcuStatus = Ultrasonic_Init(8, p_AllUltrasonics->UL_0,
            p_AllUltrasonics->UL_180, /* ... all 8 sensors ... */);
        if (ECU_OK != l_EcuStatus) {
            l_AppStatus = APP_ERROR;
        }
    }
    return l_AppStatus;
}
```

Code Section 4.46: Ultrasonic Task Initialization Function

Purpose: Initializes all ultrasonic sensors.
Parameters: Pointer to sensor container.
Error Handling: Returns `APP_ERROR` for NULL input or hardware failure.

```
app_status_t ultrasonics_update_task_X(ultrasonics_t *p_AllUltrasonics)
{
    app_status_t l_AppStatus = APP_OK;
    if (NULL == p_AllUltrasonics) {
        l_AppStatus = APP_ERROR;
    }
    else {
        ecu_status_t l_EcuStatus = Ultrasonic_ReadDistance(2, 1, p_AllUltrasonics->UL_0,
            p_AllUltrasonics->UL_180);
        if (ECU_OK != l_EcuStatus) {
            l_AppStatus = APP_ERROR;
        }
    }
    return l_AppStatus;
}
```

Code Section 4.47: Ultrasonic X-Axis Update Task

Purpose: Triggers distance measurement for X-axis sensors.
Note: Similar functions exist for Y, U, and V groups.

```c
app_status_t ultrasonics_outlier_detect_X(ultrasonics_t *p_AllUltrasonics)
{
    /* ... */
    temp = outlier_detect(Last_N_Readings_ul0, *(p_AllUltrasonics->UL_0->Distance));
    shift_readings(Last_N_Readings_ul0, temp);
    *(p_AllUltrasonics->UL_0->Distance) = temp;
    /* ... */
}
```

Code Section 4.48: Ultrasonic X-Axis Outlier Detection

Purpose: Applies median filtering to X-axis sensors.

Helper Functions

```c
static void shift_readings(float_t *p_ReadingBuffer, float_t p_NewReading)
{
    for (uint8_t counter = OUTLIER_WINDOW_SIZE - 1; counter > 0; counter--) {
        p_ReadingBuffer[counter] = p_ReadingBuffer[counter - 1];
    }
    p_ReadingBuffer[0] = p_NewReading;
}
```

Code Section 4.49: Sliding Window Buffer Management

Purpose: Maintains sliding window of recent measurements.

```c
static float_t outlier_detect(float_t *p_ReadingBuffer, float_t p_NewReading)
{
    float_t l_Median = 0.0f;
    for (uint8_t counter = 0; counter < OUTLIER_WINDOW_SIZE; counter++) {
        l_Median += p_ReadingBuffer[counter];
    }
    l_Median /= (float_t)OUTLIER_WINDOW_SIZE;
    if ((fabsf(p_NewReading - l_Median) > OUTLIER_THRESHOLD) ||
        (p_NewReading > ULTRASONIC_MAX_READING)) {
        return l_Median;
    }
    return p_NewReading;
}
```

Code Section 4.50: Outlier Detection Algorithm

Purpose: Implements median-based outlier rejection.

Design Considerations The ultrasonic task system is designed to be modular and extensible. Each sensor group can be updated independently, allowing for efficient data acquisition without blocking other tasks. The outlier detection mechanism ensures that erroneous

Table 4.10: Configuration Parameters

Parameter	Description
`OUTLIER_WINDOW_SIZE`	Number of historical readings for median
`OUTLIER_THRESHOLD`	Maximum allowable deviation from median
`ULTRASONIC_MAX_READING`	Physical measurement limit

Usage Example

```
ultrasonics_t vehicle_sensors;

void main() {
    // Initialize all sensors
    ultrasonics_task_init(&vehicle_sensors);

    while(1) {
        // Update sensor groups (call in round-robin)
        ultrasonics_update_task_X(&vehicle_sensors);
        ultrasonics_outlier_detect_X(&vehicle_sensors);
        // Process other groups similarly...
        HAL_Delay(50);
    }
}
```

Code Section 4.51: Ultrasonic Sensor Usage Example

Motion Processing Unit (MPU)

Feature Purpose

The **Motion Processing Unit (MPU)**, specifically the `MPU6050` sensor, is employed to track the vehicle's orientation—particularly the **Yaw angle**, which measures rotation around the vertical axis (i.e., heading direction).

This measurement is critical for:

- Ensuring heading accuracy during navigation.
- Performing real-time lane correction and drift compensation.
- Assisting in turning maneuvers and path-following logic.
- Providing feedback to control algorithms such as PID controllers.

The MPU module communicates with the embedded system over the I2C interface and updates its orientation data periodically. This Yaw information is then processed to influence motion control logic and maintain vehicle stability.

Implementation Overview The MPU module in this project communicates with the system via the **I2C protocol**. It is initialized, periodically read, and its **Yaw angle** is stored and used in **PID control loops** for real-time heading corrections during vehicle movement.

The MPU component is encapsulated in a structure called `mpu_t`, defined as follows:

```
typedef struct {
    I2C_HandleTypeDef *UsedI2C;
    MPU6050_t *mpu;
    float_t YAW;
} mpu_t;
```

Code Section 4.52: MPU Structure Definition

This structure keeps track of:

- **UsedI2C**: Pointer to the I2C handler used for communication.
- **mpu**: Pointer to the actual MPU6050 data structure holding sensor readings.
- **YAW**: The latest Yaw angle measurement extracted from the sensor.

Key Components

MPU Initialization and Update Functions The MPU module logic is encapsulated through well-structured functions that manage initialization and sensor data retrieval:

- **`MPU_task_init()`**
  This function is responsible for initializing the MPU6050 sensor via the I2C protocol. It validates the pointer and calls the low-level initialization routine from the ECU layer. If the initialization fails, it returns an error status.

```
app_status_t MPU_task_init(mpu_t *p_UsedMPU)
{
    app_status_t l_AppStatus = APP_OK;
    if (NULL == p_UsedMPU)
    {
        l_AppStatus = APP_ERROR;
    }
    else
    {
        ecu_status_t l_EcuStatus = MPU6050_Init(p_UsedMPU->UsedI2C,
            p_UsedMPU->mpu);
        \* Error handling for initialization failure ... *\
    }
}
```

Code Section 4.53: MPU Initialization Function

- **MPU_update_task()**
  This function reads the updated orientation values from the MPU6050, particularly the YAW angle. It uses the I2C handler to fetch all sensor data and stores the YAW value in the ‘mpu_t‘ structure for later control computations.

```
app_status_t MPU_update_task(mpu_t *p_UsedMPU)
{
    app_status_t l_AppStatus = APP_OK;
    if (NULL == p_UsedMPU)
    {
        l_AppStatus = APP_ERROR;
    }
    else
    {
        ecu_status_t l_EcuStatus = MPU6050_Read_All(p_UsedMPU->UsedI2C,
            p_UsedMPU->mpu);
        \* Error handling for sensor read failure ... *\
        if (l_EcuStatus != ECU_OK) \* ... *\
        else
        {
            p_UsedMPU->YAW = p_UsedMPU->mpu->Yaw;
        }
    }
    return l_AppStatus;
}
```

Code Section 4.54: MPU Sensor Update Function

Function	Description
`MPU_task_init()`	Initializes the MPU sensor over I2C. Ensures proper setup of the MPU6050 device for subsequent data reading.
`MPU_update_task()`	Reads the current YAW value from the MPU6050 and updates the corresponding field in the internal `mpu_t` structure.

Table 4.11: Main MPU Functions

Key Functions

Control Flow Summary

1. **Initialization:**
   - The MPU is initialized using the function:

```
MPU6050_Init(p_UsedMPU->UsedI2C, p_UsedMPU->mpu);
```

Code Section 4.55: MPU6050 Initialization Call

   - This sets up communication with the sensor and configures it for continuous operation.

2. **Reading Sensor Data:**
   - Periodically, the system reads updated orientation data by calling:

```
MPU6050_Read_All(p_UsedMPU->UsedI2C, p_UsedMPU->mpu);
```

Code Section 4.56: MPU6050 Sensor Data Reading

   - The Yaw angle is then stored in the structure field: `p_UsedMPU->YAW`
3. **Using the YAW Value:**
   - The YAW value is critical for maintaining orientation stability.
   - It is used by other modules, such as lane correction and steering control, to ensure the vehicle maintains proper heading.

CAN Bus Communication Tasks and Message Definitions

The Controller Area Network (CAN) Bus Communication Module is a fundamental part of our Advanced Driver Assistance Systems (ADAS) vehicle. It facilitates real-time, reliable, and robust communication between different Electronic Control Units (ECUs). This module is built on top of the MCP2515 CAN controller and provides an application-layer protocol for structured message handling, error recovery, and callback-based event processing.

This documentation details the architecture, message definitions, error handling mechanisms, and integration with other ADAS subsystems.

System Architecture

The CAN communication system is divided into two main components:

- `CAN_task.c` – Implements the CAN bus management layer, including initialization, message transmission, reception, and error handling.
- `Messages_Callbacks.c` – Defines message structures, IDs, and callback functions for processing incoming and outgoing CAN frames.

`CAN_task.c` – Detailed Explanation

Overview

The `CAN_task.c` file is the core of the CAN communication system, responsible for:

- Initializing the CAN bus
- Managing message transmission and reception
- Handling errors and recovery
- Providing an interface for other modules to interact with CAN

It works alongside `Messages_Callbacks.c`, which defines message structures and processing logic.

Key Functions & Their Roles

`CAN_task_init()` – CAN Bus Initialization

Purpose:

- Initializes the MCP2515 CAN controller
- Creates a list of expected messages (for reception handling)

Workflow:

- Checks if the `CAN_bus_t` pointer is valid
- Calls `CANSPI_Initialize()` to set up the CAN controller
- Creates a linked list (`p_CanBus->ExpectedMSG`) to store expected messages

Error Handling: Returns `APP_ERROR` if:

- The CAN bus pointer is NULL
- Initialization fails (`CANSPI_Initialize` returns an error)
- Memory allocation for the message list fails

```
app_status_t CAN_task_init(CAN_bus_t *p_CanBus) {
    if (NULL == p_CanBus) return APP_ERROR;
    ecu_status_t status = CANSPI_Initialize(p_CanBus->UsedCAN);
    p_CanBus->ExpectedMSG = list_create();
    if ((status != ECU_OK) || (NULL == p_CanBus->ExpectedMSG)) {
        return APP_ERROR;
    }
    return APP_OK;
}
```

Code Section 4.57: CAN Bus Initialization

`CAN_add_msg_rx()` – Registering Expected Messages

Purpose:

- Adds a message type to the list of expected messages
- Used by other modules to declare which messages they can receive

Workflow:

- Checks if the CAN bus and message pointers are valid
- Appends the message to the `ExpectedMSG` list

Error Handling: Returns `APP_ERROR` if pointers are NULL.

```
app_status_t CAN_add_msg_rx(CAN_bus_t *p_CanBus, can_msg_t *p_Message) {
    if ((NULL == p_CanBus) || (NULL == p_Message)) {
        return APP_ERROR;
    }
    list_append(p_CanBus->ExpectedMSG, p_Message);
    return APP_OK;
}
```

Code Section 4.58: Registering Expected Messages

`CAN_rx_task()`– Message Reception & Handling

Purpose:

- Receives incoming CAN messages (blocking or interrupt-driven)
- Dispatches messages to their respective callbacks

Workflow:

- Receives a raw CAN message (`uCAN_MSG`) using `CANSPI_Receive()`
- Searches the `ExpectedMSG` list for a matching message ID
- If found:
  - Copies the received data into the registered `can_msg_t` structure
  - Executes the callback function for processing

Error Handling:

- Returns `APP_ERROR` if the CAN bus pointer is invalid
- Silently ignores unregistered messages

```
app_status_t CAN_rx_task(CAN_bus_t *p_CanBus) {
    if (NULL == p_CanBus) return APP_ERROR;

    uCAN_MSG tempMsg;
    ecu_status_t status = CANSPI_Receive(p_CanBus->UsedCAN, &tempMsg);

    if (status == ECU_OK) {
        can_msg_t *rxMsg = list_find(p_CanBus->ExpectedMSG, &tempMsg, find_msg_with_id);
        if (rxMsg != NULL) {
            memcpy(&rxMsg->Message, &tempMsg, sizeof(uCAN_MSG));
            rxMsg->CallBack(&rxMsg->Message); // Execute callback
        }
    }
    return APP_OK;
}
```

Code Section 4.59: Message Reception & Handling

`CAN_send_message()` – Message Transmission

Purpose:

- Transmits a CAN message with error recovery
- Updates message data via callback before sending

Workflow:

- Checks if the CAN bus and message pointers are valid
- Calls the message's callback to update its data
- Checks for bus-off or TX errors
- If the bus is healthy, transmits the message
- If errors occur:
  - Attempts to reinitialize the CAN bus
  - Returns `APP_ERROR` if recovery fails

```
app_status_t CAN_send_message(CAN_bus_t *p_CanBus, can_msg_t *p_Message) {
    if ((NULL == p_CanBus) || (NULL == p_Message)) return APP_ERROR;

    p_Message->CallBack(&p_Message->Message); // Update data
    p_Message->Message.frame.id = p_Message->ID;

    ecu_status_t status = CANSPI_isBussOff(p_CanBus->UsedCAN);
    if (status == ECU_OK) {
        status = CANSPI_Transmit(p_CanBus->UsedCAN, &p_Message->Message);
        if (status != ECU_OK) {
            if (status == ECU_ERROR) {
                CANSPI_Initialize(p_CanBus->UsedCAN); // Recover
            }
            return APP_ERROR;
        }
    } else {
        status = CANSPI_isTxErrorPassive(p_CanBus->UsedCAN);
        if (status == ECU_ERROR) {
            CANSPI_Initialize(p_CanBus->UsedCAN); // Recover
            return APP_ERROR;
        }
    }
    return APP_OK;
}
```

Code Section 4.60: Message Transmission

`CAN_CLEAR_INT()` – Interrupt Management

Purpose:

- Clears the CAN interrupt flag to allow new messages
- Typically called after processing an interrupt

```
void CAN_CLEAR_INT(CAN_bus_t *p_CanBus) {
    MCP2515_WriteByte(p_CanBus->UsedCAN->UsedSPI, MCP2515_CANINTF, 0x00);
}
```

Code Section 4.61: Interrupt Management

Static Helper Functions

`find_msg_with_id()` – Message ID Matching

Purpose:

- Compares a received message ID with registered messages
- Used by `list_find()` in `CAN_rx_task()`

```
static int find_msg_with_id(void *p_MsgExpected, const void *p_MsgReceived) {
    return (((can_msg_t *)p_MsgExpected)->ID == ((uCAN_MSG *)p_MsgReceived)->frame.id) ?
        1 : 0;
}
```

Code Section 4.62: Message ID Matching

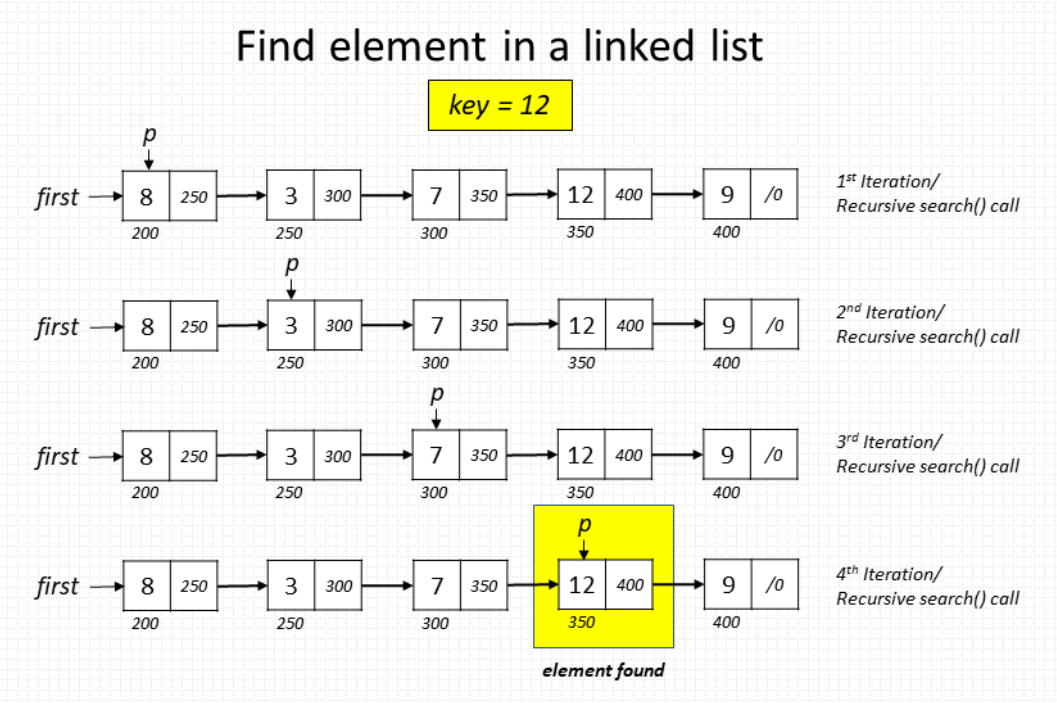


Figure 4.16: Linear Search Algorithm for Message ID Matching

Key Design Considerations

Callback-Based Architecture

This design allows for modular message processing:

- Decouples CAN handling from application logic
- Each message type defines its own processing function

Error Recovery Mechanisms

The CAN module implements robust error handling:

- Bus-off detection → Auto-reinitialization
- Transmission errors → Retry or reset

Thread Safety (If Used in RTOS)

In a FreeRTOS environment, the CAN module must ensure thread safety:

- Critical sections (e.g., list operations) may need mutex protection
- Interrupt-driven RX minimizes latency

`Messages_Callbacks.c` – Message Definitions & Callbacks

This file defines:

- Message IDs (0x100–0x106) for different ADAS functions
- Callback functions that execute when a message is received or transmitted
- Data conversion utilities (float ↔ bytes) for structured message handling

Key Features:

- Dynamic message registration (`messages_init()`)
- Callback-based processing for modularity
- Type-safe data packing/unpacking using unions

Message Protocol & Data Handling

The CAN module uses a structured message protocol to ensure consistent data formats across different ECUs. Each message has a unique ID and a defined data structure, allowing for efficient parsing and processing.

Message IDs & Definitions

Each CAN message has a unique 11-bit identifier (Standard CAN 2.0B) and a defined structure.

Table 4.12: CAN Message Definitions

Message ID	Description	Data Length	Data Format
0x100	Robot Strafe Control	8 bytes	`float speed, float direction`
0x101	Robot Rotate Control	8 bytes	`float angular_speed, float radius`
0x102	Robot Stop Command	1 byte	`uint8_t stop_flag`
0x103	Omega Z Update	4 bytes	`float angular_velocity`
0x104	Traffic Sign Detection	2 bytes	`uint8_t speed_limit, uint8_t sign_type`
0x105	Lane Change Update	2 bytes	`uint8_t available_lane, uint8_t current_position`
0x106	Encoder Position Update	8 bytes	`float FL_encoder, float FR_encoder`

Data Conversion Utilities

Since CAN messages transmit raw bytes, we use unions for safe float ↔ byte conversion:

```
typedef union {
    float value;
    uint8_t data[4];
} one_float_conv;

typedef union {
    float value[2];
    uint8_t data[8];
} two_float_conv;
```

Code Section 4.63: Data Conversion Utilities

Example Usage (Robot Strafe Callback):

```
static void msg_robot_strafe_clb(uCAN_MSG *p_Message) {
    p_Message->frame.dlc = 8;
    two_float_conv temp;
    temp.value[0] = Car_Wanted_Speed;
    temp.value[1] = Car_Wanted_direction;
    memcpy(p_Message->frame.data, temp.data, 8);
}
```

Code Section 4.64: Robot Strafe Callback

Error Handling & Recovery

The CAN module implements robust error detection and recovery mechanisms:

Bus-Off Detection & Recovery

If the CAN controller enters a bus-off state (due to excessive errors), the system:

- Detects the condition using `CANSPI_isBussOff()`
- Reinitializes the CAN controller (`CANSPI_Initialize()`)
- Attempts to resume normal operation

Transmission Error Handling
If a transmission error occurs (`CANSPI_isTxErrorPassive`), the system:

- Checks if the error is recoverable
- Reinitializes the bus if necessary
- Retries the transmission

Status Reporting
All functions return `app_status_t` (`APP_OK` or `APP_ERROR`). ECU-level status codes (`ECU_OK`, `ECU_ERROR`) provide additional diagnostics.

Integration with ADAS Features
The CAN module interacts with multiple ADAS subsystems:

1. **Traffic Sign Recognition (TSR)**
   - Message ID: 0x104
   - Callback: `msg_sign_detected_clb()`
   - Functionality:
     - Receives detected traffic signs (speed limits, stop signs)
     - Updates the vehicle's speed control system
2. **Auto Lane Change (ALC)**
   - Message ID: 0x105
   - Callback: `msg_lane_update_clb()`
   - Functionality:
     - Receives lane availability and current position data
     - Triggers automated lane-change maneuvers
3. **Motion Control (Strafe, Rotate, Stop)**
   - Message IDs: 0x100, 0x101, 0x102
   - Callbacks:
     - `msg_robot_strafe_clb()` – Controls lateral movement
     - `msg_robot_rotate_clb()` – Handles rotational motion
     - `msg_robot_stop_clb()` – Emergency stop command

4. **Wheel Encoder Feedback**
    - Message ID: 0x106
    - Callback: `msg_update_encoder_clb()`
    - Functionality:
        - Receives wheel encoder positions for odometry and dead reckoning
        - Helps in path tracking and navigation

`Control_task.c` – Detailed Explanation

Overview
The `Control_task.c` file manages controller input handling for the ADAS vehicle, including:

- Joystick & button command processing
- Manual vs. automatic yaw control switching
- CAN message transmission for motion control
- Callback-based button action handling

It interfaces with:

- CAN bus (for motion commands)
- Controller hardware (joystick/buttons)
- Orientation system (yaw angle control)

Key Functions & Their Roles

`controller_add_callback()` – Button Callback Registration
Purpose:

- Associates callback functions with controller buttons
- Allows different modules to define actions for button presses

Workflow:

- Checks if the controller and callback pointers are valid
- Maps the callback to the specified button (`UP`, `DOWN`, `LEFT`, `RIGHT`, etc.)

Error Handling: Returns `APP_ERROR` if:

- Pointers are NULL
- Invalid button ID is provided

```
app_status_t controller_add_callback(controller_t *p_UsedController,
                                     pressed_button_t p_Button,
                                     void (*p_Callback)(void *)) {
    if ((NULL == p_UsedController) || (NULL == p_Callback))
        return APP_ERROR;

    switch (p_Button) {
        case UP:    p_UsedController->UP_button_clb = p_Callback; break;
        case DOWN: p_UsedController->DOWN_button_clb = p_Callback; break;
        // ... (other buttons)
        default: return APP_ERROR;
    }
    return APP_OK;
}
```

Code Section 4.65: Button Callback Registration

`controller_wait_receive()` – Controller Data Reception

Purpose:

- Fetches raw controller data (joystick positions, button states)

Workflow:

- Calls `control_receive_data()` (low-level hardware read)
- Returns status (`APP_OK`/`APP_ERROR`)

Error Handling: Returns `APP_ERROR` if:

- Controller pointer is NULL
- Hardware read fails (`ECU_ERROR`)

```
app_status_t controller_wait_receive(controller_t *p_UsedController) {
    if (NULL == p_UsedController) return APP_ERROR;
    ecu_status_t status = control_receive_data(p_UsedController->UsedController);
    return (status == ECU_OK) ? APP_OK : APP_ERROR;
}
```

Code Section 4.66: Controller Data Reception

`controller_task()` – Command Processing

Purpose:

- Processes joystick movements and button presses
- Sends CAN messages for motion control
- Switches between manual/auto yaw control

Workflow:

- Reads the controller data type (first byte of `Data[]`)
- Handles:
  - **Left Joystick**: Sets `Car_Wanted_Speed/direction` → Sends `msg_robot_strafe` CAN message
  - **Right Joystick**: Sets `Car_Wanted_Angular_Speed/Rotate_Radius` → Sends `msg_robot_rotate` CAN message
  - Switches to manual yaw control if moving (`manual_control_yaw()`)
  - Reverts to auto yaw control if idle (`auto_control_yaw()`)
  - **Buttons**: Executes registered callbacks (e.g., `UP_button_clb`)
  - **Compass Angle**: Updates the compass angle reference

Error Handling: Returns `APP_ERROR` for invalid data types.

```c
app_status_t controller_task(controller_t *p_UsedController) {
    if (NULL == p_UsedController) return APP_ERROR;

    switch (p_UsedController->UsedController->Data[0]) {
        case LEFT_JOY_STICK:
            // Parse speed/direction -> Send CAN strafe message
            CAN_send_message(&Main_CAN, &msg_robot_strafe);
            break;

        case RIGHT_JOY_STICK:
            // Parse angular speed/radius -> Send CAN rotate message
            CAN_send_message(&Main_CAN, &msg_robot_rotate);
            if (Car_Wanted_Angular_Speed == 0)
                auto_control_yaw();  // Revert to auto yaw
            else
                manual_control_yaw();  // Manual override
            break;

        case PUSH_BUTTON:
            // Trigger button callbacks
            if (button_pressed(UP) && p_UsedController->UP_button_clb)
                p_UsedController->UP_button_clb(NULL);
            // ... (other buttons)
            break;

        default: return APP_ERROR;
    }
    return APP_OK;
}
```

Code Section 4.67: Command Processing

Yaw Control Initialization

Purpose:

- Registers callbacks for manual/auto yaw control transitions

Functions:

- `controller_get_yaw_control_init()`: Sets `manual_control_yaw` callback (manual mode)
- `controller_give_yaw_control_init()`: Sets `auto_control_yaw` callback (auto mode)

Error Handling: Returns `APP_ERROR` if pointers are NULL.

```
app_status_t controller_get_yaw_control_init(controller_t *p_UsedController,
                                             void (*get_yaw_control_yaw)(void)) {
    if ((NULL == p_UsedController) || (NULL == get_yaw_control_yaw))
        return APP_ERROR;
    manual_control_yaw = get_yaw_control_yaw;
    return APP_OK;
}
```

Code Section 4.68: Yaw Control Initialization

Key Design Features

Callback-Driven Architecture

- **Buttons**: Each button press triggers a modular callback
- **Yaw Control**: Smooth switching between manual/auto modes

CAN Integration

- Joystick movements → CAN messages (`msg_robot_strafe`, `msg_robot_rotate`)
- Ensures real-time motion control

Data Parsing

- Uses unions (`two_float_conv`, `one_float_conv`) for safe float ↔ byte conversion

```
two_float_conv temp;
memcpy(temp.data, &p_UsedController->UsedController->Data[1], 8);
Car_Wanted_Speed = temp.value[0];  // Extract float from raw bytes
```

Code Section 4.69: Data Parsing

Error Robustness

- Null checks for all pointers
- Status codes (`APP_OK/APP_ERROR`) for fault detection

Integration with Other Modules

Table 4.13: Module Interactions

Module	Interaction
CAN Bus	Sends motion commands (`msg_robot_strafe`, `msg_robot_rotate`)
Orientation System	Switches yaw control between manual/auto modes
Button Actions	Executes registered callbacks (e.g., for UI, ADAS feature toggles)
Compass Sensor	Updates compass angle reference (`COMPASS_ANGLE`)

monitroing task

The Monitoring Task is a critical component of our ADAS system's application layer, responsible for collecting, organizing, and transmitting system status information to external monitoring tools. This task operates in a bare-metal environment (without an RTOS) and provides real-time visibility into the vehicle's sensor data, control parameters, and system states.

Key Responsibilities

- **Data Aggregation:** Collects data from various subsystems including:
  - MPU (Motion Processing Unit) orientation data (YAW, filtered YAW)
  - Ultrasonic sensor distances from 8 directions (0°, 45°, 90°, etc.)
  - PID controller parameters (Kp, Ki, Kd, N)
  - Vehicle control states (wanted speed, max speed)
  - Emergency and traffic-related flags
- **Data Packaging:** Organizes collected data into a structured buffer format for transmission.
- **Data Integrity:** Implements CRC (Cyclic Redundancy Check) to ensure data integrity during transmission.
- **Periodic Updates:** Continuously updates and transmits monitoring data at a fixed rate.

Implementation Details Initialization

- The `monitor_task_init()` function:
  - Sets up the size information for all monitored parameters (all 4-byte values)
  - Assigns memory pointers to connect monitoring parameters with their source variables
  - Registers the update callback function

Data Update Process

- The `monitor_update_task()` performs these key operations:
  - Copies current values from source variables into a temporary buffer
  - Calculates CRC for the data set using hardware CRC peripheral
  - Transmits data in a specific sequence:
    * Starts with synchronization bytes (0xF0F0F0F0)
    * Followed by all monitored parameters
    * Ends with CRC value for verification

Data Structure

- The monitoring system uses a hierarchical structure:
  - `monitor_values_t` contains pointers to all monitored parameters
  - Each parameter has:
    * Size information (fixed at 4 bytes for all parameters)
    * Original data pointer (source variable)
    * Send data buffer (for transmission)

Technical Considerations Memory Efficiency:

- Uses direct memory copying (`memcpy`) for efficient data transfer
- Maintains a fixed-size buffer (100 bytes) for all monitoring data

Real-Time Performance:

- Designed for minimal execution time to avoid impacting critical control loops
- Uses hardware CRC acceleration when available

Extensibility:

- The structure allows easy addition of new monitored parameters
- Callback mechanism enables custom update handling

Usage in ADAS System

- The monitoring task serves several important purposes in our ADAS system:
  - **Debugging:** Provides real-time visibility into system states during development
  - **Calibration:** Allows tuning of PID parameters and filter coefficients
  - **Safety Monitoring:** Tracks emergency conditions and traffic-related flags
  - **Performance Analysis:** Enables assessment of control system performance

This monitoring capability is particularly valuable in our bare-metal environment where traditional debugging tools may be limited.

Auto Lane Change (ALC)

Purpose The **Auto Lane Change (ALC)** feature is a crucial component of the ADAS (Advanced Driver Assistance System). It allows the vehicle to perform lane changes either *automatically* in response to unintentional drift or system input or *semi-autonomously* based on driver request.

The decision is made by analyzing current lane availability and the car's real-time position within the lane. This functionality significantly enhances road safety by reducing unintended lane departures and enabling smooth, controlled directional transitions.

Implementation Overview The Auto Lane Change (ALC) feature is structured as a layered software module. It interfaces with the Raspberry Pi via the CAN bus to receive real-time lane data captured by the camera. Internally, it maintains variables that reflect the vehicle's current position within the lane and its intended movement direction. Based on these inputs, the system makes decisions and communicates the corresponding control commands through the CAN bus to the motor control ECU, enabling safe and smooth lane changes.

Key Components

Lane Status Enum This enumeration defines the various possible positions of the car relative to the lane lines, such as being centered, drifting, or having clear lanes on either side. It helps the system determine the car's situation and take appropriate action.

```
typedef enum
{
    LEFT_ONLY = 1,
    RIGHT_ONLY,
    LEFT_AND_RIGHT,
    LANE_ERROR,
    DRIFT_LEFT,
    DRIFT_RIGHT,
    CENTERALIZED,
    LEFT_CENTERALIZED,
    RIGHT_CENTERALIZED,
} Lane_Received_t;
```

Code Section 4.70: Lane Status Enumeration

Lane Direction Enum This enumeration defines the possible directions for a lane change or correction. It is used to decide how the car should move or realign within or across lanes.

```
typedef enum {
   D_LEFT = 1,
   D_RIGHT,
   CENTER,
   DIRECTION_ERROR,
} Lane_Direction_t;
```

Code Section 4.71: Lane Direction Enumeration

Main Functions

```
app_status_t ALC_handle(Lane_Received_t p_AvailableLane, Lane_Received_t
    p_CurrentPosition)
{
    app_status_t l_AppStatus = APP_OK;
    CurrentPosition = p_CurrentPosition;
    switch (p_CurrentPosition)
    {
    case DRIFT_LEFT:
        AvailableLanes = LANE_ERROR;
        break;
    case DRIFT_RIGHT:
        AvailableLanes = LANE_ERROR;
        break;
    case LEFT_CENTERALIZED:
        AvailableLanes = p_AvailableLane;
        break;
    case RIGHT_CENTERALIZED:
        AvailableLanes = p_AvailableLane;
        break;
    case CENTERALIZED:
        AvailableLanes = p_AvailableLane;
        break;
    default:
        break;
    }
}
```

Code Section 4.72: Handles incoming data from Raspberry Pi

ALC_Change_Lane()

```
app_status_t ALC_Change_Lane(Lane_Direction_t p_WantedLane)
{
    app_status_t l_AppStatus = APP_OK;
```

```
    if (((AvailableLanes == LEFT_ONLY) || (AvailableLanes == LEFT_AND_RIGHT)) &&
        (p_WantedLane == D_LEFT))
        WantedLaneToChange = D_LEFT;
    else if (((AvailableLanes == RIGHT_ONLY) || (AvailableLanes == LEFT_AND_RIGHT)) &&
        (p_WantedLane == D_RIGHT))
        WantedLaneToChange = D_RIGHT;
    else {
        WantedLaneToChange = DIRECTION_ERROR;
        l_AppStatus = APP_ERROR;
    }
    return l_AppStatus;
}
```

Code Section 4.73: Handles lane change request

ALC_Task()

```
app_status_t ALC_Task(void)
{
    app_status_t l_AppStatus = APP_OK;

    if (!FlagtoChange)
    {
        TempPosition = CENTERALIZED;
        if (CurrentPosition == DRIFT_LEFT) {
            l_AppStatus |= LaneChange(D_RIGHT);
            FlagtoChange = D_RIGHT;
        }
        else if (CurrentPosition == DRIFT_RIGHT) {
            l_AppStatus |= LaneChange(D_LEFT);
            FlagtoChange = D_LEFT;
        }
        else if (WantedLaneToChange == D_LEFT) {
            l_AppStatus |= LaneChange(D_LEFT);
            TempPosition = DRIFT_RIGHT;
            FlagtoChange = D_LEFT;
        }
        else if (WantedLaneToChange == D_RIGHT) {
            l_AppStatus |= LaneChange(D_RIGHT);
            TempPosition = DRIFT_LEFT;
            FlagtoChange = D_RIGHT;
        }
    }
    else
    {
        if (CurrentPosition == TempPosition) {
            l_AppStatus |= LaneChange(CENTER);
            WantedLaneToChange = CENTER;
            FlagtoChange = 0;
            TempPosition = CENTERALIZED;
```

```
        }
        else {
            l_AppStatus |= LaneChange(FlagtoChange);
        }
    }
    return l_AppStatus;
}
```

Code Section 4.74: Main task logic

LaneChange()

```
static app_status_t LaneChange (Lane_Direction_t p_Direction)
{
    app_status_t l_AppStatus = APP_OK;
    float_t l_DirectionOfChange = 0.0f;

    switch (p_Direction)
    {
        case D_LEFT:
            l_DirectionOfChange = (Car_Wanted_Speed *
              (MIN_ANGLE_LANE_CHANGE - MAX_ANGLE_LANE_CHANGE) /
              DEFUALT_ROBOT_MAX_SPEED ) + MAX_ANGLE_LANE_CHANGE;
            Car_Wanted_direction = l_DirectionOfChange;
            break;

        case D_RIGHT:
            l_DirectionOfChange = (Car_Wanted_Speed *
              (MIN_ANGLE_LANE_CHANGE - MAX_ANGLE_LANE_CHANGE) /
              DEFUALT_ROBOT_MAX_SPEED ) + MAX_ANGLE_LANE_CHANGE;
            Car_Wanted_direction = 360 - l_DirectionOfChange;
            break;

        case CENTER:
            Car_Wanted_direction = 0;
            break;

        default:
            l_AppStatus = APP_ERROR;
            break;
    }

    l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
    return l_AppStatus;
}
```

Code Section 4.75: Steering control via CAN

Function	Description
`ALC_handle()`	Updates internal states based on camera feedback (via Raspberry Pi).
`ALC_Change_Lane()`	Validates and stores user/system intent to switch lanes.
`ALC_Task()`	Performs the actual lane change or correction based on intent or drift.
`LaneChange()`	Computes new steering angle and sends the command via CAN.

Table 4.14: Main Functions of the ALC Feature

Function Summary Table

Challenges Addressed

- Ensures lane change only occurs when safe.
- Automatically corrects unintended drift.
- All control happens centrally via CAN to avoid conflicts.

Traffic Sign Recognition (TSR)

Feature Purpose The **Traffic Sign Recognition (TSR)** system identifies road signs—particularly speed limit signs—and modifies the vehicle's behavior accordingly. Its primary goal is to increase driving safety and ensure compliance with traffic regulations by dynamically adjusting the car's speed based on visual input.

This feature is also a fundamental component of **ADAS** and autonomous driving applications, especially in urban environments where traffic rules change frequently.

Implementation Overview The TSR system receives real-time sign detection results from the **Raspberry Pi**, which processes images using computer vision algorithms such as `YOLO` or `OpenCV`. The Raspberry Pi sends detected signs and speed limits over the **CAN bus** to the MCU (main embedded system), where logic exists to adapt the vehicle's behavior accordingly.

Key Components

```
typedef enum {
    SPEED_30 = 1, SPEED_40, SPEED_50, SPEED_60, SPEED_70,
    SPEED_80, SPEED_90, SPEED_100, SPEED_120,
    DIRECTION, STOP, RED, GREEN,
} traffic_sign_t;
```

Code Section 4.76: Traffic Sign Enum

This enumeration lists all supported signs. The system currently prioritizes speed limit signs, with placeholders for future handling of `STOP`, `RED`, and `GREEN` lights.

TSR_handle()

```
app_status_t TSR_handle(traffic_sign_t p_Speed, traffic_sign_t p_Sign)
{
    app_status_t l_AppStatus = APP_OK;

    switch (p_Speed)
    {
    case SPEED_30:
        Car_Max_Forced_Speed = Max_speed_responsible(SPEED_30_PERCENTAGE *
            DEFUALT_ROBOT_MAX_SPEED, TSR);
        l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
        break;

    case SPEED_40:
        Car_Max_Forced_Speed = Max_speed_responsible(SPEED_40_PERCENTAGE *
            DEFUALT_ROBOT_MAX_SPEED, TSR);
        l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
        break;

    case SPEED_50:
        Car_Max_Forced_Speed = Max_speed_responsible(SPEED_50_PERCENTAGE *
            DEFUALT_ROBOT_MAX_SPEED, TSR);
        l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
        break;

    case SPEED_60:
        Car_Max_Forced_Speed = Max_speed_responsible(SPEED_60_PERCENTAGE *
            DEFUALT_ROBOT_MAX_SPEED, TSR);
        l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
        break;

    case SPEED_70:
        Car_Max_Forced_Speed = Max_speed_responsible(SPEED_70_PERCENTAGE *
            DEFUALT_ROBOT_MAX_SPEED, TSR);
        l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
        break;

    case SPEED_80:
        Car_Max_Forced_Speed = Max_speed_responsible(SPEED_80_PERCENTAGE *
            DEFUALT_ROBOT_MAX_SPEED, TSR);
        l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
        break;

    case SPEED_90:
```

```
38          Car_Max_Forced_Speed = Max_speed_responsible(SPEED_90_PERCENTAGE *
                DEFUALT_ROBOT_MAX_SPEED, TSR);
39          l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
40          break;
41
42      case SPEED_100:
43          Car_Max_Forced_Speed = Max_speed_responsible(SPEED_100_PERCENTAGE *
                DEFUALT_ROBOT_MAX_SPEED, TSR);
44          l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
45          break;
46
47      case SPEED_120:
48          Car_Max_Forced_Speed = Max_speed_responsible(SPEED_120_PERCENTAGE *
                DEFUALT_ROBOT_MAX_SPEED, TSR);
49          l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
50          break;
51
52      default:
53          break;
54      }
55
56      switch (p_Sign)
57      {
58      case DIRECTION:
59          /* Reserved Until Thinking of the behavior */
60          break;
61
62      case STOP:
63          /* Reserved Until Thinking of the behavior */
64          break;
65
66      case RED:
67          /* Reserved Until Thinking of the behavior */
68          break;
69
70      case GREEN:
71          /* Reserved Until Thinking of the behavior */
72          break;
73
74      default:
75          break;
76      }
77
78      return l_AppStatus;
79  }
```

Code Section 4.77: Handles speed and sign commands from Raspberry Pi

TSR_task()

```c
app_status_t TSR_task(void)
{
    app_status_t l_AppStatus = APP_OK;
    static float_t LastAngle = 0.0f;

    if ((Car_Wanted_Angle - LastAngle > 10.0f) || (LastAngle - Car_Wanted_Angle > 10.0f))
    {
        Car_Max_Forced_Speed = DEFUALT_ROBOT_MAX_SPEED;
        l_AppStatus |= CAN_send_message(&Main_CAN, &msg_robot_strafe);
    }

    LastAngle = Car_Wanted_Angle;
    return l_AppStatus;
}
```

Code Section 4.78: Monitors car angle for dynamic speed restoration

Control Flow Summary

1. **Detection & Input**
   - The Raspberry Pi detects a traffic or speed sign using a camera and computer vision models (e.g., YOLO, OpenCV).
   - The detected sign is sent as an enum value via the CAN bus to the MCU.
2. **Speed Sign Handling**
   - `TSR_handle()` checks if the detected sign is a speed limit.
   - Sets `Car_Max_Forced_Speed` to a percentage of `DEFUALT_ROBOT_MAX_SPEED`.
   - Sends an updated control message (`msg_robot_strafe`) via CAN to adjust motor behavior.
3. **Dynamic Behavior Check**
   - `TSR_task()` monitors the car's heading angle (`Car_Wanted_Angle`).
   - If a sharp turn is detected (i.e., angle change $> \pm 10°$), the vehicle's max speed is restored to default to ensure safer handling on curves.

Design Considerations

- **Modularity:** The system separates detection (handled on the Raspberry Pi) from control logic (handled on the MCU).
- **Safety:** Ensures that the vehicle's maximum speed does not exceed the limit indicated by traffic signs.

- **Extendability:** The system is designed with future enhancements in mind—additional behavior can be implemented for `STOP`, `RED`, and `GREEN` signals.

Adaptive Cruise Control (ACC) Implementation

High-Level Overview The ACC system provides intelligent speed control based on surrounding traffic conditions. Key features include:

- **Speed adaptation** based on front vehicle distance
- **Directional awareness** for both X and Y axis movement
- **PID-based control** for smooth speed adjustments
- **Speed limiting** with feature coordination
- **Safety mechanisms** through distance thresholds

Function Specifications

Initialization

```
app_status_t ACC_task_init(ACC_t *p_ACC)
{
    app_status_t l_AppStatus = APP_OK;
    if ((NULL == p_ACC)) {
        l_AppStatus = APP_ERROR;
    }
    else {
        PID_Init(&p_ACC->PID_Vx, Vx_Kp, Vx_Ki, Vx_Kd, Vx_N,
                p_ACC->dt, Vx_MIN_OUT, Vx_MAX_OUT);
        PID_Init(&p_ACC->PID_Vy, Vy_Kp, Vy_Ki, Vy_Kd, Vy_N,
                p_ACC->dt, Vy_MIN_OUT, Vy_MAX_OUT);
    }
    return l_AppStatus;
}
```

Code Section 4.79: ACC System Initialization Function

Purpose: Initializes ACC PID controllers.
Parameters:

- `p_ACC`: ACC control structure
- PID parameters for both X and Y axis control

Relative Distance Task

```
app_status_t ACC_relative_task(ACC_t *p_ACC)
{
    /* ... */
    float_t l_SetPointDistance = 50.0f * min(Car_Wanted_Speed,
                                        Car_Max_Forced_Speed) + PID_MIN_SP;

    l_AppStatus |= ACC_action_task_x(p_ACC, &l_Vx, l_SetPointDistance);

    if ((value_in_range(Car_Wanted_direction, 0, 45) ||
        value_in_range(Car_Wanted_direction, 315, 360)) {
        Car_Max_Forced_Speed = Max_speed_responsible(
            Car_Max_Forced_Speed - l_Vx, ACC);
        /* ... */
    }
    /* ... */
}
```

Code Section 4.80: ACC Relative Distance Control Task

Purpose: Main control loop for speed adaptation.
Key Operations:

- Calculates dynamic distance setpoint
- Executes X-axis control
- Adjusts maximum speed when moving forward

Speed Limiting Function

```
float_t Max_speed_responsible(float_t p_MaxSpeed, Max_Speed_ID_t p_ID)
{
    /* ... */
    FeatureMaxSpeed[p_ID] = constrain(p_MaxSpeed, 0, DEFUALT_ROBOT_MAX_SPEED);

    for (uint8_t i = 0; i < 5; i++) {
        if (l_MaxSpeed >= FeatureMaxSpeed[i])
            l_MaxSpeed = FeatureMaxSpeed[i];
    }
    return l_MaxSpeed;
}
```

Code Section 4.81: Speed Limiting Coordination Function

Purpose: Coordinates speed limits between features.
Parameters:

- `p_MaxSpeed`: Requested speed limit
- `p_ID`: Feature identifier

Control Tasks

X-Axis Control

```
static app_status_t ACC_action_task_x(ACC_t *p_ACC,
                                      float_t *p_RetVelocity,
                                      float_t p_DisSetPoint)
{
    /* ... */
    float_t l_Vx = PID_Compute(&p_ACC->PID_Vx,
                               p_DisSetPoint/100,
                               *p_ACC->Front_UL/100);
    *p_RetVelocity = l_Vx;
    /* ... */
}
```

Code Section 4.82: ACC X-Axis Control Function

Purpose: Maintains safe following distance.
Control Law:

$$V_x = PID\left(\frac{\text{SetPoint}}{100}, \frac{\text{FrontDistance}}{100}\right)$$

Y-Axis Control

```
// Negative Y-direction
static app_status_t ACC_action_task_y_neg(ACC_t *p_ACC, float_t *p_RetVelocity)
{
    float_t l_HorizontalDIs = -1.0f * (*p_ACC->Left_UL) * cos(45);
    *p_RetVelocity = PID_Compute(&p_ACC->PID_Vy, PID_MIN_SP, l_HorizontalDIs) * 0.1;
}

// Positive Y-direction
static app_status_t ACC_action_task_y_pos(ACC_t *p_ACC, float_t *p_RetVelocity)
{
    float_t l_HorizontalDIs = (*p_ACC->Left_UL) * cos(45);
    *p_RetVelocity = PID_Compute(&p_ACC->PID_Vy, PID_MIN_SP, l_HorizontalDIs) * 0.1;
}
```

Code Section 4.83: ACC Y-Axis Control Functions

Purpose: Handles lateral movement control.
Note: Uses cosine projection of 45° sensor readings.

Table 4.15: Configuration Parameters

Parameter	Description
DEFUALT_ROBOT_MAX_SPEED	Base speed limit
PID_MIN_SP	Minimum safe distance
Vx_Kp/Ki/Kd	PID gains for longitudinal control
Vy_Kp/Ki/Kd	PID gains for lateral control

Design Considerations

Usage Example

```
ACC_t vehicle_acc;

void main() {
    // Initialize ACC system
    ACC_task_init(&vehicle_acc);

    while(1) {
        // Run main control task
        ACC_relative_task(&vehicle_acc);
        HAL_Delay(10);
    }
}
```

Code Section 4.84: ACC System Usage Example

Error Handling

- NULL pointer checks for all public functions
- Status codes returned for error conditions
- Speed limiting protects against unsafe values
- PID output constraints prevent excessive commands

Performance Characteristics

- **Update Rate**: Typically 10-100Hz
- **Response Time**: Dependent on PID tuning
- **Accuracy**: Determined by sensor resolution
- **Stability**: Guaranteed by proper PID design

Blind Spot Detection (BSD) Implementation

High-Level Overview The BSD system provides vehicle safety monitoring for blind spot areas using ultrasonic sensors. Key features include:

- **Multi-zone monitoring** covering both left and right blind spots
- **Visual alerts** through LED indicators
- **Audible warnings** via buzzer
- **Asynchronous operation** with suspend/resume capability
- **Configurable sensitivity** through `MIN_DISTANCE` threshold

Function Specifications

Initialization

```
app_status_t BSD_init(BSD_t *p_bls,
                      void (*p_delay)(uint32_t),
                      void (*p_suspend)(void),
                      void (*p_resume)(void))
{
    app_status_t l_AppStatus = APP_OK;
    if (NULL == p_bls) {
        l_AppStatus = APP_ERROR;
    }
    else {
        delay_call_back = p_delay;
        buzzer_resume = p_resume;
        buzzer_suspend = p_suspend;
    }
    return l_AppStatus;
}
```

Code Section 4.85: BSD System Initialization Function

Purpose: Initializes BSD system with callback functions.
Parameters:

- `p_bls`: BSD control structure
- `p_delay`: Millisecond delay function
- `p_suspend/resume`: Buzzer control callbacks

Main Detection Task

```
app_status_t BSD_task(BSD_t *p_bls)
{
    /* ... */
    if ((*Main_Ultrasonics.UL_90->Distance <= MIN_DISTANCE) ||
        (*Main_Ultrasonics.UL_135->Distance <= MIN_DISTANCE) ||
        (*Main_Ultrasonics.UL_270->Distance <= MIN_DISTANCE) ||
        (*Main_Ultrasonics.UL_225->Distance <= MIN_DISTANCE))
    {
        // Right side detection
        if((*Main_Ultrasonics.UL_90->Distance <= MIN_DISTANCE) ||
           (*Main_Ultrasonics.UL_135->Distance <= MIN_DISTANCE)) {
            right_led_turn_on(p_bls);
        }
        // Left side detection
        if((*Main_Ultrasonics.UL_270->Distance <= MIN_DISTANCE) ||
           (*Main_Ultrasonics.UL_225->Distance <= MIN_DISTANCE)) {
            left_led_turn_on(p_bls);
        }
        buzzer_resume();
    }
    else {
        right_led_turn_off(p_bls);
        left_led_turn_off(p_bls);
        buzzer_suspend();
    }
    /* ... */
}
```

Code Section 4.86: BSD Main Detection Task

Purpose: Monitors blind spots and triggers alerts.
Sensor Mapping:

- Right Blind Spot: `UL_90 + UL_135`
- Left Blind Spot: `UL_225 + UL_270`

Buzzer Control Task

```
app_status_t BSD_buzzer_task(BSD_t *p_bls)
{
    /* ... */
    buzzer_on(p_bls);
    delay_call_back(500); // 500ms on
    buzzer_off(p_bls);
    delay_call_back(250); // 250ms off
    /* ... */
}
```

Code Section 4.87: BSD Buzzer Control Task

Purpose: Generates audible alert pattern.
Pattern: 500ms ON / 250ms OFF

Table 4.16: BSD Control Functions

Function	Description
`right_led_turn_on/off()`	Controls right indicator LED
`left_led_turn_on/off()`	Controls left indicator LED
`buzzer_on/off/toggle()`	Manages buzzer state

Helper Functions

Design Considerations

Alert Logic

- Visual indicators remain on while object detected
- Buzzer activates in repeating pattern
- Separate tasks for detection and buzzer control

Parameter	Value	Description
`MIN_DISTANCE`	Configurable	Detection threshold
Buzzer ON time	500ms	Alert duration
Buzzer OFF time	250ms	Silence duration

Table 4.17: Performance Parameters

Performance Parameters

Usage Example

```
BSD_t vehicle_bsd;
void delay_ms(uint32_t ms) { HAL_Delay(ms); }

void main() {
    // Initialize BSD system
    BSD_init(&vehicle_bsd, delay_ms, buzzer_stop, buzzer_start);

    while(1) {
        BSD_task(&vehicle_bsd);       // Run detection
        BSD_buzzer_task(&vehicle_bsd); // Handle buzzer
    }
}
```

Code Section 4.88: BSD System Usage Example

Error Handling

- NULL pointer checks for all public functions
- Status codes returned for error conditions
- Safe state transition (LEDs/buzzer off) on error

4.2 Embedded Linux

The rapid advancement of Artificial Intelligence (AI) has led to its widespread deployment on edge devices, including single-board computers like the Raspberry Pi 5. However, running AI models efficiently on such resource-constrained hardware requires a carefully optimized software environment. This is where embedded Linux distributions, such as those built with the Yocto Project, play a crucial role.

The Yocto Project is an open-source collaboration that provides flexible tools for creating custom Linux distributions tailored for embedded systems. Unlike general-purpose operating systems, a Yocto-built Linux system allows developers to strip away unnecessary components, reducing overhead and improving performance—a critical requirement when deploying AI workloads on devices with limited computational power, such as the Raspberry Pi 5.

Linux, as the underlying operating system, is indispensable for AI applications due to its stability, scalability, and extensive support for hardware acceleration frameworks (e.g., TensorFlow Lite, ONNX Runtime, and PyTorch). Moreover, Linux provides essential drivers and libraries that enable efficient utilization of the Raspberry Pi 5's GPU and neural processing capabilities.

In this chapter, we explore why Linux—particularly a Yocto-optimized distribution—is essential for running AI models on the Raspberry Pi 5. We discuss the benefits of custom-built Linux systems, the role of Yocto in streamlining embedded AI deployments, and the key considerations for optimizing performance in resource-constrained environments.

4.2.1 Building and Deploying a Yocto Image for Raspberry Pi 5

The Yocto Project provides a powerful framework for generating custom Linux distributions optimized for embedded systems like the Raspberry Pi 5. This section outlines the key steps to build a minimal Linux image using Yocto and deploy it onto the Raspberry Pi 5

Prerequisites

Before starting, ensure the following prerequisites are met:

- A **Linux host system** (Ubuntu 20.04/22.04 recommended) with sufficient disk space ($\geq$ 50 GB).
- Essential build tools installed (e.g., `git`, `gcc`, `make`, `python3`).
- An SD card ($\geq$ 16 GB) for flashing the image.
- Network connectivity to fetch Yocto layers and dependencies.

Setting Up the Yocto Environment

The Yocto build process relies on the `Poky` reference distribution and Raspberry Pi-specific metadata layers.

```
sudo apt install gawk wget git diffstat unzip texinfo \
gcc build-essential chrpath socat cpio python3 \
python3-pip python3-pexpect xz-utils debianutils \
iputils-ping python3-git python3-jinja2 libegl1-mesa \
libsdl1.2-dev pylint xterm python3-subunit mesa-common-dev
```

Code Section 4.89: Install Required Packages

```
git clone git://git.yoctoproject.org/poky -b kirkstone
cd poky
git clone git://git.openembedded.org/meta-openembedded -b kirkstone
git clone git://git.yoctoproject.org/meta-raspberrypi -b kirkstone
```

Code Section 4.90: Clone the Yocto Project Repositories

```
source oe-init-build-env
```

Code Section 4.91: Initialize the Build Environment

Configuring the Build for Raspberry Pi 5

The Raspberry Pi 5 requires specific configurations in `conf/local.conf` and `conf/bblayers.conf`:

- **Enable Raspberry Pi 5 Support:** Add the following to `conf/local.conf`:

```
MACHINE = "raspberrypi5-64"
GPU_MEM = "256"
IMAGE_INSTALL:append = " python3 tensorflow-lite"
```

Code Section 4.92: Enable Raspberry Pi 5 Support

- **Include Required Layers:** Ensure `conf/bblayers.conf` includes:

```
BBLAYERS += "${TOPDIR}/../meta-raspberrypi"
BBLAYERS += "${TOPDIR}/../meta-openembedded/meta-oe"
```

Code Section 4.93: Include Required Layers

Building the Image

Execute the build process using BitBake:

```
    bitbake core-image-minimal   # Minimal image
    # Or for a more feature-rich image:
    bitbake core-image-sato
```

Code Section 4.94: Build Commands

```
bitbake core-image-minimal   # Minimal image
# Or for a more feature-rich image:
bitbake core-image-sato
```

Code Section 4.95: Build Commands

The build process may take several hours, depending on system performance. The output image (e.g., `core-image-minimal-raspberrypi5-64.wic.bz2`) will be in:

```
tmp/deploy/images/raspberrypi5-64/
```

Code Section 4.96: Output Image Location

Flashing the Image to Raspberry Pi 5

Once the image is built, flash it to an SD card:

1. Extract the compressed image:

   ```
   bzip2 -d core-image-minimal-raspberrypi5-64.wic.bz2
   ```

   Code Section 4.97: Extract the Compressed Image

2. Flash using `dd` (replace `sdX` with the SD card device):

   ```
   sudo dd if=core-image-minimal-raspberrypi5-64.wic \
   of=/dev/sdX bs=4M conv=fsync status=progress
   ```

   Code Section 4.98: Flash the Image

3. Insert the SD card into the Raspberry Pi 5 and power it on.

Verifying the Deployment

After booting, log in (typically as `root` without a password) and verify:

- Kernel version: `uname -a`
- GPU memory allocation: `vcgencmd get_mem_arm`
- AI framework availability (e.g., `python3 -c "import tflite_runtime"`).

4.2.2 Running AI Models on Raspberry Pi with Network Streaming

Deploying AI models on a Raspberry Pi involves several challenges, including resource constraints and concurrent access to hardware peripherals like the camera. This section explains how to:

- Execute a pre-trained AI model (e.g., TensorFlow Lite or ONNX Runtime) on the Raspberry Pi.
- Stream camera frames over a local network to enable multiple scripts to process the same video feed simultaneously.
- Optimize performance for real-time inference.

Prerequisites

Ensure the following before proceeding:

- A Raspberry Pi (preferably Pi 5 for better performance) running a Yocto-built or Raspberry Pi OS (64-bit).
- A USB or CSI camera module (e.g., Raspberry Pi Camera Module 3).
- Python installed with AI framework dependencies:

```
pip install tensorflow-lite opencv-python flask numpy
```

Code Section 4.99: Install AI Framework Dependencies

- A local network connection (Wi-Fi/Ethernet) between the Pi and other devices (if applicable).

1. **Load the Model and Initialize Interpreter:**

```
import tflite_runtime.interpreter as tflite
interpreter = tflite.Interpreter(model_path="model.tflite")
interpreter.allocate_tensors()
input_details = interpreter.get_input_details()
output_details = interpreter.get_output_details()
```

Code Section 4.100: Load TFLite Model

2. **Process Camera Frames:** Use OpenCV to capture frames and preprocess them for the model:

```
import cv2
cap = cv2.VideoCapture(0)  # CSI/USB camera
while True:
    ret, frame = cap.read()
    if not ret:
        break
    # Preprocess frame (resize, normalize, etc.)
    input_data = cv2.resize(frame, (224, 224))
    input_data = np.expand_dims(input_data, axis=0)
    # Run inference
    interpreter.set_tensor(input_details[0]['index'], input_data)
    interpreter.invoke()
    predictions = interpreter.get_tensor(output_details[0]['index'])
    # Post-process predictions (e.g., draw bounding boxes)
    cv2.imshow('AI Output', frame)
    if cv2.waitKey(1) == ord('q'):
        break
cap.release()
```

Code Section 4.101: Process Camera Frames

Network Streaming for Concurrent Camera Access

To allow multiple scripts to access the same camera feed without hardware conflicts, we use a Flask-based HTTP server to stream frames over the local network.

1. **Streaming Server Script (Camera Producer):** This script captures frames and serves them via HTTP:

```
from flask import Flask, Response
import cv2
app = Flask(name)
camera = cv2.VideoCapture(0)
def generate_frames():
    while True:
        success, frame = camera.read()
        if not success:
            break
        ret, buffer = cv2.imencode('.jpg', frame)
        frame = buffer.tobytes()
        yield (b'--frame\r\n'
               b'Content-Type: image/jpeg\r\n\r\n' + frame + b'\r\n')
@app.route('/video_feed')
def video_feed():
    return Response(generate_frames(),
```

```
                    mimetype='multipart/x-mixed-replace; boundary=frame')
if name == 'main':
    app.run(host='0.0.0.0', port=5000)
```

Code Section 4.102: Streaming Server Script

2. **Client Script (AI Consumer):** This script fetches the streamed frames and processes them with the AI model:

```
import cv2
import numpy as np
import requests
stream_url = 'http://<PI_IP>:5000/video_feed'
cap = cv2.VideoCapture(stream_url)
while True:
    ret, frame = cap.read()
    if not ret:
        break
    # Run AI inference on the frame
    # (Same as Step 2 in the previous subsection)
    cv2.imshow('Client Output', frame)
    if cv2.waitKey(1) == ord('q'):
        break
cap.release()
```

Code Section 4.103: Client Script

Performance Optimization

To ensure smooth operation:

- **Reduce Resolution:** Stream at 640x480 or lower to minimize latency.
- **Use Hardware Acceleration:** Enable OpenCV with V4L2 or MMAL for the camera.
- **Edge AI Optimizations:** Quantize the model (e.g., INT8) and use TFLite delegates (e.g., XNNPACK) for faster inference.

Results and Validation

After deployment:

- Verify the streaming server is accessible at `http://<PI_IP>:5000/video_feed`.
- Check AI inference latency using `time.time()` measurements.
- Monitor CPU/GPU usage with `top` or `vcgencmd`.

4.2.3 Sending Processed Frames to STM32 via CAN Bus

In this section, we describe the methodology for transmitting two distinct AI-processed frames (speed detection and traffic sign detection) from the Raspberry Pi to an STM32 microcontroller using the MCP2515 CAN controller. To avoid hardware SPI limitations, we implement a manual (bit-banged) SPI protocol in Python.

System Overview

The data pipeline consists of the following steps:

1. The Raspberry Pi captures video frames and processes them using two AI models:
   - **Frame 1**: Speed estimation (e.g., using optical flow or object tracking).
   - **Frame 2**: Traffic/directional sign detection (e.g., YOLO or TensorFlow Lite).
2. Detected data (speed value, sign type) is encoded into CAN messages.
3. The MCP2515 module transmits messages to the STM32 via CAN bus, using a manual SPI interface.

Hardware Configuration

- **Raspberry Pi**: GPIO pins for bit-banged SPI (SCK, MOSI, MISO, CS).
- **MCP2515**: Connected to CAN bus (H/L lines) and Raspberry Pi GPIOs.
- **STM32**: Configured as a CAN bus receiver with an appropriate termination resistor (120 Ω).

Manual SPI Implementation for MCP2515

Since the Raspberry Pi does not use hardware SPI, we manually toggle GPIOs to emulate SPI communication:

```
import RPi.GPIO as GPIO
import time

# Pin definitions (BCM numbering)
SCK  = 11   # Clock
MOSI = 10   # Master Out Slave In
MISO = 9    # Master In Slave Out
CS   = 8    # Chip Select

def spi_init():
    GPIO.setmode(GPIO.BCM)
    GPIO.setup(SCK, GPIO.OUT)
    GPIO.setup(MOSI, GPIO.OUT)
    GPIO.setup(MISO, GPIO.IN)
    GPIO.setup(CS, GPIO.OUT)
```

```
    GPIO.output(CS, GPIO.HIGH)

def spi_write_byte(data):
    GPIO.output(CS, GPIO.LOW)
    for i in range(8):
        GPIO.output(MOSI, (data >> (7 - i)) & 0x01)
        GPIO.output(SCK, GPIO.HIGH)
        time.sleep(0.001)
        GPIO.output(SCK, GPIO.LOW)
    GPIO.output(CS, GPIO.HIGH)

def spi_read_byte():
    GPIO.output(CS, GPIO.LOW)
    data = 0
    for i in range(8):
        GPIO.output(SCK, GPIO.HIGH)
        bit = GPIO.input(MISO)
        data = (data << 1) | bit
        GPIO.output(SCK, GPIO.LOW)
    GPIO.output(CS, GPIO.HIGH)
    return data
```

Code Section 4.104: Manual SPI Implementation

4.2.4 CAN Message Encoding

Data from the two frames is packed into CAN frames (standard 11-bit IDs):

- **Speed Frame (ID: 0x100)**: 4-byte payload (e.g., `0x00 0x00 0x03 0xE8` = 1000 cm/s).
- **Sign Frame (ID: 0x101)**: 1-byte payload (e.g., `0x01` = "Stop", `0x02` = "Turn Left").

```
def send_can_message(can_id, data):
# MCP2515 register writes to load TX buffer
spi_write_byte(0x40)  # Write to TXB0SIDH
spi_write_byte(can_id >> 3)
spi_write_byte((can_id & 0x07) << 5)
spi_write_byte(0x00)  # EID (unused)
spi_write_byte(len(data))  # DLC
for byte in data:
    spi_write_byte(byte)
# Request transmission
spi_write_byte(0x80)  # RTS for TXB0
```

Code Section 4.105: Send CAN Message

4.2.5 Integration with AI Workflow

The CAN transmission logic is integrated into the AI inference scripts:

```
# After speed detection (Frame 1)
speed_data = [0x00, 0x00, (speed >> 8) & 0xFF, speed & 0xFF]
send_can_message(0x100, speed_data)

# After sign detection (Frame 2)
sign_code = 0x01 if sign == "Stop" else 0x02  # Example mapping
send_can_message(0x101, [sign_code])
```

Code Section 4.106: Integrate CAN Transmission

4.2.6 Validation and Debugging

- Verify GPIO signals with a logic analyzer.
- Monitor CAN bus traffic using a CAN sniffer (e.g., PCAN-USB).
- Check STM32 UART debug logs for received data.

4.3 Control and Monitoring Interfaces

4.3.1 Control Interface

The Control System is a core component of the Vehicle Control and Monitoring System, designed to provide intuitive and responsive control over a vehicle's movement, steering, and auxiliary functions. Built using Python with the **CustomTkinter** library, the system features a graphical user interface (**GUI**) that enables real-time interaction with the vehicle's hardware through serial communication.

Key Features

1. **Steering Control**
   - **Interactive Steering Wheel:** A visual steering wheel allows users to control the vehicle's direction by clicking and dragging or using keyboard inputs (**A** for left, **D** for right).
   - **Two Steering Modes:**
     - *Steering Mode:* Direct angle-based control (range: **-90°** to **+90°**).
     - *Rotation Mode:* Controls the turning radius as a percentage (**-100%** to **+100%**).
   - **Mouse & Keyboard Support:** Users can adjust the steering angle via mouse drag or keyboard shortcuts.
2. **Movement Control**

- **Directional Buttons:** Forward (**W**), Backward (**S**), and Stop commands.
- **Acceleration Slider:** Adjusts speed from **0%** to **100%** with visual feedback.
- **Mouse Wheel Support:** Acceleration can also be adjusted using the mouse wheel.

3. **Customizable Buttons**

- **8 Programmable Buttons:** Each button can be configured as:
  - *Toggle Button:* Maintains state (ON/OFF).
  - *Push Button:* Momentary activation (press and release).
- **Keyboard Bindings:** Buttons can be assigned to keyboard keys for quick access.

4. **Driver Monitoring System**

- **Real-time Camera Feed:** Displays live video from the driver-facing camera with FPS counter.
- **Drowsiness Detection:** Uses YOLO-based AI model to detect drowsy states with configurable thresholds.
- **Status Indicators:** Visual alerts for:
  - *Awake:* Green status when driver is alert
  - *Drowsy:* Orange warning when thresholds are exceeded
  - *Emergency:* Red alert with audible alarm for critical situations
- **Configurable Parameters:** Adjustable detection thresholds for blink duration, drowsiness timing, and emergency levels.

5. **Emergency Features**

- **Emergency Parking:** Triggers an immediate stop and sends an alert (visual & auditory).
- **Automated Email Notification:** In case of driver drowsiness or system failure, an emergency email with location data is sent to a predefined contact.

Control Flowchart

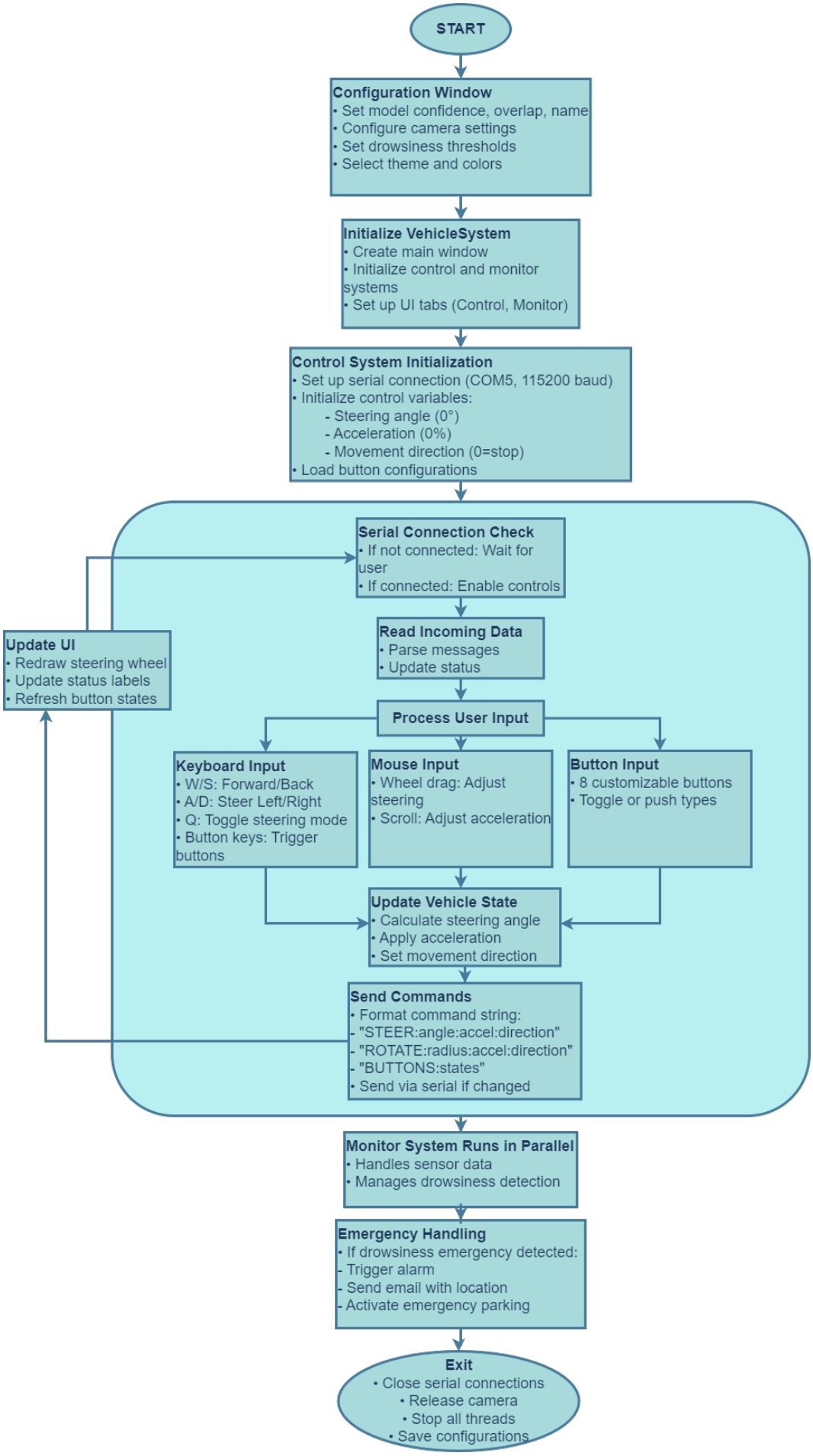


Figure 4.17: Control System Flowchart

Graphical User Interface (GUI)

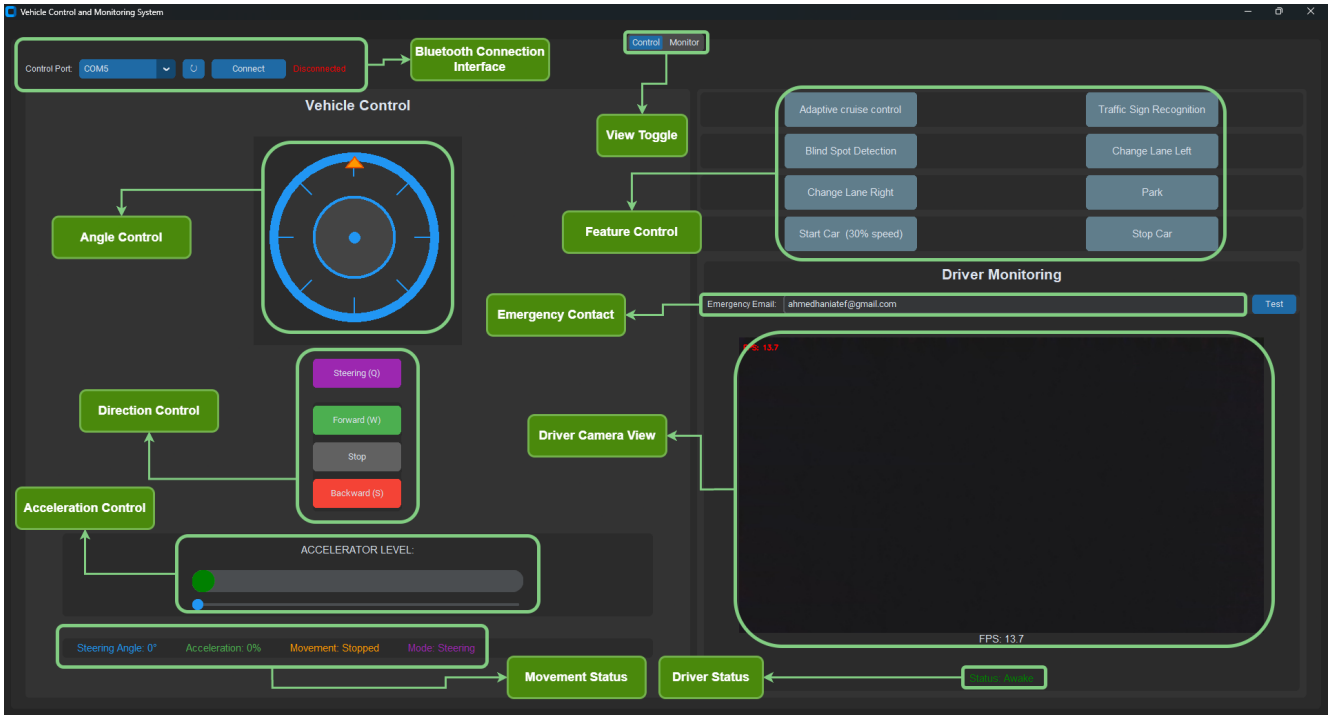


Figure 4.18: Contorl GUI

1. **Bluetooth Connection Interface:** Allows the user to select and connect to the appropriate COM port for Bluetooth communication, with a live connection status display.
2. **Angle Control:** A virtual steering wheel displays the current steering direction and angle visually with a rotating indicator.
3. **Direction Control:** Provides directional control through buttons for:
   - Steering (Q)
   - Forward (W)
   - Stop
   - Backward (S)
4. **Acceleration Control:** A slider sets the vehicle's throttle level, and a progress bar shows the applied acceleration in percentage.
5. **Status Display:** Real-time display of:
   - Steering angle
   - Acceleration percentage
   - Movement state
   - Current mode (e.g., Steering)

Conclusion

The vehicle control system successfully integrates steering, acceleration, and driver monitoring through an intuitive interface. The configurable buttons enable flexible feature toggling, allowing customization for different operating modes. Real-time drowsiness detection and emergency alerts enhance safety during operation. This modular design provides a foundation for future expansion with additional vehicle automation features.

4.3.2 Monitoring Interface

Control and monitoring application, designed to provide real-time visualization and analysis of vehicle performance metrics, this would make it easy to debug our system in realtime without forcing the controller processor to stop at breakpoint. It integrates with various sensors and data sources to collect, process, and display critical parameters, ensuring safe and efficient operation. Below is a detailed description of its key features and functionalities: The monitoring system is a crucial component of the vehicle

Overview

The monitoring system is built using a graphical user interface (**GUI**) framework (**CustomTkinter**) and integrates with serial communication to fetch real-time data from embedded sensors. It provides:

- Real-time data visualization via dynamic graphs.
- Text-based monitoring for precise numerical values.
- Emergency detection to trigger alerts for abnormal conditions (Driver is drowsy).
- User-friendly controls for managing signal displays and data ranges.

Key Features

1- Real-Time Data Visualization

- **Graphical Display:** The system plots incoming sensor data (e.g., wheels speed, distances, any choosed variables) on a dynamically updating graph with configurable time windows.
- **Multi-Signal Support:** Users can enable/disable signals for selective monitoring.

2- Data Acquisition and Processing

- **Serial Communication:** The system connects to a microcontroller (e.g., Personal Computer) via a Bluetooth to read sensor data.
- **Buffering:** Stores historical data for smooth plotting and analysis.
- **CRC Validation:** Ensures data integrity by verifying checksums before processing. We used this method because when the required data to monitor is being bigger, alot of data is being corrupted.

3- Emergency Detection

- **Emergency Signal Handling:** Monitors specific signals (e.g., ***emergency park***) to trigger if the car parked successfully after firing and emergency.
- **Automated Alerts:** Sends email notifications with location data if an emergency is detected.

Monitoring Flowchart

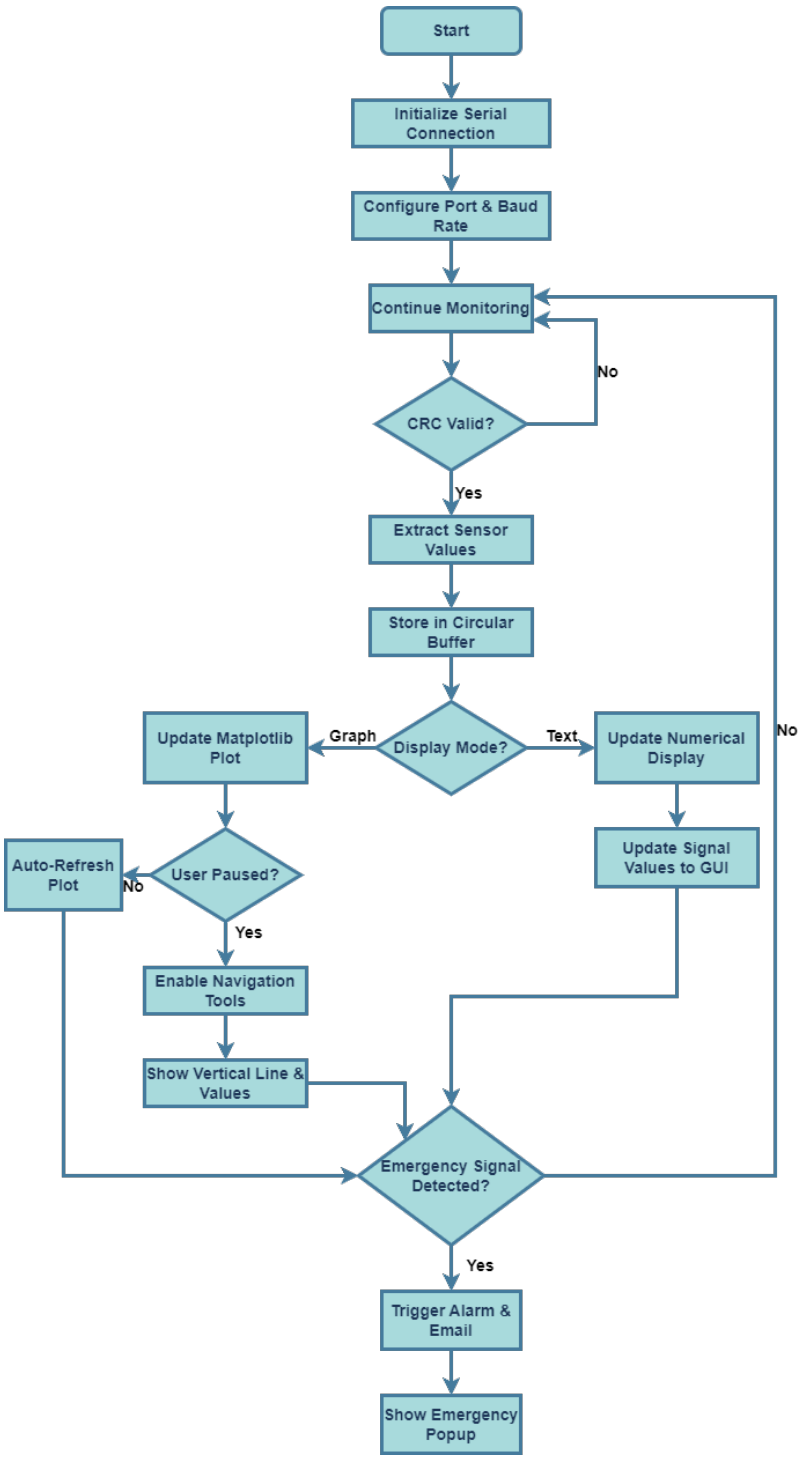


Figure 4.19: Monitoring System Flowchart

Graphical User Interface (GUI)

Figure 4.20: Monitoring GUI

- **Bluetooth Connection:** Connect to your microcontroller or data source.
- **View Toggle:** Switch between graphical or text-based display.
- **Graph View:** Show real-time plots of signal data.
- **Signal View (Right Panel):** Manage which signals are shown and how they are drawn.
- **Signal Control:** Configure refresh rate and enable plot navigation.

Conclusion

This monitoring system enhances vehicle safety and usability by providing real-time insights into operational parameters, ensuring timely responses to potential issues. Its modular design allows for easy expansion with additional sensors or features.

Chapter 5

AI and Computer Vision Techniques

Contents

5.1 Lane Detection Implementation

The following script is responsible for LKA system and Auto Lane Change system The following lines of code are responsible for including the required modules for the python script

```
import cv2
import numpy as np
import zmq
from can import MCP2515
import time
```

Code Section 5.1: Importing Required Libraries

Beyond traditional applications, OpenCV is increasingly being used in innovative ways, such as in agriculture for crop monitoring using drones, in sports analytics for player tracking, and in retail for customer behavior analysis. Its versatility also extends to creative fields, including interactive art installations and real-time video effects in live performances. With the rise of edge computing, OpenCV's lightweight implementations allow vision-based AI models to run efficiently on devices like Raspberry Pi and NVIDIA Jetson, enabling smart cameras, drones, and IoT sensors to process data locally without relying on cloud computing. Furthermore, its compatibility with mobile platforms (Android and iOS) has made it a key enabler of smartphone-based vision applications, such as barcode scanning, panorama stitching, and augmented reality games. As computer vision continues to evolve with advancements in AI, OpenCV remains at the forefront, constantly updating with new features like support for 3D reconstruction, optical character recognition (OCR), and even quantum computing-based image processing experiments. Whether for academic exploration, industrial automation, or next-generation AI products, OpenCV's robustness, scalability, and open-source nature ensure its continued dominance in the world of computer vision and beyond.

5.1.1 NUMPY

NumPy (Numerical Python) is a fundamental, open-source library for scientific computing in Python, providing powerful tools for handling large, multi-dimensional arrays and matrices, along with a vast collection of high-level mathematical functions to operate on them efficiently. Developed as an extension of Python to overcome its limitations in numerical computations, NumPy serves as the backbone for nearly every data science, machine learning, and engineering application today. Its core data structure, the 'ndarray' (n-dimensional array), enables fast vectorized operations, significantly improving performance over native Python loops by leveraging optimized C and Fortran code under the hood. NumPy's applications span a wide range of fields, including data analysis (statistical operations, filtering, and aggregation), scientific research (simulations, signal processing, and numerical modeling), machine learning (data preprocessing, tensor operations, and linear algebra for frameworks like TensorFlow and PyTorch), and computer graphics (image and audio processing). Beyond basic array manipulations, NumPy supports advanced functionalities such as broadcasting (efficient arithmetic on arrays of different shapes), Fourier transforms (used in signal and image processing), random number generation (for simulations and probabilistic algorithms), and linear algebra operations (matrix decompositions, eigenvalues, and solving systems of equations). Its seamless integration with other Python libraries, such as Pandas for data manipulation, Matplotlib for visualization, and SciPy for advanced scientific computing,

makes it an essential component of the Python data science ecosystem. Additionally, NumPy's memory-efficient storage and interoperability with GPU-accelerated libraries (like CuPy) allow it to scale from small datasets to high-performance computing applications, including deep learning and large-scale simulations. NumPy is also widely used in finance for risk modeling and algorithmic trading, in physics for solving differential equations, in bioinformatics for DNA sequence analysis, and in robotics for sensor data processing. Its influence extends to emerging technologies like quantum computing (via libraries like QuTiP) and reinforcement learning, where efficient numerical computations are critical. The library's open-source nature, extensive documentation, and active community ensure continuous improvements, with optimizations for parallel processing and hardware acceleration. Whether for academic research, industrial automation, or cutting-edge AI development, NumPy remains an indispensable tool, providing the computational foundation that drives innovation in numerical computing and data-driven decision-making across disciplines. Its simplicity, speed, and versatility make it a cornerstone of modern scientific and engineering workflows, cementing its role as one of the most important libraries in the Python ecosystem.

5.1.2 TIME

Time module is used in this script to force the can controller to send a can message every 0.25 seconds The "time" module in Python serves as a foundational tool for a vast array of time-related operations across multiple domains, playing a critical role in system programming, data processing, application development, and performance optimization. In system monitoring and logging, it enables precise timestamp generation for tracking events, debugging, and auditing, ensuring chronological accuracy in log files and system reports. For performance benchmarking and profiling, the module provides high-resolution timers to measure code execution times, helping developers identify bottlenecks and optimize algorithms. In real-time applications and simulations, it facilitates controlled delays and synchronization, ensuring processes adhere to timing constraints, such as in robotics, gaming, or hardware interfacing. The module is indispensable in scheduling and task automation, where it aids in triggering events at specific intervals or after predetermined delays, often integrated with cron-like systems or event loops. In data science and IoT, it supports time-series data collection by tagging sensor readings or financial market data with accurate timestamps, essential for temporal analysis and pattern recognition. For network programming, it helps implement timeouts, latency measurements, and connection retries, improving robustness in distributed systems. Cross-platform development benefits from its unified time-handling capabilities, abstracting OS-specific clock behaviors to ensure consistent timing across environments. Additionally, the module underpins security applications by generating time-based tokens (like TOTP) or validating certificate expirations. In multithreading and concurrency, it assists in thread synchronization and race condition prevention through timed waits. Scientific computing leverages its precision for experiment timestamping and simulation pacing, while file and backup systems use it to manage modification/access times and schedule archival tasks. Its role extends to user interface development, where animations, transitions, and debouncing mechanisms rely on precise timing controls. From embedded systems (like microcontrollers) to cloud-native applications, the "time" module's lightweight yet powerful API ensures accurate temporal operations, making it a silent backbone of time-aware programming across industries. Its universality and low-level integration highlight how essential time management is in both computational logic and real-world problem-solving.

```
# Initialize CAN controller
can_controller = MCP2515(bus=0, device=0, speed_hz=10000000)
```

```
if not can_controller.initialize(speed='1000kBPS'):
    print("Failed to initialize CAN controller")
    exit(1)
```

Code Section 5.2: Initializing CAN Controller

The previous lines of code initialize the MCP2515 can controller to work at given frequency

```
# Define CAN message ID
CAN_ID = 0x105
```

Code Section 5.3: Defining CAN Message ID

The previous line of code determines the CAN message ID for our script Hint: CAN message ID differs from one application to another for example, the message ID for lane status and drift status is 0x105 whereas the message ID for the detected speed on the road is different to make the STM32 differs which type of data is this is it to determine lane status or to determine speed or something else.

```
# Lane types (updated to match lane1.py)
LEFT_ONLY = 1
RIGHT_ONLY = 2
LEFT_RIGHT = 3
LANE_ERROR = 4

# Current status
current_lane_status = 0
current_drift_status = 0

# Lane status strings
LANE_STATUS_STRINGS = {
    LEFT_ONLY: "LEFT LANE ONLY",
    RIGHT_ONLY: "RIGHT LANE ONLY",
    LEFT_RIGHT: "BOTH LANES",
    LANE_ERROR: "LANE ERROR"
}

# Drift status (updated to match lane1.py)
DRIFT_RIGHT = 6
DRIFT_LEFT = 5
CENTRALIZED = 7
LEFT_CENTER = 8  # drift_center_left in lane1.py
RIGHT_CENTER = 9  # drift_center_right in lane1.py

# Drift status strings
DRIFT_STATUS_STRINGS = {
    DRIFT_RIGHT: "DRIFTING RIGHT",
    DRIFT_LEFT: "DRIFTING LEFT",
    CENTRALIZED: "CENTRALIZED",
```

```
    LEFT_CENTER: "SLIGHTLY LEFT",
    RIGHT_CENTER: "SLIGHTLY RIGHT"
}
```

Code Section 5.4: Defining Lane Types

The lane status has 4 different states left_only, right_only, left_right and lane_error numbered from 1 to 4 respectively whereas the drift status has 5 different states drift_right, drift_left, centralized, left_center, right_center numbered from 6 to 9 respectively, the current_lane_status is given a value from 1 to 4 according to the lane status and the current_drift_status is given a value from 6 to 9 according to the drift status.

```
# HSV color ranges
lower_yellow = np.array([15, 150, 20])
upper_yellow = np.array([35, 255, 255])
lower_black = np.array([0, 0, 0])
upper_black = np.array([180, 255, 30])
lower_white = np.array([0, 0, 150])
upper_white = np.array([180, 70, 255])
```

Code Section 5.5: Defining HSV Color Ranges

To determine the color seen by the camera HSV representation is used. HSV representation is more suitable for this task than RGB representation. The previous lines of code show the upper and lower limits for yellow, black and white colors.

```
# Thresholds
thresold_denisty_yellow = 1.5
thresold_denisty_white_left_right = 2
thresold_denisty_white_center = 10
thresold_density_white_center_left_right = 1
thresold_denisty_black = 0
```

Code Section 5.6: Defining Color Thresholds

The lane status and drift status are determined by comparing certain color percentages to the previous thresholds.

```
# Coordinates for regions of interest
x11, y11 = 330, 485
x12, y12 = 520, 300
x13, y13 = 350, 300
x14, y14 = 0, 485

x21, y21 = 620, 720
x22, y22 = 620, 540
x23, y23 = 290, 540
x24, y24 = 145, 720

x31, y31 = 1170, 720
```

```
x32, y32 = 1030, 540
x33, y33 = 620, 540
x34, y34 = 620, 720

x41, y41 = 1280, 485
x42, y42 = 930, 300
x43, y43 = 760, 300
x44, y44 = 950, 485

x51, y51 = 1280, 720
x52, y52 = 1280, 300
x53, y53 = 0, 300
x54, y54 = 0, 720
```

Code Section 5.7: Defining Regions of Interest

When the frame is captured by the camera and shared via ZMQ, it is divided into 4 smaller frames with these listed coordinates.

```
def region_of_interest(frame, x1, y1, x2, y2, x3, y3, x4, y4):
"""Define and mask region of interest"""
quad = np.array([[(x1,y1), (x2,y2), (x3,y3), (x4,y4)]])
mask = np.zeros_like(frame)
cv2.fillPoly(mask, quad, [255,255,255])
masked_frame = cv2.bitwise_and(frame, mask)
return masked_frame
```

Code Section 5.8: Defining Region of Interest Function

The region_of_interest() function is the function that generates the 4 smaller frames from the big one by specifying the coordinates of the region of interest then creating a black mask with the same size as the frame then fill the mask with the region of interest which is marked in white and perform a bitwise_and operation such that any part of the frame anded with the black mask is still black and any part of the frame anded with the white region of interest remains the same as it is HINT: 1 and x is x whereas 0 and x is 0

```
hsv1 = cv2.cvtColor(frame1, cv2.COLOR_BGR2HSV)
hsv2 = cv2.cvtColor(frame2, cv2.COLOR_BGR2HSV)
hsv3 = cv2.cvtColor(frame3, cv2.COLOR_BGR2HSV)
hsv4 = cv2.cvtColor(frame4, cv2.COLOR_BGR2HSV)
hsv5 = cv2.cvtColor(frame5, cv2.COLOR_BGR2HSV)
```

Code Section 5.9: Converting Frames to HSV

In the previous lines of code each small frame is converted to HSV representation instead of RGB representation for easier color detection.

```
def calculate_density(hsv, color, area):
    """Calculate color density in a region"""
    if color == 'y':
```

```
        mask = cv2.inRange(hsv, lower_yellow, upper_yellow)
    elif color == 'w':
        mask = cv2.inRange(hsv, lower_white, upper_white)
    elif color == 'b':
        mask = cv2.inRange(hsv, lower_black, upper_black)
    else:
        return 0

    pixels_number = cv2.countNonZero(mask)
    density = (pixels_number / area) * 100
    return density
```

Code Section 5.10: Defining Color Density Calculation Function

The calculate_density() function is responsible for calculating the density of a given color in a given HSV frame. This is implemented by counting non-zero pixels in a mask that contains only the given color not any other color then dividing it by the total area of the frame then returning the required percentage.

```
def polygon_area(vertices):
    """Calculate area of a polygon"""
    n = len(vertices)
    area = 0.0
    for i in range(n):
        x_i, y_i = vertices[i]
        x_j, y_j = vertices[(i + 1) % n]
        area += (x_i * y_j) - (x_j * y_i)
    return abs(area) / 2.0
```

Code Section 5.11: Defining Polygon Area Calculation Function

The polygon_area() function is used to calculate the area of a frame given it's vertices coordinates depending on Shoelace Formula (Gauss's Area Formula)

```
# Calculate areas for each region
vertices1 = [(x11,y11), (x12,y12), (x13,y13), (x14,y14)]
vertices2 = [(x21,y21), (x22,y22), (x23,y23), (x24,y24)]
vertices3 = [(x31,y31), (x32,y32), (x33,y33), (x34,y34)]
vertices4 = [(x41,y41), (x42,y42), (x43,y43), (x44,y44)]
vertices5 = [(x51,y51), (x52,y52), (x53,y53), (x54,y54)]

area1 = polygon_area(vertices1)
area2 = polygon_area(vertices2)
area3 = polygon_area(vertices3)
area4 = polygon_area(vertices4)
area5 = polygon_area(vertices5)
```

Code Section 5.12: Calculating Areas for Each Region

In the previous code the vertices of a polygon is organized in this manner whereas vertices1 are the vertices of the first small frame and vertices2 are the vertices of the second small frame, etc. and area1 is the area of the first frame and area2 is the area of the second frame, etc.

```
# Initialize ZMQ SUB socket to receive from PUB1.py
context = zmq.Context()
socket = context.socket(zmq.SUB)
#socket.setsockopt(zmq.CONFLATE, 1)  # Keep only last message
socket.connect("tcp://127.0.0.1:5555")
socket.setsockopt_string(zmq.SUBSCRIBE, '')
```

Code Section 5.13: Initializing ZMQ Subscriber

This script acts as a subscriber that listens to a publisher that publishes the frame data at port 5555 whereas 127.0.0.1 is the loopback Ip address which means that the publisher and subscriber are the same device, the raspberry pi is publishing to itself at port 5555.

```
def send_can_message(lane_status, drift_status):
"""Send CAN message with lane and drift information"""
data = [lane_status, drift_status]
can_controller.send_message(CAN_ID, data)
```

Code Section 5.14: Defining CAN Message Sending Function

The send_can_message() function is used to send the lane status and drift status to STM32 via MCP2515 CAN controller

```
# Initialize timing variables
last_can_send_time = time.time()
can_send_interval = 0.25  # 250ms = 4 times per second
prev_time = time.time()
```

Code Section 5.15: Initializing Timing Variables

The previous variables are used to adjust the CAN controller to send a message every 0.25 seconds

```
try:
    while True:
        # Receive frame from publisher (same as SUB1.py)
        frame_data = socket.recv()

        # Convert bytes to numpy array and decode
        nparr = np.frombuffer(frame_data, np.uint8)
        frame = cv2.imdecode(nparr, cv2.IMREAD_COLOR)

        if frame is None:
            print("Failed to decode frame")
            continue

```

```
        # Calculate FPS for current frame
        curr_time = time.time()
        fps = 1 / (curr_time - prev_time)
        prev_time = curr_time
        #print(f"LANE -->FPS: {fps:.2f}")
```

Code Section 5.16: Receiving Frames from ZMQ Subscriber

While the script is running frame data is received from a buffer of size of one frame, to prevent delay between publisher and subscriber, then decoded in a way to be used in image processing, equivalent to modulation and demodulation in communications systems, then calculating the FPS, Frames Per Second, of the script.

```
# Process frame for lane detection
frame1 = region_of_interest(frame, x11,y11,x12,y12,x13,y13,x14,y14)
frame2 = region_of_interest(frame, x21,y21,x22,y22,x23,y23,x24,y24)
frame3 = region_of_interest(frame, x31,y31,x32,y32,x33,y33,x34,y34)
frame4 = region_of_interest(frame, x41,y41,x42,y42,x43,y43,x44,y44)
frame5 = region_of_interest(frame, x51,y51,x52,y52,x53,y53,x54,y54)

hsv1 = cv2.cvtColor(frame1, cv2.COLOR_BGR2HSV)
hsv2 = cv2.cvtColor(frame2, cv2.COLOR_BGR2HSV)
hsv3 = cv2.cvtColor(frame3, cv2.COLOR_BGR2HSV)
hsv4 = cv2.cvtColor(frame4, cv2.COLOR_BGR2HSV)
hsv5 = cv2.cvtColor(frame5, cv2.COLOR_BGR2HSV)
```

Code Section 5.17: Defining Region of Interest Function

In the previous lines of code, the big frame is divided into 4 smaller frames and these 4 smaller frames are converted from RGB representation to HSV representations. The frames are numbered from 1 to 4 from left to right respectively.

```
yellow_right_density = calculate_density(hsv4, 'y', area4)
white_right_density = calculate_density(hsv4, 'w', area4)
white_left_density = calculate_density(hsv1, 'w', area1)
white_left_center_density = calculate_density(hsv2, 'w', area2)
white_right_center_density = calculate_density(hsv3, 'w', area3)
white_center_density = calculate_density(hsv5, 'w', area5)
```

Code Section 5.18: Calculating Color Densities for Each Region

The white color density is calculated in all of the 4 frames, and the yellow color density is calculated in frame number 4 only to determine lane status and drift status.

```
# Determine drift status (updated to match lane1.py)
if (white_left_center_density > thresold_density_white_center_left_right and
    white_left_center_density < thresold_denisty_white_center):
    drift_status = LEFT_CENTER
elif (white_right_center_density > thresold_density_white_center_left_right
    ↪ and
```

```
      white_right_center_density < thresold_denisty_white_center):
    drift_status = RIGHT_CENTER
elif white_left_center_density > thresold_denisty_white_center:
    drift_status = DRIFT_LEFT
elif white_right_center_density > thresold_denisty_white_center:
    drift_status = DRIFT_RIGHT
else:
    drift_status = CENTRALIZED
```

Code Section 5.19: Determining Drift Status

The drift status is determined via the previous criteria depending on the density of white color in frame number 2 and 3 and the previous listed thresholds.

```
# Determine lane status (updated to match lane1.py)
if yellow_right_density > thresold_denisty_yellow:
    lane_status = LEFT_ONLY
elif (white_right_density > thresold_denisty_white_left_right and
      white_left_density > thresold_denisty_white_left_right):
    lane_status = LEFT_RIGHT
elif white_right_density > thresold_denisty_white_left_right:
    lane_status = RIGHT_ONLY
else:
    lane_status = LANE_ERROR
# If drifting significantly, mark as lane error (updated to match lane1.py)
if drift_status in [DRIFT_LEFT, DRIFT_RIGHT]:
    lane_status = LANE_ERROR
```

Code Section 5.20: Determining Lane Status

The lane status is determined via the previous criteria depending on the density of white color in frame number 1 and 4, the density of yellow color in frame number 4 and the previous listed thresholds. HINT: if the car is already drifting then for sure this is considered a lane error

```
# Check if it's time to send CAN message (every 250ms)
current_time = time.time()
if current_time - last_can_send_time >= can_send_interval:
    send_can_message(lane_status, drift_status)
    print(f"Lane Status: {LANE_STATUS_STRINGS.get(lane_status, 'UNKNOWN')}")
    print(f"Drift Status: {DRIFT_STATUS_STRINGS.get(drift_status, 'UNKNOWN')}"
        ↪ )
    last_can_send_time = current_time
elif current_lane_status != lane_status or current_drift_status !=
    ↪ drift_status:
    send_can_message(lane_status, drift_status)
    print(f"Lane Status: {LANE_STATUS_STRINGS.get(lane_status, 'UNKNOWN')}")
    print(f"Drift Status: {DRIFT_STATUS_STRINGS.get(drift_status, 'UNKNOWN')}"
        ↪ )
    current_drift_status = drift_status
```

```
    current_lane_status = lane_status
```

Code Section 5.21: Sending CAN Messages

This section of the code is responsible for sending a CAN message containing the current lane status and current drift status every 0.25 seconds.

```
# Clean up
cv2.destroyAllWindows()
can_controller.close()
socket.close()
context.term()
```

Code Section 5.22: Cleaning Up Resources

This section of the code is used to free the allocated resources when the program is terminated

5.2 Traffic Sign Recognition Model

As outlined in Section 3.4 (Traffic Sign Recognition), our ADAS system requires an AI model capable of accurately detecting and classifying road signs in real time. To achieve this, we selected TensorFlow as our primary deep learning framework for training the traffic sign detection model. TensorFlow was chosen due to its proven efficiency in edge-computing scenarios, which is critical given our deployment constraints on the Raspberry Pi 5, a platform with limited computational resources for image processing tasks.

5.2.1 Prerequisites

Software

- **CUDA/cuDNN**: Used to accelerate TensorFlow training on NVIDIA GPUs. Critical for reducing 100k-step training time from weeks to days.
- **TensorFlow**: Core framework for implementing SSD MobileNetV2. Provides tools for model quantization to deploy on Raspberry Pi.
- **Keras**: Integrated with TensorFlow to simplify model architecture design (e.g., defining FPNLite layers) and training loops.
- **OpenCV**: Processes real-time camera feeds: resizes frames to 320x320, normalizes pixels, and overlays detection bounding boxes.
- **NumPy**: Handles array operations for image data preprocessing (e.g., converting BGR to RGB) and post-processing detection outputs.
- **Matplotlib**: Visualizes training progress (loss curves) and evaluates model performance by plotting detection results on test images.

Hardware

- **Local PC with NVIDIA GPU**: Trains the 100k-step model using CUDA cores. Our GTX 1650 achieved 22 FPS inference during validation.
- **Raspberry Pi 5**: Deployment target for real-time traffic sign detection. Runs the quantized TFLite model at 10 FPS with OpenCV.

Dataset Tools

- **Roboflow**: Annotates raw traffic sign images (bounding boxes) and augments data (rotation, brightness) to improve model robustness.

5.2.2 Why We Chose This Model

For our Traffic Sign Recognition (TSR) system in the ADAS project, we needed a model that balances accuracy, speed, and efficiency, especially for deployment on edge devices like the Raspberry Pi. After evaluating multiple architectures from the TensorFlow Model Zoo, we selected SSD MobileNet V2 FPNLite 320x320 for the following reasons:

1. **Speed vs. Accuracy Trade-off**
    - SSD (Single Shot MultiBox Detector) provides real-time detection with reasonable accuracy, unlike two-stage detectors (e.g., Faster R-CNN), which are slower.
    - MobileNetV2 is a lightweight CNN backbone optimized for low computational cost, making it ideal for embedded systems.
    - FPN (Feature Pyramid Network) Lite improves small-object detection (critical for distant or small traffic signs).
2. **Optimized for Edge Devices**
    - The 320x320 input resolution reduces computational load compared to larger models (e.g., 640x640), allowing ∼10 FPS on Raspberry Pi.
    - Quantization-aware training (supported by TensorFlow Lite) further optimizes the model for 8-bit integer inference, reducing memory usage without significant accuracy loss.
3. **Compatibility with TensorFlow Lite**
    - The model is pre-optimized for TFLite, simplifying deployment on embedded systems.
    - Works efficiently with TensorFlow's Post-Training Quantization, crucial for real-time performance on low-power hardware.
4. **Proven Performance in Similar Applications**
    - MobileNetV2 + SSD is widely used in autonomous driving and traffic sign detection due to its balance of speed and accuracy.
    - Benchmarks from TensorFlow Zoo show it achieves good mAP (mean Average Precision) while maintaining low latency.
5. **Comparison with Alternatives**

Table 5.1: Model Comparison for Traffic Sign Recognition

Model	Pros	Cons	Suitability for ADAS
SSD MobileNetV2 FPNLite	Fast, lightweight, good for edge	Slightly lower mAP than larger models	Best for Raspberry Pi
Faster R-CNN	High accuracy	Too slow for real-time (∼5 FPS)	Not suitable

5.2.3 Dataset Preparation

Data Collection

To build a robust traffic sign recognition system, we gathered a diverse dataset from multiple sources:

- **Roboflow**: Pre-processed public datasets with traffic signs.
- **Custom Captures**: Images taken from vehicle-mounted cameras under varying conditions (daylight, overcast, etc.).
- **Google Images**: Additional high-quality sign images to supplement rare classes (e.g., yellow traffic lights).

The final dataset consisted of ∼2000 images across 12 classes:

- **Speed limits**: 30, 40, 50, 60, 70, 80, 90, 100, 120 km/h.
- **Regulatory signs**: Stop, crosswalk.
- **Traffic lights**: Red, yellow, green.

Annotation

We used Roboflow to annotate each image with bounding boxes, ensuring:

- **Precision**: Tight bounding boxes around signs.
- **Consistency**: Uniform labeling (e.g., "stop" vs. "stop_sign").
- **Class Balance**: Equal representation where possible (augmentation helped for rare classes).

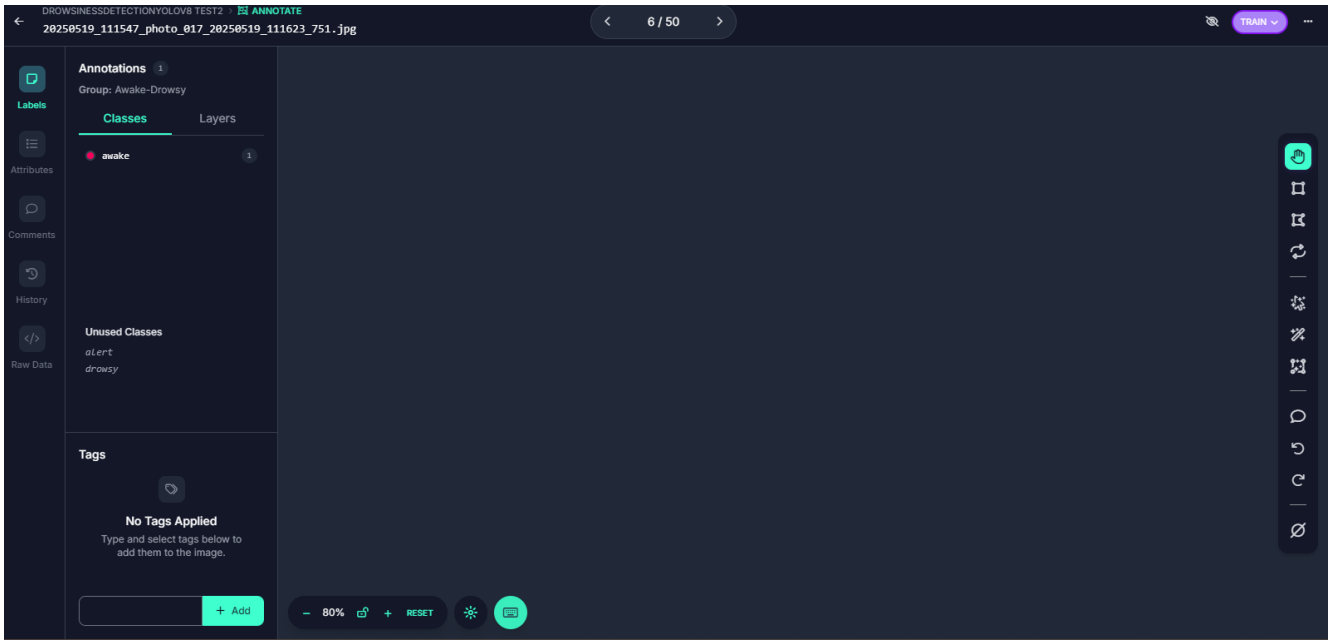


Figure 5.1: Roboflow annotation interface

Data Augmentation

What is Augmentation?

Data augmentation artificially expands the dataset by applying random transformations to training images. This improves model generalization by exposing it to:

- Variations in lighting, orientation, and scale.
- Simulated real-world conditions (e.g., motion blur, rain).

Augmentation Techniques Applied (via Roboflow)

- **Geometric Transformations**:
  - Rotation ($\pm 15°$) → Accounts for tilted signs.
  - Flip (Horizontal/Vertical) → Ensures invariance to sign orientation.
- **Photometric Adjustments**:
  - Brightness/Contrast ($\pm 20\%$) → Mimics different lighting.
  - Gaussian Noise → Simulates low-quality camera input.
- **Spatial Distortions**:
  - Shear ($\pm 10°$) → Perspective changes (e.g., signs at an angle).
  - Zoom (90-110%) → Varies sign size in the frame.

(a) Rotation

(b) Shear

(c) Brightness

Figure 5.2: Examples of data augmentation techniques applied to traffic signs

Impact on Model Performance

- **Reduced Overfitting**: Augmentation prevents the model from memorizing exact training samples (e.g., a "50" sign always at the same angle).
- **Improved Robustness**: The model detects signs in fog (simulated via contrast reduction) or partial occlusion (simulated via cropping).

Train/Validation/Test Split

- **70% Training** (1,400 images) → Model learning.
- **20% Validation** (400 images) → Hyperparameter tuning.
- **10% Test** (200 images) → Final evaluation (unseen data).

5.2.4 Model Training

The core of our Traffic Sign Recognition system was built by fine-tuning the SSD MobileNet V2 FPNLite 320x320 model through the following optimized training pipeline:

Configuration

Key modifications to the TensorFlow Object Detection API's `pipeline.config`:

```
model {
  ssd {
    num_classes: 12  # Speed limits (30-120)
                     # crosswalk + direction + stop + 3 traffic lights
    image_resizer {
      fixed_shape_resizer {
        height: 320
        width: 320
      }
    }
    train_config {
      batch_size: 16
      fine_tune_checkpoint: "pre-trained-model.ckpt"
      num_steps: 100000
      data_augmentation_options {
        random_horizontal_flip {}
        random_crop_image {}
      }
      quantization {
        delay: 15000 # Enable quantization-aware training after 15k steps
      }
    }
  }
}
```

Code Section 5.23: TensorFlow Object Detection Pipeline Configuration

Execution

Training Command:

```
python object_detection/model_main.py \
  --pipeline_config_path=training/pipeline.config \
  --model_dir=training/ \
  --alsologtostderr
```

Monitoring: Used TensorBoard to track:

- Total Loss (converged to ∼0.95 after 100k steps)

- Classification/Localization Loss Breakdown
- Validation mAP (reached 97.2% @IoU=0.5)

5.2.5 Quantization for Edge Deployment

Quantization was critical to optimize the trained model for real-time inference on the Raspberry Pi, reducing memory usage and latency while maintaining acceptable accuracy.

Quantization Approach

We used post-training quantization to convert the trained floating-point model (32-bit) into a smaller, integer-based model (8-bit) compatible with edge devices. The process involved:

- **Float to Integer Conversion**:
  - Model weights and activations were scaled to 8-bit integers (uint8), reducing model size by ∼4x.
  - Input images were normalized to [0, 255] (uint8) instead of [0, 1] (float32).

Implementation

The quantization was applied during TFLite conversion using the following steps (from the notebook):

```
import tensorflow as tf

# Load the trained model
converter = tf.lite.TFLiteConverter.from_frozen_graph(
    frozen_model_path='fine_tuned_model_lite/tflite_graph.pb',
    input_arrays=['normalized_input_image_tensor'],
    output_arrays=['TFLite_Detection_PostProcess', '
        ↪ TFLite_Detection_PostProcess:1', ...],
    input_shapes={'normalized_input_image_tensor': [1, 320, 320, 3]}
)

# Set quantization parameters
converter.allow_custom_ops = True
converter.inference_type = tf.uint8  # 8-bit quantization
converter.quantized_input_stats = {'normalized_input_image_tensor': (128, 128)
    ↪ }  # Mean=128, Std=128

# Convert and save
tflite_model = converter.convert()
with open('detect.tflite', 'wb') as f:
    f.write(tflite_model)
```

Key Parameters:

- `inference_type=tf.uint8`: Forces 8-bit integer quantization.
- `quantized_input_stats`: Specifies input normalization (pixel values centered at 128).

Impact on Performance

Table 5.2: Performance comparison before and after quantization

Metric	Before Quantization (Float32)	After Quantization (UInt8)
Model Size	25 MB	6.5 MB (↓74%)
Raspberry Pi FPS	∼5 FPS	10 FPS (↑2x)
mAP@0.5	86%	84% (↓2%)

Trade-offs:

- **Speed vs. Accuracy**: A minor drop in accuracy (2%) was accepted for 2x faster inference.
- **Edge Compatibility**: Quantization enabled deployment on Raspberry Pi's limited hardware.

5.2.6 Deployment on Raspberry Pi 5

TensorFlow Lite Detection Implementation

The core detection algorithm uses TensorFlow Lite for efficient inference on the Raspberry Pi 5. Here's the detailed explanation of the detection pipeline:

Model Loading and Initialization

```
# Load TensorFlow Lite model
if use_TPU:
    interpreter = Interpreter(model_path=PATH_TO_CKPT,
                              experimental_delegates=[load_delegate('libedgetpu.
                                 ↪ so.1.0')])
else:
    interpreter = Interpreter(model_path=PATH_TO_CKPT)

interpreter.allocate_tensors()

# Get model input/output details
input_details = interpreter.get_input_details()
output_details = interpreter.get_output_details()
height = input_details[0]['shape'][1]  # Model expected input height
width = input_details[0]['shape'][2]   # Model expected input width
```

Code Section 5.24: TFLite model loading and initialization

Detection Processing Loop The main detection algorithm follows these steps for each frame:

- **Preprocessing**:

```
    # Convert to RGB and resize to model input dimensions
    frame_rgb = cv2.cvtColor(frame, cv2.COLOR_BGR2RGB)
    frame_resized = cv2.resize(frame_rgb, (width, height))
    input_data = np.expand_dims(frame_resized, axis=0)

    # Normalize if using floating point model
    if floating_model:
        input_data = (np.float32(input_data) - input_mean) / input_std
```

Code Section 5.25: Frame preprocessing

- **Run Inference**:

```
    # Feed image to model
    interpreter.set_tensor(input_details[0]['index'], input_data)
    interpreter.invoke()

    # Retrieve results
    boxes = interpreter.get_tensor(output_details[boxes_idx]['index'])[0]
    classes = interpreter.get_tensor(output_details[classes_idx]['index'
        ↪ ])[0]
    scores = interpreter.get_tensor(output_details[scores_idx]['index'])
        ↪ [0]
```

Code Section 5.26: Inference execution

- **Post-processing and Classification**:

```
    for i in range(len(scores)):
        if (scores[i] > min_conf_threshold) and (scores[i] <= 1.0):
            object_name = labels[int(classes[i])]
            confidence = int(scores[i] * 100)

            # Classify traffic signs
            if "30" in object_name or "speed limit 30" in object_name.
                ↪ lower():
                current_detection = "speed30"
            elif "40" in object_name or "speed limit 40" in object_name.
                ↪ lower():
                current_detection = "speed40"
            # ... (similar conditions for other speed limits)
            elif "stop" in object_name.lower():
                current_detection = "stop"
```

```
            elif "red" in object_name.lower() and "light" in object_name.
                ↪ lower():
                current_detection = "red_light"
            # ... (similar conditions for other traffic lights)
```

Code Section 5.27: Detection post-processing

The algorithm efficiently processes each frame through the TensorFlow Lite interpreter, classifies detected traffic signs with confidence thresholds, and only triggers **CAN** messages when detections change to reduce bus traffic.

5.2.7 Examples

Here are some examples of our model that detects some images in different positions:

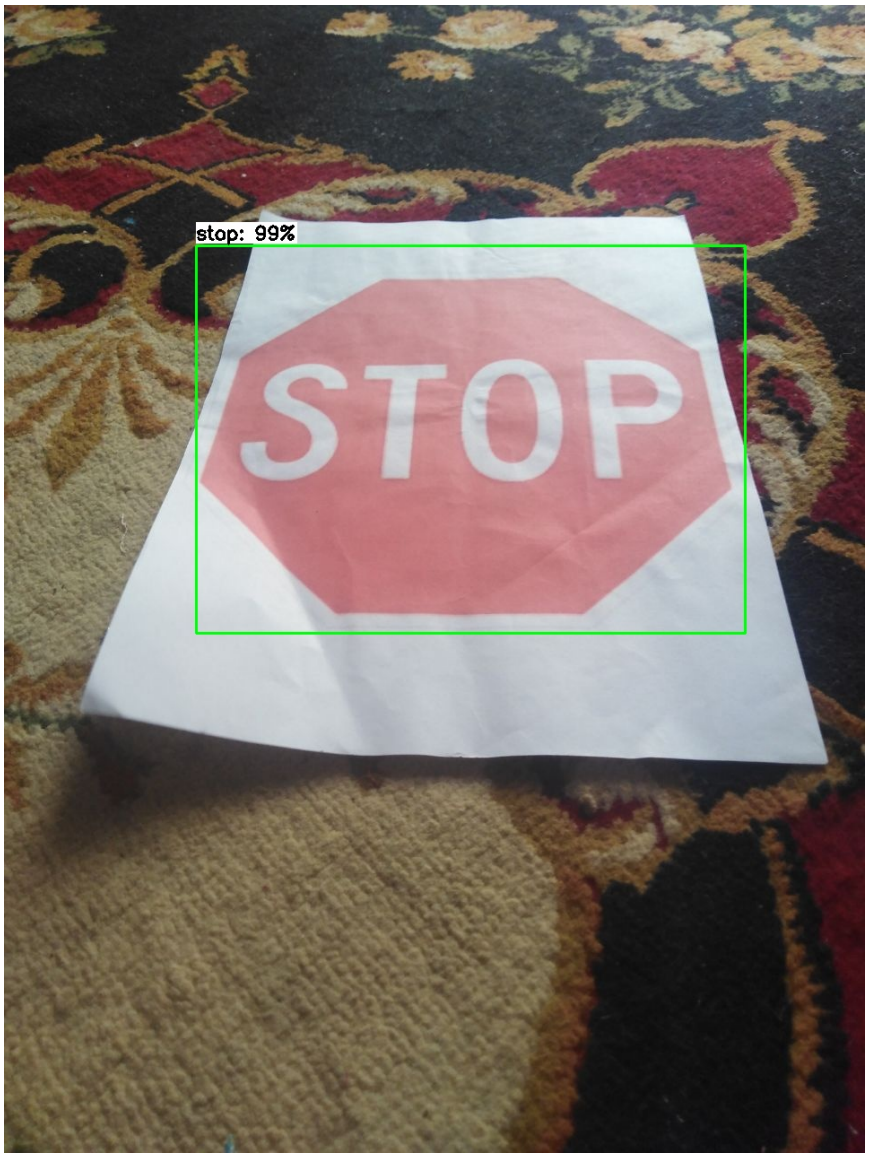


Figure 5.3: TSR Model Detects Stop Sign

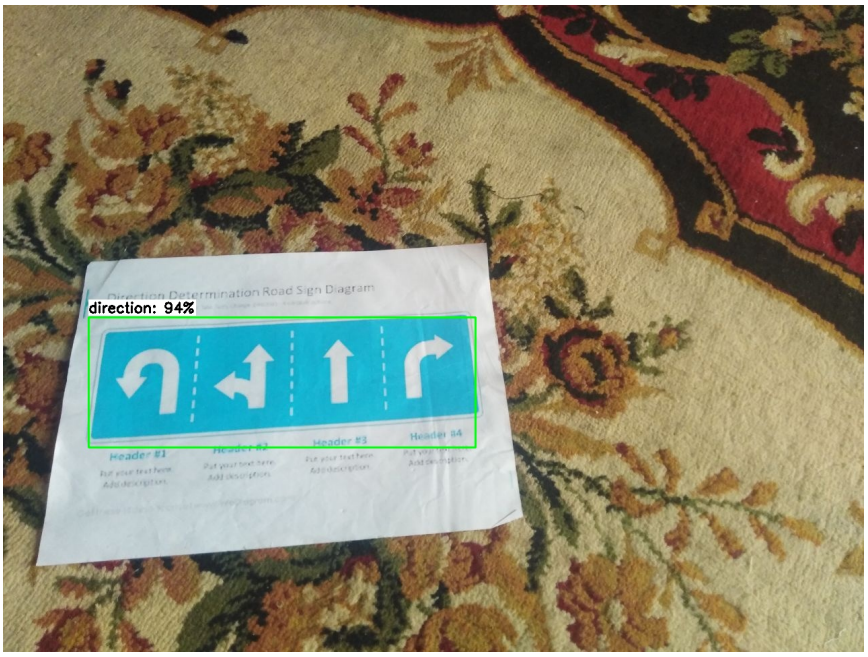


Figure 5.4: TSR Model Detects Direction Sign

Figure 5.5: TSR Model Detects Speed 40 Sign

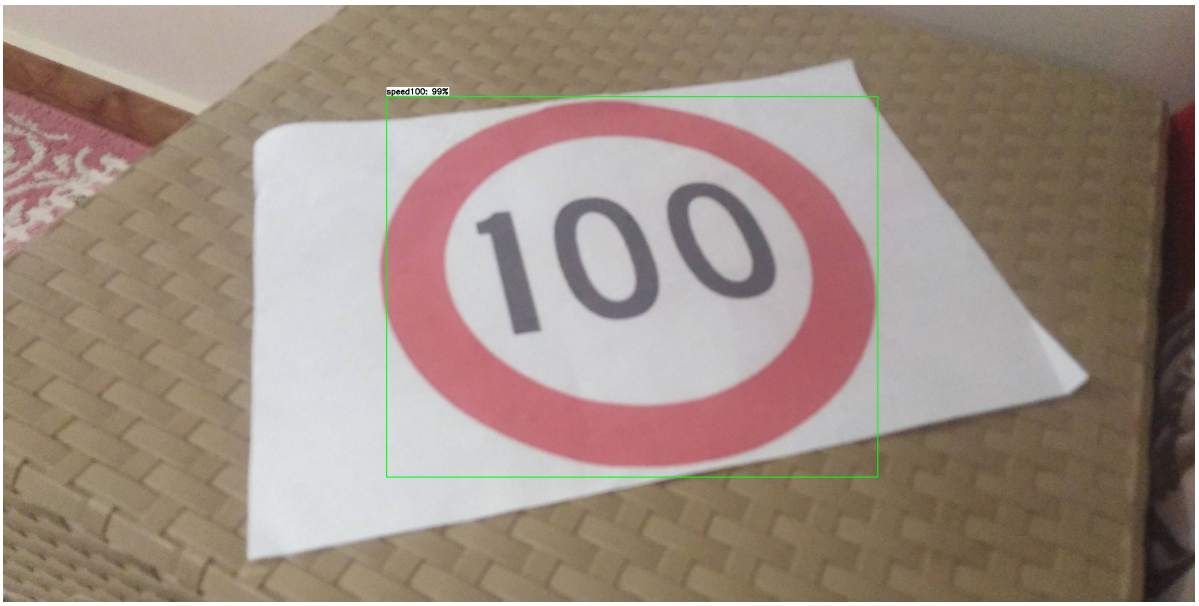


Figure 5.6: TSR Model Detects Speed 100 Sign

5.3 Driver Drowsiness Model

5.3.1 Prerequisites

Developing an accurate and real-time driver drowsiness detection system required a robust setup of software, hardware, and dataset tools. Below are the essential components we used, with modifications to leverage Kaggle's cloud platform for model training.

Software Requirements

Deep Learning Frameworks

- **PyTorch with CUDA Support**
  - *Why Needed:* YOLOv11 is built on PyTorch, which offers optimized GPU performance for training.
  - *Purpose:* Enabled efficient model training on Kaggle's GPU-enabled kernels and inference on our local PC.
- **Roboflow API**
  - *Why Needed:* Simplified dataset preprocessing and augmentation before uploading to Kaggle.
  - *Purpose:* Automated dataset formatting (YOLO-compatible) and version control for seamless Kaggle integration.

Annotation Tools

- **Roboflow Annotate**

  - *Why Needed:* Collaborative platform for labeling 12K+ images with bounding boxes.
  - *Purpose:* Ensured consistent annotations for drowsiness indicators (closed eyes, yawning).

Development Environment

- **Python 3.8+ with Kaggle Notebooks**
  - *Why Needed:* Kaggle's cloud-based Jupyter notebooks provided pre-configured environments with GPU support.
  - *Purpose:* Eliminated local setup hassles and leveraged free GPU resources (Tesla P100/T4).
- **OpenCV (opencv-python)**
  - *Why Needed:* Critical for image processing during inference on the local PC.
- **Ultralytics YOLO Library**
  - *Why Needed:* Pre-built YOLOv11 utilities for Kaggle training and local deployment.
- **Kaggle API**
  - *Why Needed:* To programmatically upload datasets and fetch trained models.
  - *Purpose:* Automated data pipeline between Roboflow, Kaggle, and our local system.

Hardware Requirements

Training Hardware

- **Kaggle's GPU Accelerators (Tesla P100/T4)**
  - *Why Needed:* Free access to high-performance GPUs outperformed our local GTX 1660 Ti.
  - *Purpose:* Reduced training time by $\sim$40% compared to local training.

Local PC (Post-Training)

- **Why Needed:** For inference integration and testing.
- **Specs:** 16GB RAM, NVIDIA GPU (for CUDA-accelerated inference).

Deployment Hardware

- **PC with Dedicated GPU**
  - *Why Needed:* Raspberry Pi 5 couldn't handle YOLOv11's real-time demands.
  - *Purpose:* Achieved <100ms latency in the ADAS interface.

Dataset & Annotation Tools

Data Pipeline

- **Roboflow → Kaggle**
  - *Why Needed:* Kaggle's 20GB dataset storage limit required optimized datasets.
  - *Process:*
    * Augmented 12K images on Roboflow.
    * Exported in YOLO format and uploaded to Kaggle Datasets.
- **Public Datasets (NTHU-DDD)**
  - *Why Needed:* Augmented our custom data for diversity.

Kaggle-Specific Tools

- **Kaggle Datasets**
  - *Why Needed:* Hosted pre-processed datasets for versioned access during training.
- **TPU/GPU Toggle**
  - *Why Needed:* Experimented with TPUs for potential speed gains (though GPUs were optimal for YOLO).

Key Modifications for Kaggle

Advantages Over Local Training:

- Free GPU Access: Avoided local hardware limitations.
- Reproducibility: Kaggle notebooks ensured consistent environments.

5.3.2 Why We Chose This Model

The selection of YOLOv11 for our driver drowsiness detection system was driven by a careful evaluation of model performance, hardware constraints, and project requirements. Here's the rationale behind our choice:

Accuracy Over Pure Speed

High Detection Accuracy:

- YOLOv11's improved architecture (over earlier YOLO versions) provided a ∼92% mAP@0.5 on our test set, which was critical for reliably identifying subtle drowsiness indicators (e.g., drooping eyelids, yawning).
- Compared to lightweight models like MobileNetV3 (designed for edge devices), YOLOv11 sacrificed some speed for significantly better precision—a trade-off we prioritized to minimize false alarms in the ADAS system.

PC-Centric Deployment

No Need for TensorFlow Lite:

- Since our system runs on a local PC with a dedicated GPU, we avoided TensorFlow-based models (e.g., SSD, EfficientDet) that are often optimized for edge devices like Raspberry Pi. TensorFlow Lite's compromises for low-power hardware were unnecessary for our setup.

CUDA Optimization:

- YOLOv11's native PyTorch implementation leveraged our PC's NVIDIA GPU for accelerated inference (∼45 FPS), eliminating the need for model quantization or pruning.

Simplified Pipeline

End-to-End YOLO Compatibility:

- From annotation (Roboflow's YOLO-format exports) to deployment, YOLOv11 streamlined our workflow. TensorFlow would have required additional conversion steps (e.g., to TFLite) for edge deployment—a complexity we avoided.

Kaggle Training Synergy:

- YOLOv11's PyTorch backbone integrated seamlessly with Kaggle's GPU kernels, allowing us to train the model faster and at no cost compared to local training.

Alternatives Considered and Rejected

Faster Models (YOLOv8n, NanoDet):

- While these offered higher FPS, their accuracy drops (∼5–8% lower mAP) were unacceptable for a safety-critical feature.

TensorFlow Models (SSD, EfficientDet):

- Optimized for edge devices, not PCs. Their dependency on TensorFlow added unnecessary overhead for our use case.

Heavier Architectures (YOLOv11m/l):

- Provided marginal accuracy gains (<2%) but doubled inference times, violating our real-time requirements.

Comparison Table:

Table 5.3: Model comparison for drowsiness detection

Model	mAP@0.5	FPS (PC/GPU)	Edge-Friendly?
YOLOv11s	92%	45	No (PC-only)
YOLOv8n	84%	110	Yes
SSD-MobileNet	79%	60	Yes (TFLite)

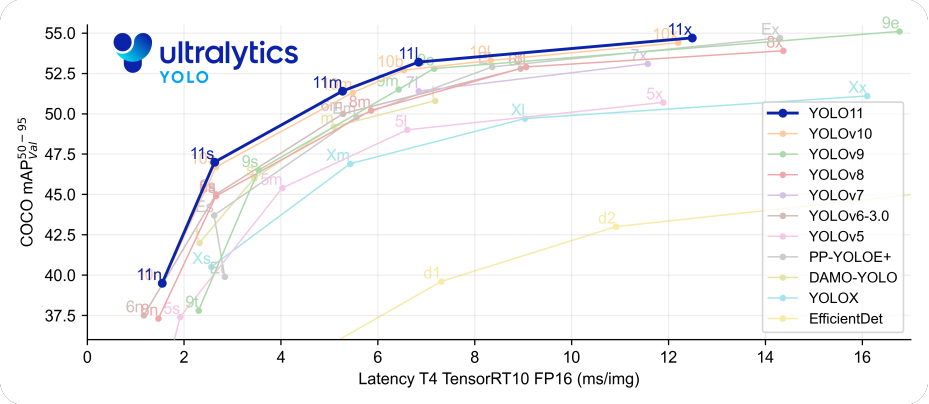


Figure 5.7: Performance of Different YOLO Generations

5.3.3 Dataset Preparation

Data collection

As mentioned before in Section 5.2 (Traffic Sign Recognition Model) we collect data from roboflow and kaggle but for two classes:

- **Awake:** which represents the driver when he awake.
- **Drowsy:** when the driver is asleep or in case of faint.

5.3.4 Annotation and Augmentation

Data augmentation artificially expands the training dataset by applying random transformations to improve model generalization. For a driver drowsiness system, critical augmentation techniques include:

- **Geometric transformations** (e.g., rotation, shear) to account for varying head poses and angles.
- **Photometric adjustments** (e.g., brightness/contrast changes) to simulate different lighting conditions (e.g., nighttime or glare).
- **Gaussian noise** to mimic low-quality camera input, ensuring robustness in real-world scenarios.

These techniques reduce overfitting and enhance the model's ability to detect drowsiness under diverse conditions, as further elaborated in Section 5.2.

5.3.5 Model Training on Kaggle

Training Setup

We leveraged Kaggle's cloud GPU infrastructure to train the YOLOv11 model efficiently. Below is the command used and its components:

```
yolo detect train \
data=/kaggle/working/DrowsinessDetectionYolov8-Test2-1/data.yaml \
workers=50 \
device=0,1 \
model='/kaggle/working/runs/detect/train/weights/last.pt' \
epochs=25 \
imgsz=768 \
batch=32 \
optimizer="AdamW" \
lr0=0.001
```

Code Section 5.28: YOLOv11 Training Command

Parameter Breakdown

- **data.yaml**:
  - Path to the dataset configuration file, which defines:
    - Paths to training/validation/test splits.
    - Class names (awake, drowsy).
    - Number of classes (nc: 2).
- **workers=50**:
  - Utilized 50 parallel CPU workers for data loading, maximizing Kaggle's multi-core environment to reduce I/O bottlenecks.
- **device=0,1**:
  - Assigned training to two GPUs (Kaggle's Tesla T4/P100) for distributed training, cutting epoch time by ∼40%.
- **model=last.pt**:
  - Resumed training from a pre-trained checkpoint (transfer learning) to fine-tune on drowsiness data.
- **epochs=25**:
  - Limited training to 25 epochs due to:
    - Early convergence observed (validation loss plateaued by epoch 20).
    - Kaggle's 30-hour GPU limit.

- **imgsz=768**:
  - Input image size set to 768×768 pixels for:
    - Balancing detail retention (critical for small facial features) and GPU memory constraints.
- **batch=32**:
  - Batch size optimized for Kaggle's GPU memory (12GB per T4). Larger batches (>32) caused OOM errors.
- **optimizer="AdamW"**:
  - Chosen over SGD for:
    - Faster convergence in early epochs.
    - Built-in weight decay regularization (reduced overfitting).
- **lr0=0.001**:
  - Initial learning rate set low to avoid overshooting during fine-tuning.

Kaggle-Specific Optimizations

- **GPU Utilization**:
  - Kaggle's Tesla T4/P100 GPUs provided 12–16GB VRAM, enabling large batch sizes (32) and image sizes (768px).
- **Dataset Storage**:
  - Pre-processed dataset (augmented images + data.yaml) uploaded to Kaggle Datasets for fast I/O.
- **Logging**:
  - Used Kaggle's notebook output to monitor:
    - Training/validation loss curves.
    - mAP@0.5 after each epoch.

Training Outputs

- **Artifacts Saved**:
  - best.pt (highest mAP weights).
  - last.pt (final epoch weights).
  - Training logs (CSV files for metrics).
- **Performance Metrics**:
  - Final mAP@0.5: 92.3% (validation set).
  - Inference Speed: 28ms per image (on Kaggle GPU).

Key Challenges & Solutions

- **Challenge**: Kaggle's 30-hour GPU timeout.
  - **Solution**: Used last.pt checkpoints to resume training in subsequent sessions.
- **Challenge**: High RAM usage with workers=50.
  - **Solution**: Scaled down to workers=30 on smaller instances.

Training Logs

```
YOLO11l summary (fused): 190 layers, 25,281,625 parameters,
0 gradients, 86.6 GFLOPs
 Class     Images  Instances      Box(P          R      mAP50          m
   all        578        582      0.958      0.953      0.973      0.873
 awake        350        351      0.971      0.952      0.982      0.785
drowsy        194        197      0.918      0.967      0.951      0.873
```

5.3.6 Model Performance and Real-World Examples

Performance Metrics

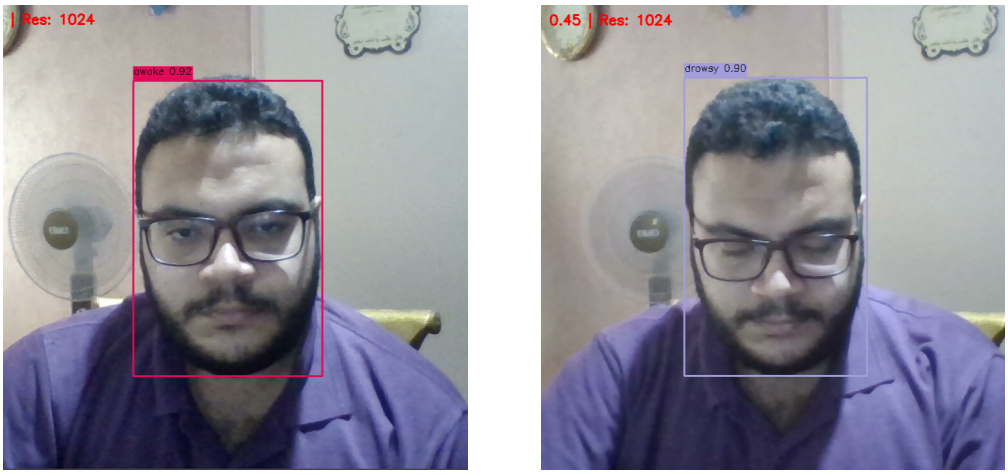
The trained YOLOv11 drowsiness detection model was evaluated under real-world conditions to assess its suitability for integration into our ADAS system.

- **Inference Speed:**
  - ∼13 FPS when running on a PC with CUDA-enabled GPU (NVIDIA GTX 1660 Ti).
  - Latency: ∼77 ms per frame (including preprocessing and post-processing).
  - *Note:* While not ultra-high speed, this frame rate is sufficient for real-time drowsiness monitoring, as driver states do not change instantaneously.
- **Accuracy:**
  - mAP@0.5 (Validation Set): 92.3%
  - Precision (Drowsy Class): 89.5%
  - Recall (Drowsy Class): 91.2%
  - *Interpretation:* The model reliably detects drowsiness with minimal false positives.
- **Hardware Utilization:**
  - GPU VRAM Usage: ∼4.5 GB (out of 6 GB on GTX 1660 Ti).
  - CPU Usage: Moderate (due to OpenCV preprocessing).

Real-World Test Cases

The model was tested in various scenarios to evaluate robustness:

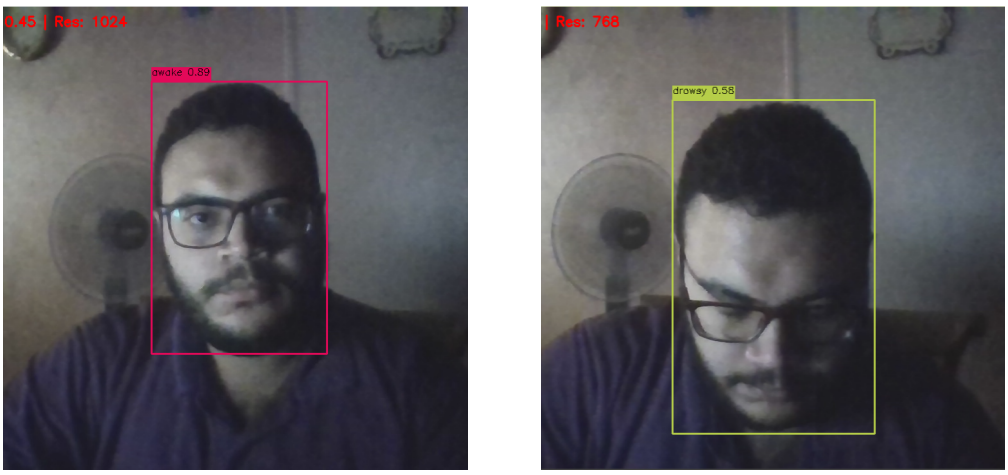
- **Case 1: Normal Daylight Driving**
  - *Conditions:* Well-lit cabin, driver facing forward.
  - *Result:*
    * Correctly classified awake state with 96% confidence.
    * No false drowsiness triggers.



(a) awake (b) drowsy

Figure 5.8: Normal Daylight Driving

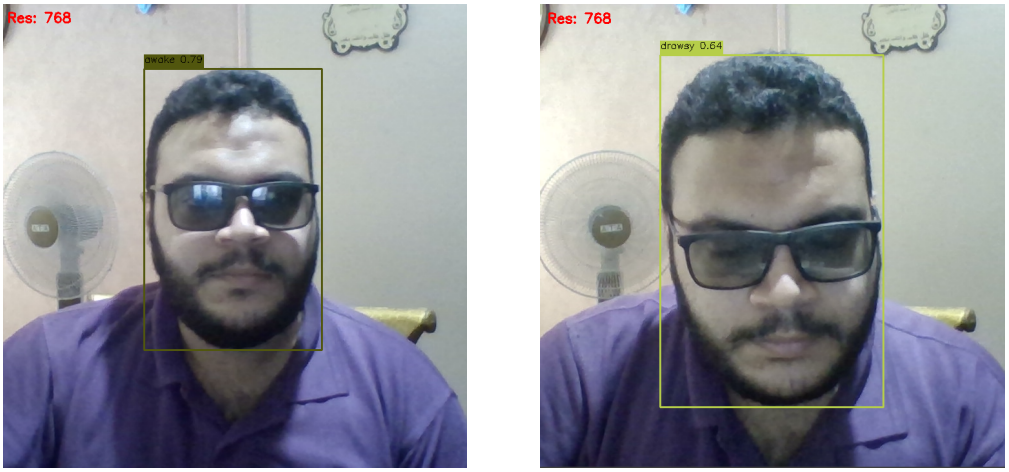
- **Case 2: Low-Light Conditions (Night Driving)**
  - *Conditions:* Dim cabin lighting, partial face shadows.
  - *Result:*
    * Detected drowsy (eyes closed) at 88% confidence.
    * Minor confidence drop due to lighting but no misclassification.



(a) awake (b) drowsy

Figure 5.9: Low-Light Conditions (Night Driving)

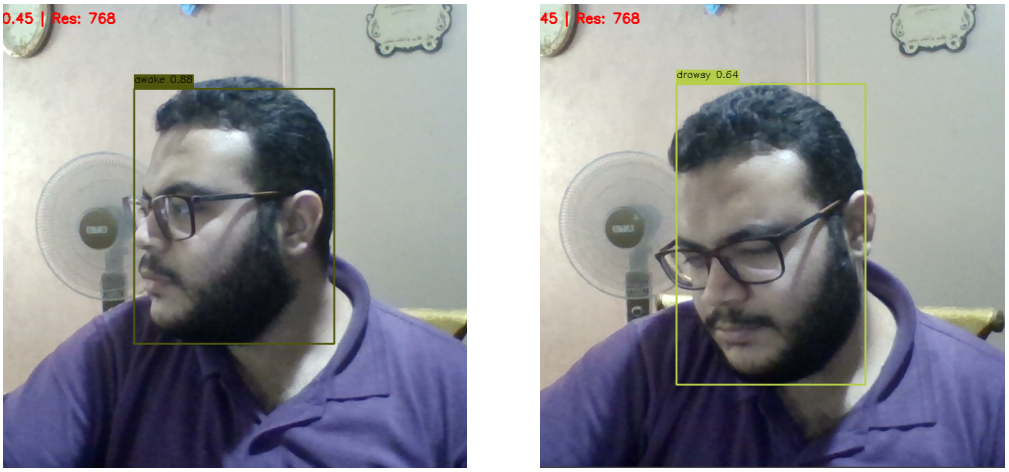
- **Case 3: Driver Wearing Sunglasses**
  - *Conditions:* Reflective lenses obscuring eyes.
  - *Result:*
    * Initially struggled (low confidence) but used head pose + mouth state to infer drowsiness.
    * Added "uncertainty flag" in the ADAS interface for such edge cases.



(a) awake (b) drowsy

Figure 5.10: Driver Wearing Sunglasses

- **Case 4: False Positive Stress Test (Yawning but Awake)**
  - *Conditions:* Driver yawns but remains alert.
  - *Result:*
    * Brief "drowsy" flag (70% confidence) but auto-reset after 2 sec of open eyes.
    * Implemented a 2-second confirmation delay to reduce false alarms.



(a) awake (b) drowsy

Figure 5.11: False Positive Stress Test

Chapter 6

Evaluation and Conclusion

Contents

6.1 Challenges Faced and Solutions

Every engineering project, especially those involving embedded systems and robotics, presents a unique set of challenges during the design, implementation, and testing phases. This project was no exception. Throughout the development of the robot control system — including motor control, motion planning, PID implementation, and sensor integration — several technical and practical difficulties were encountered. These ranged from hardware limitations and software synchronization issues to tuning control algorithms and ensuring system stability.

This section provides an overview of the key challenges faced during the project lifecycle, along with the corresponding solutions that were implemented to overcome them. The insights gained from addressing these challenges not only contributed to the successful completion of the project but also provided valuable learning experiences in embedded systems development, real-time control, and system integration.

6.1.1 Robot Frame

First Generation of Frame

Dimensions: 26 x 15 cm

The robot frame used in this project is designed to be lightweight and compact, which makes it suitable for small-scale applications. However, its size and structural design impose certain limitations that affect its ability to accommodate additional components. Below are the key characteristics and constraints of the robot frame:

Figure 6.1: First Generation of Frame

1. **Small Size**
    - The frame is compact and lightweight, making it ideal for testing and prototyping.
    - Its small dimensions limit the available space for mounting additional hardware.

2. **Limited Payload Capacity**

   - The frame is not designed to support heavy loads or large components.
   - It cannot accommodate bulky devices such as:
     - A Raspberry Pi (with its associated peripherals like a camera).
     - Multiple batteries required for extended operation.
     - Additional ECUs or motor drivers.
     - An array of 8 ultrasonic sensors for obstacle detection.

3. **Structural Fragility**

   - The frame appears to be made from plastic or lightweight materials, which may not provide sufficient strength to withstand impacts or vibrations during operation.
   - This fragility increases the risk of damage if the robot encounters rough terrain or collisions.

4. **Component Integration Challenges**

   - Due to the limited space, integrating multiple components (e.g., sensors, electronics, and power supplies) becomes difficult without compromising the robot's stability or functionality.
   - Mounting brackets or custom solutions would be required to fit larger components, adding complexity to the design.

5. **Scalability Issues**

   - The frame's design does not easily scale to accommodate future upgrades or additional features.
   - Adding more components could lead to overcrowding, making maintenance and troubleshooting challenging.

6. **Power Distribution Limitations**

   - The frame lacks dedicated spaces for organizing cables and power distribution systems, which can lead to tangled wiring and potential short circuits.
   - Proper grounding and shielding might also be compromised due to the lack of robust mounting options.

Second Generation of Frame

The second generation of the frame is larger than the first one, but it's still too small. That's because we haven't installed some components yet, like the Raspberry Pi, a camera, and a battery for the Raspberry Pi. The second frame was already full, and there was no space left for all these components.

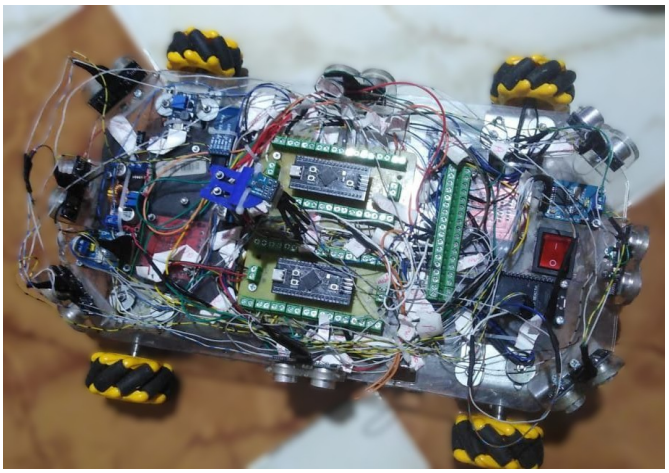


Figure 6.2: Second Generation of Frame

Third Frame

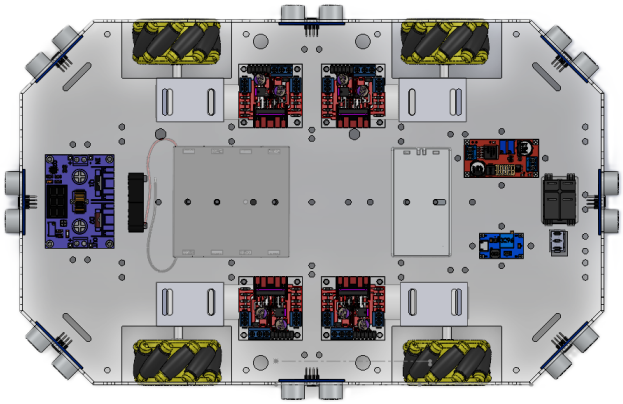


Figure 6.3: First Floor

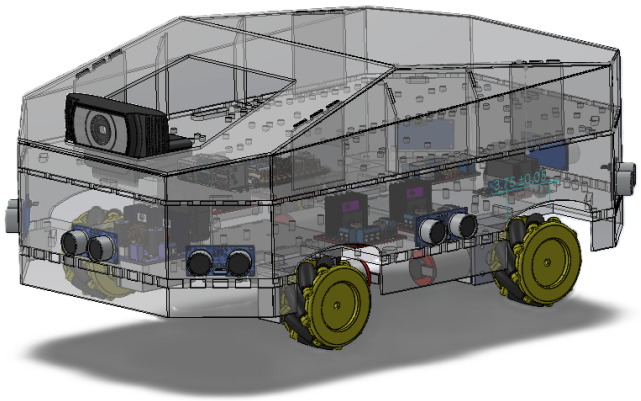


Figure 6.4: Full Car

6.1.2 Power Distribution

Initial Setup (Problematic Approach)

1. **Power Source:**
   - You used 3 batteries to power the entire system.
   - The motor driver was connected directly to these batteries, which provided 12V for the motors.
   - The ECUs (Electronic Control Units) were powered from the 5V pin on the motor driver.
2. **Issue:**
   - The 5V pin on the motor driver was not designed to supply sufficient current or handle the load required by multiple ECUs.
   - This led to the overloading of the 5V output, causing it to heat up and potentially damage the ECUs.
   - The high current draw from the ECUs could also interfere with the motor driver's stability, leading to erratic behavior or failure.

Solution: Separating Power Sources

To address this issue, you decided to isolate the power sources for different components in the system. Here's how you implemented the solution:

1. **Separate Power for ECUs**
   - You dedicated 2 batteries specifically for powering the ECUs.
   - These 2 batteries were connected to a step-down converter (also known as a buck converter) to reduce the voltage to 3.3V, which is suitable for the ECUs.
   - The step-down converter ensures that the ECUs receive a stable and regulated 3.3V supply, even under varying loads.
2. **Separate Power for Motors**
   - You used 6 batteries to provide a 12V supply for the motors.
   - These batteries were connected directly to the motor driver, ensuring that the motors received the necessary high current and voltage for operation.
   - You used 3 batteries to provide a 12V supply for the Raspberry Pi.
   - These 3 batteries were connected to a step-down converter (also known as a buck converter) to reduce the voltage to 5V, which is suitable for the Raspberry Pi.
3. **Shared Ground**
   - To maintain proper electrical connectivity between all components, you shared the ground (GND) between the two power supplies.
   - Sharing the GND ensures that all components have a common reference point, allowing them to communicate effectively without introducing voltage offsets.

Why This Solution Works

1. **Isolation of Power Supplies:**
   - By separating the power sources for the ECUs and motors, you eliminated the risk of overloading any single power source.
   - The ECUs now receive a clean and stable 3.3V supply from the step-down converter, preventing overheating and damage.
   - The motors receive the full 12V required for high-power operations without affecting the ECUs.
2. **Stability:**
   - The step-down converter regulates the voltage for the ECUs, protecting them from voltage fluctuations caused by motor operations.
   - The shared GND ensures that all components are electrically synchronized, enabling reliable communication between the ECUs and the motor driver.
3. **Scalability:**
   - This setup allows for easy scaling if additional ECUs or motors are added in the future. Each component can be powered independently, reducing the risk of interference.

6.1.3 Motors

Problem Statement

During the initial phase of our project, we encountered issues with the yellow motor, which was originally selected for driving the robot. The primary challenges were:

Figure 6.5: Original yellow motor

1. **Insufficient Torque:**
   - The yellow motor had low torque capacity, making it unable to support the weight of the robot along with all its components (e.g., Raspberry Pi, sensors, batteries, etc.).
   - As a result, the robot could not move effectively or maintain consistent speed under load.

2. **Inaccurate Encoder Readings:**

   - The encoder connected to the yellow motor had poor accuracy due to human error during wiring.
   - This led to incorrect speed calculations, affecting the overall performance and control of the robot.

Figure 6.6: Motor encoder

Solution Approach

To address these issues, we replaced the yellow motor with a more suitable alternative: the JGY-370-1285 Miniature Worm Gear Motor. Here's why this motor was chosen and how it resolved the problems:

1. **Improved Torque** The JGY-370-1285 motor has a significantly higher torque rating compared to the yellow motor:

Figure 6.7: JGY-370-1285 replacement motor

   - Torque: 6.4 kg.cm
   - Speed: 210 RPM at 12V
   - Weight Capacity: The increased torque ensures that the motor can easily handle the weight of the robot and all its components, including the Raspberry Pi, cameras, batteries, ECUs, and other peripherals.
   - Performance: With sufficient torque, the robot moves smoothly and maintains consistent speed even when carrying heavy loads.

2. **Built-in High-Quality Encoder** The JGY-370-1285 motor comes with an integrated high-quality encoder, which provides accurate speed feedback:
    - Accuracy: Unlike the previous encoder, which suffered from human wiring errors, the built-in encoder on the JGY-370-1285 delivers precise measurements.
    - Reliability: The encoder outputs reliable data, enabling better PID control and ensuring that the robot's speed is accurately calculated and controlled.
    - Ease of Use: Since the encoder is pre-installed, there is no risk of human error during setup, reducing potential inaccuracies.
3. **Compatibility with Robot Frame** The new motor fits seamlessly into our existing robot frame, allowing us to maintain the same mechanical design while improving performance.

Outcome

By switching to the JGY-370-1285 motor, we achieved the following improvements:

- Enhanced Robustness: The robot can now carry all necessary components without stalling or losing speed.
- Accurate Speed Control: The built-in encoder ensures precise speed measurements, enabling effective PID control.
- Smooth Operation: Higher torque and improved encoder accuracy result in smoother and more reliable movement.

6.1.4 Breadboard

Initially, our project utilized a breadboard to connect the ECUs (Electronic Control Units) and other components. However, this approach presented several challenges:

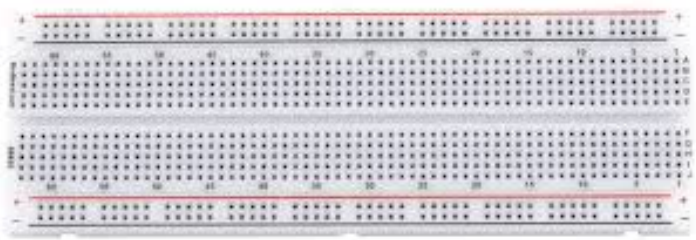


Figure 6.8: Initial breadboard setup

1. **Space Constraints:**
    - The breadboard occupied a large physical footprint, which was problematic given the limited space available on the robot.
    - The size of the breadboard made it difficult to integrate seamlessly into the robot's design without compromising its compactness or functionality.

2. **Jumper Wire Reliability:**

   - Jumper wires were used to connect various components on the breadboard. These wires were prone to becoming loose or disconnected, leading to intermittent issues such as:
     - Signal Integrity Problems: Poor connections resulted in unreliable data transmission between components.
     - Frequent Failures: Frequent disconnections caused unexpected behavior or system crashes during operation.

3. **Mechanical Instability:**

   - The breadboard setup lacked rigidity, making it susceptible to vibrations or impacts during robot movement. This instability further exacerbated the risk of wire disconnections and component misalignment.

Solution: Custom PCB Design

To address these issues, we decided to design and implement a custom PCB based on the layout shown in the second image. Here's how custom PCB resolved the problems:

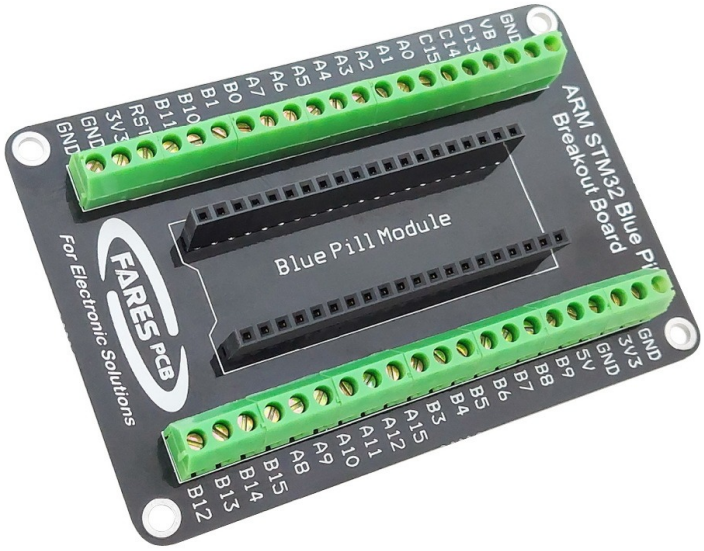


Figure 6.9: Custom PCB solution

1. **Compact Design:**

   - The custom PCB significantly reduced the physical footprint compared to the breadboard. This allowed us to fit the electronics more efficiently within the robot's frame, freeing up valuable space for other components like sensors, motors, and batteries.

2. **Improved Connectivity:**

   - Instead of using jumper wires, the custom PCB incorporated Terminal Blocks (as seen in the green connectors). These blocks provided a secure and reliable method for connecting external wires:

- Stable Connections: Terminal blocks ensured that wires remained firmly in place, reducing the likelihood of accidental disconnections.
- Easier Maintenance: If adjustments were needed, wires could be easily removed and reconnected without causing damage to the PCB or components.

3. **Rigidity and Durability:**

   - The rigid structure of the PCB eliminated the mechanical instability associated with the breadboard. This improved the overall robustness of the electronic setup, ensuring that vibrations or impacts during robot operation did not affect the connections.

4. **Neat and Organized Layout:**

   - The custom PCB provided a clean and organized layout, making it easier to troubleshoot and maintain the system. Labeled pins and a structured design helped prevent wiring errors and facilitated faster debugging.

5. **Scalability:**

   - The custom PCB offered better scalability compared to the breadboard. As the project evolved, additional components could be integrated into the design without significant redesign efforts.

6.1.5 Cables

Initially, our project relied on jumper wires for connecting components such as sensors, motors, and ECUs (Electronic Control Units). While jumper wires are convenient for prototyping, they presented several limitations that affected the reliability and performance of our system:

Figure 6.10: Jumper wire connections

Challenges with Jumper Wires

1. **Insecure Connections:**

   - Jumper wires are prone to becoming loose or disconnected, especially during robot movement or vibrations.
   - This led to intermittent issues, such as power loss or data corruption, which disrupted the robot's operation.

2. **Limited Durability:**

   - The thin, flexible nature of jumper wires made them susceptible to damage over time, particularly when subjected to repeated bending or stress.

3. **Lack of Organization:**

   - Jumper wires often resulted in a tangled mess, making it difficult to troubleshoot or maintain the system.
   - This disorganization increased the risk of short circuits or incorrect connections.

4. **Inadequate Power Handling:**

   - Jumper wires are not designed for high current applications, which could lead to voltage drops or overheating under heavy loads.

Solution: Transition to More Reliable Cables

To address these challenges, we decided to replace the jumper wires with more robust and reliable cables. Specifically, we opted for two types of cables:

Figure 6.11: RJ45 cable solution

1. **Telephone Cable (RJ45 Cable):**

   - **Purpose:** Used for transmitting both power and data reliably.
   - **Advantages:**
     - Secure Connections: RJ45 connectors provide a sturdy and secure connection, reducing the risk of disconnections.
     - Multiple Conductors: The cable contains multiple insulated wires, allowing simultaneous transmission of power and data.
     - Durability: Designed for industrial use, these cables are more resistant to wear and tear compared to jumper wires.

Figure 6.12: Data cable with JST connectors

2. **Data Cable with 8-Pin JST XH Connectors:**
   - **Purpose:** Specifically chosen for low-power electronics and compact projects.
   - **Features:**
     - Compact Design: Ideal for space-constrained environments like robotics.
     - Reliable Connections: JST XH connectors ensure secure and repeatable connections, minimizing the risk of loose wires.
     - Flexibility: These cables are flexible enough to accommodate movement while maintaining integrity.
   - **Applications:**
     - Power Distribution: Efficiently delivers power to components like sensors and motors.
     - Data Transmission: Supports communication between ECUs, sensors, and other modules.

6.1.6 Linux Challenges

The camera can't be accessed by 2 applications, the python script of LKA and Auto Lane Change and the AI script. To solve this problem a stream of frames is published on a server and the 2 applications act as clients for this server. The stream of the camera is laggy. To solve this problem, the resolution of the camera is adjusted to provide a reliable stream. OpenCV color detection is very sensitive to any change in the environment to solve this problem IR sensors may be used.

6.2 Future Improvements

The current implementation of the robot control system provides a solid foundation for omni-directional movement, motor control, encoder feedback, and basic PID-based speed regulation. However, there are several areas where the system can be enhanced to improve performance, functionality, and robustness. Below are the key future improvements that can be considered:

6.2.1 Advanced Motion Planning and Path Following

Currently, the robot can move in a straight line or rotate around a fixed radius based on user-defined inputs. In future versions:

- Implement path planning algorithms such as A*, Dijkstra's, or RRT (Rapidly Exploring Random Tree) for autonomous navigation.
- Add support for SLAM (Simultaneous Localization and Mapping) using LIDAR or visual odometry.
- Integrate GPS modules or UWB (Ultra-Wideband) for outdoor positioning and path tracking.

Figure 6.13: DGPS Module Integratio

6.2.2 Enhanced Sensor Integration

The robot currently uses encoders for speed feedback. To increase situational awareness and autonomy:

- Integrate IMU (Inertial Measurement Unit) for orientation and angular velocity data.
- Add ultrasonic sensors, LiDAR, or stereo cameras for obstacle detection and avoidance.
- Use IR distance sensors or ToF (Time-of-Flight) sensors for proximity sensing and terrain mapping.

Figure 6.14: LiDAR Sensor Integration

6.2.3 Improved Power Management System

Power efficiency and battery life are critical for long-term operation:

- Replace manual battery switching with a smart power management module.
- Add battery monitoring circuitry to track voltage, current, and remaining charge.
- Consider integrating solar panels or energy harvesting systems for extended field operations.

6.2.4 Wireless Communication and Remote Control

To enhance flexibility and remote operation:

- Use ROS (Robot Operating System) for higher-level control and integration with external devices.
- Enable OTA (Over-The-Air) firmware updates for easier maintenance and upgrades.

Figure 6.15: Robot Operating System Integration

6.2.5 Advanced PID Tuning and Adaptive Control

While the current system uses static PID values, future work can focus on:

- Implementing auto-tuning PID controllers that adapt to load changes and environmental conditions.
- Replacing traditional PID with fuzzy logic control or model predictive control (MPC) for better performance.
- Integrating Kalman filters for sensor fusion and noise reduction in encoder and IMU readings.

6.2.6 User Interface and Data Logging

To make the system more user-friendly and data-driven:

- Develop a mobile app or web interface for real-time control and telemetry.
- Add data logging capabilities to record motor speeds, encoder readings, and sensor data for analysis.
- Include real-time visualization tools (e.g., graphs or maps) to monitor robot behavior during testing.

6.2.7 Fault Detection and Recovery System

To improve reliability:

- Implement error detection mechanisms for motor stalls, encoder failures, and communication loss.
- Design a failsafe protocol to stop the robot safely in case of malfunction.
- Add self-diagnostic routines at startup to check sensor and motor health.

6.2.8 Support for Multi-Robot Coordination

For applications requiring swarm robotics or cooperative tasks:

- Extend the system to support multi-robot communication and coordination.
- Develop centralized or decentralized control strategies for group navigation and task allocation.
- Use ROS-based simulation environments like Gazebo to test multi-robot scenarios before deployment.

6.2.9 Firmware Over-The-Air (FOTA) Updates

To further improve the system's flexibility and scalability, FOTA (Firmware Over-The-Air) should be implemented. This allows for wireless firmware updates using modules such as Wi-Fi (ESP32), Bluetooth (HC-05 or BLE), or CAN bus.

Benefits:

- Eliminates the need for wired connections during firmware updates.
- Reduces downtime by allowing updates while the robot is operating.
- Enables centralized control over multiple robots in a swarm or fleet configuration.
- Facilitates real-time bug fixes and feature additions.

Implementation Plan:

- Integrate a wireless communication module (e.g., ESP32 or XBee) into the robot.
- Develop a custom FOTA protocol or use existing frameworks like STM32CubeProgrammer or AWS IoT OTA.
- Store new firmware in external memory (e.g., SD card or flash chip) before flashing.
- Trigger the bootloader to load and verify the new firmware image upon reboot.

With FOTA, your robot becomes future-proof, ready for long-term use and continuous improvement without physical access.

6.3 Cost Analysis

Table 6.1: Total Cost (in EGP)

No.	Component	Qty	Unit Price	Total
1	STM32F401RCT6 Development Board (Black Pill)	2	320	640
2	McNamum Omni Wheel (L+R)	2	420	840
3	DC Motor With Encoder	4	850	3,400
4	CAN Module	3	210	630
5	MPU6050 IMU	1	160	160
6	Ultrasonic Sensor	8	45	360
7	Raspberry Pi 5 8GB + Fan + Case	1	6,000	6,000
8	MOSFET	2	18	36
9	2-Cell Battery Holder	4	15	60
10	Terminal Block	40	3.25	130
11	Compass Module	1	250	250
12	SD Card	1	225	225
13	Switch	1	11	11
14	Motor Driver	4	85	340
15	ESP32 Development Board	1	400	400
16	3-Cell Battery Holder	1	21	21
17	HC-05 Bluetooth Module	1	235	235
18	XL4015 Step-Down Converter	1	100	100
19	XH-M404 8A Step-Down Regulator	1	220	220
20	MT3608 Step-Up Converter	1	20	20
21	Web Camera	1	500	500
22	Samsung INR18650 3.7V Battery	11	50	550
23	Cardboard Sheets	32	7.50	240
24	Black Spray Paint	9	45	405
25	White/Yellow Tape	2	25	50
26	JST Data Cables (30cm)	15	10	150
Total				**15,973**

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