Design and Implementation of the Embedded Control System for an Autonomous Cleaning Robot

Oke Iyanuoluwa Enoch

Team members: Love Akinrele, Ifeorah Anthony, Revanth Reddy

@00659936

Lecturer: Dr Theo Theodoridis

Module Title: Mechatronics

Programme: MScs. Robotics and Automation

School of CSE, University of Salford, Manchester M5 4WT, UK

i.e.oke@edu.salford.ac.uk

*Abstract -* This report details the design and implementation of the control system for an autonomous cleaning robot. The project covers the design and development of key electronic subsystems, including a Power Supply Unit (PSU), USB Control Unit (UCU), Micro-Controller Unit (MCU), and Motor Driver Unit (MDU). Using Altium Designer Software for schematic designs and PCB layout were created for each subsystem. The design adheres to professional standards, ensuring efficient operation and integration of sensors and actuators. Performance tests demonstrate the robustness of the system, providing a reliable foundation for further development in robotic cleaning applications.

1. Introduction

The rapid growth in demand for automation in both household and industrial cleaning tasks has significantly advanced robotic technologies. Robots' ability to perform repetitive, labor-intensive tasks autonomously and efficiently has made them indispensable in these environments. This report focuses on the design and implementation of the electronic control system for an embedded cleaning robot, which integrates key components such as motor drivers, sensors, and power management units. These components form the foundation of the robot’s functionality, enabling it to navigate, clean, and avoid obstacles effectively.

The motivation behind this investigation lies in the challenge of developing a cost-effective, reliable, and efficient cleaning robot capable of operating in diverse environments. The growing adoption of smart home and industrial automation solutions inspired this project, as these technologies aim to enhance productivity and streamline routine tasks. The primary objective of this study is to design an electronic control system that optimally manages the robot’s operations, from basic movement and cleaning behaviors to advanced obstacle detection and avoidance.

This investigation is particularly important for advancing the field of embedded robotic systems. Improvements in control systems, such as optimized motor drivers and power management, can significantly enhance the performance, efficiency, and adaptability of autonomous robots. Additionally, the integration of advanced control algorithms into the system contributes to the development of more sophisticated and capable robotic platforms. The system developed in this project lays the groundwork for future innovations in autonomous cleaning robots, providing a scalable solution that can be further refined for broader applications.

Throughout this project, collaborating with students from Pakistan and Nigeria emphasized the significance of fostering an inclusive and supportive environment. Each team member brought a unique cultural, ethnic, and educational perspective, so we prioritized open communication and mutual respect. We actively encouraged the sharing of diverse viewpoints during brainstorming sessions and problem-solving discussions, which enriched our project by providing fresh insights into design challenges.

We recognized the importance of accommodating religious and cultural differences by remaining flexible with meeting times to respect prayer schedules and personal commitments. Additionally, we were mindful of varying educational backgrounds, ensuring that technical concepts were openly discussed so everyone felt supported in understanding and contributing to the project's technical aspects.

By cultivating a culture of respect, inclusion, and cooperation, we enhanced both teamwork and creativity. This inclusive approach allowed us to collaborate harmoniously, providing equal opportunities for every member to contribute. Ultimately, this not only improved the quality of our work but also led to the overall success of the project, showcasing the value of diversity in achieving shared goals.

The remainder of this report is organized as follows. The Literature Review section examines current research and technological advancements related to embedded cleaning robots. The Methods section provides an in-depth description of the electronic subsystems' design, including Power Supply Unit, USB Control Unit, Micro-Controller Unit, and Motor Driver Unit. In the Results section, experimental outcomes and performance evaluations are presented. Finally, the Conclusions section discusses the findings and potential directions for future work.

This report focuses solely on the electronic design aspect of the project, while programming and mechanical design are covered in team members' reports, collectively providing comprehensive documentation of the embedded control system for an autonomous cleaning robot.

1. Literature Review

The growing demand for autonomous cleaning solutions in households and industries has driven research in robotic control systems, sensor integration, and power management. This review explores key technologies in embedded cleaning robots, focusing on control units, motor drivers, and energy systems. It highlights areas for innovation and advancements in control algorithms to enhance performance and reliability.

The author [3] presents the development of a vacuum cleaner robot aimed at automating household cleaning. The robot is designed with an Arduino-based control system, utilizing ultrasonic sensors for navigation and obstacle detection. It features a disk-shaped body, two rear wheels, and a front caster for maneuverability, with rotating sweepers to gather dirt into a vacuum. Powered by lithium-ion batteries, it operates for two hours on a full charge. The study demonstrates the robot’s efficiency in cleaning and navigating, though limitations such as the dustbin size and navigation glitches were noted. Future improvements could involve scaling up the dustbin and enhancing navigation systems for broader applications in home and office environments.

The authors [4] present the development of an autonomous robotic vacuum cleaner designed to save time and reduce effort for users. The system employs multiple sensors, such as infrared (IR) and ultrasonic sensors, for obstacle detection and navigation. A central ARM Cortex M3 controller processes sensor data and controls the robot's movement via permanent magnet DC (PMDC) and servo motors. The vacuum cleaner operates autonomously, utilizing suction to collect dirt. The robot is designed to assist busy individuals, the elderly, and physically challenged users. With future advancements, the robot has potential applications in homes, offices, and other public spaces​.

The authors [5] present the development of a smart vacuum cleaner designed to operate autonomously without human intervention. The system integrates an RC car carrying a vacuum cleaner, controlled via an Arduino UNO microcontroller. An ultrasonic sensor detects obstacles, guiding the car to adjust its path based on obstacle distance. A CPU fan provides suction, collecting dust into a detachable container. The cleaner is powered by batteries, making it portable and efficient. The system offers a cost-effective and straightforward design, with potential applications in hazardous environments and daily cleaning tasks. Future improvements may include enhanced dust collection mechanisms and further automation.

The authors [6] present a Bluetooth-based smart vacuum cleaner designed for autonomous cleaning using IoT technology. The system includes a vacuum mounted on a mobile robot chassis equipped with sensors, a microcontroller, and Bluetooth communication. Controlled via a mobile app, the vacuum cleaner can navigate around obstacles and perform tasks remotely. The system uses sensors to detect its environment and an RFID-based positioning system for accurate location tracking. The robot autonomously cleans predefined areas and self-charges when needed. The study demonstrates that the integration of IoT and open-source hardware can facilitate daily household tasks, providing a functional and cost-effective solution for smart cleaning.

The authors [7] designed and implemented a low-cost vacuum cleaner robot controlled via a smartphone, aimed at being accessible to more users. The robot autonomously navigates around obstacles using ultrasonic and infrared sensors while being controllable through a mobile application. It integrates basic cleaning algorithms such as random walk and snake movement to clean efficiently, avoiding walls and cliffs. The study highlights the robot’s ability to provide efficient, low-power cleaning with cost-effective components, demonstrating that affordable robotic solutions for household chores are viable.

The authors [8] present the design and development of a prototype robot vacuum cleaner, using low-cost, off-the-shelf components. The navigation system employs fuzzy logic to enable efficient movement in unknown environments. The hardware includes a Rex-12 Round Robot Base and SRF08 ultrasonic sensors, while the software relies on eLinOS and Simulink for control and navigation. The system was validated using Software-in-the-Loop (SIL) simulations and a virtual prototype to test the navigation algorithm. However, experimental tests revealed the need for improvements in the sensing system to enhance position estimation accuracy.

The authors [9] designed a dual-mode robot vacuum cleaner prototype based on Arduino Uno, which operates in both automatic and manual modes. The robot uses a Sharp GP proximity sensor for obstacle detection and a Bluetooth HC-05 module for smartphone control. In automatic mode, the robot navigates randomly, avoiding obstacles, while in manual mode, users control the robot via a smartphone app. The prototype was tested for suction efficiency and maneuverability, showing limitations in steep slopes and larger debris handling. Further improvements are recommended for enhanced performance.

The authors [10] developed a wireless charging system for robot vacuum cleaners using inductive power transfer (IPT) technology. The system employs curved coils and passive power repeaters to enhance magnetic field coupling, improving charging efficiency despite coil misalignment. The prototype, tested with a 32W power transfer capacity at 100 kHz, demonstrated successful charging under simulated conditions. However, the system showed some limitations in power transfer optimization, suggesting future improvements in coil design and the potential use of active power repeaters for greater efficiency.

The authors [11] developed an Arduino-based smart vacuum cleaner robot, designed to clean autonomously without human intervention. The robot uses an Arduino Uno, ultrasonic sensors for obstacle detection, and motor shields to control movement. Powered by a 12V battery, the vacuum system includes a fan and motor for suction, effectively cleaning hazardous environments. The robot was tested for its obstacle avoidance and cleaning capabilities. While cost-effective and customizable, limitations were noted in efficiency when handling uneven surfaces, and further improvements were suggested for enhanced performance.

The author [12] discusses the design of a vacuum cleaner motor drive inverter using the EPC9176 evaluation board. The inverter uses three EPC23102 eGaN ICs in a three-phase configuration, providing high efficiency and power density. It operates at switching frequencies up to 250 kHz and delivers 18 ARMS with a heatsink. The design incorporates protection functions, current and temperature sensing, and a microcontroller interface. The system is optimized for BLDC motor control, demonstrating reduced torque oscillations, improved efficiency, and better current waveforms for vacuum cleaner applications​

The authors [13] designed and analyzed an automatic robotic vacuum cleaner using an Arduino microcontroller and axial fan. The robot uses ultrasonic sensors for obstacle detection and a motor-driven wheel system for movement. Powered by a 12V rechargeable Li-Po battery, it runs for 20-30 minutes on a full charge. Simulation was performed using Coppelia Robotics and ANSYS Fluent to analyze vacuum efficiency. The design is affordable and suitable for Indian markets, with potential applications in households and industries​.

The authors [14] designed and fabricated a robotic vacuum cleaner with autonomous functionality using an Arduino Uno and various sensors. The robot features a vacuum system, mopping mechanism, and drying capability, supported by 12V motors for movement. It integrates IR and ultrasonic sensors for obstacle detection and navigation. The control system allows the robot to switch between various cleaning modes and adjust its speed. The study highlights the potential of this cost-effective design for domestic use, especially for elderly or busy individuals​.

The authors [15] proposed the integration of Altium Designer software in teaching electronic circuits. The software provides a platform for schematic capture, simulation, and PCB design, allowing students to visualize and analyze circuits effectively. It simplifies debugging and error correction while offering features like fourier analysis, waveform simulation, and cross-probing. The study demonstrates how Altium Designer enhances students' learning experience by reducing manual tasks, improving accuracy, and offering hands-on circuit design, making it an essential tool for both education and research​.

The authors [16] developed an autonomous robotic vacuum cleaner that operates in three modes: manual, automatic, and timer-based. The device integrates a NodeMCU microcontroller and ultrasonic sensors for obstacle detection, along with a vacuum and wet mopping mechanism. Controlled via a smartphone app, the robot can clean surfaces by avoiding obstacles and adjusting its path accordingly. It features both vacuuming and wet mopping capabilities for comprehensive cleaning. Testing demonstrated successful obstacle avoidance and efficient cleaning, though the authors suggest further refinement for wider applications.

The authors [17] proposed a cost-effective IoT-based vacuum and mopping robot designed with an Arduino Uno board, ultrasonic and infrared sensors, and Bluetooth control. The robot operates in both automatic and Bluetooth-controlled modes, utilizing a vacuum kit for dust collection and side brushes for efficient cleaning. Ultrasonic sensors detect obstacles, while an L293D motor driver controls the robot's movement. The design aims for maximum cleaning coverage and mobility. Testing showed efficient cleaning and obstacle avoidance, with potential for further enhancements in sensor accuracy and functionality​.

The authors [18] developed a robot vacuum cleaner using the Arduino Mega 2560 microcontroller, incorporating ultrasonic sensors for obstacle detection and dust sensors for cleaning. The robot uses four ultrasonic sensors to navigate in cardinal directions and detects dust levels below 0.30 mg/mm³ to activate cleaning. The vacuum operates in forward, backward, and turning movements based on sensor input. The system's performance is displayed on an LCD, with the robot stopping if thicker dust or obstacles are detected. Testing confirmed effective movement and cleaning within the specified parameters​.

The authors [19] designed an autonomous vacuum cleaning robot with a focus on cost optimization. The robot features an Arduino Mega 2560 microcontroller, limit switches, infrared sensors, and a DC motor to control movement and obstacle avoidance. A bevel gear system reduces the need for individual motors for each cleaning brush. The robot is designed to vacuum dust and small debris efficiently while navigating obstacles and stairs. With a low manufacturing cost of ₹5,410, the prototype performs well for commercial cleaning but could benefit from additional features such as GPS and automatic charging systems.

The authors [20] developed an intelligent vacuum cleaner that integrates sensor, positioning, and control technologies for autonomous cleaning. The system features an Stc89c52rc microcontroller, infrared sensors for tracking and obstacle avoidance, and ultrasonic sensors for distance detection. The vacuum cleaner can navigate, avoid obstacles, and clean efficiently without manual control. It also includes a motor control circuit for dust collection and a remote control for user interaction. The design emphasizes intelligence, efficiency, and ease of use, marking a significant advancement in household cleaning technology.

The authors [21] designed a smart vacuum cleaner equipped with indoor localization and obstacle detection. The robot uses TurtleBot technology with a SLAM algorithm for simultaneous mapping and localization. It features infrared and ultrasonic sensors for object detection, a motor driver system, and is controlled by an Arduino microcontroller. The vacuum can operate in both manual and autonomous modes. The study emphasizes the use of simulation environments like ROS and Gazebo to optimize path planning and improve cleaning efficiency, showcasing potential applications in homes and commercial spaces.

1. Methods

The intelligent system architecture of the Embedded Cleaning Robot integrates four core functions: rectangular path navigation, target tracking for recharging, obstacle avoidance, and random wandering to explore uncovered areas. Each function is managed by the robot's main control board, consisting of a Power Supply Unit, USB Control Unit, Micro-Controller Unit, and Motor Driver Unit, enabling efficient, adaptive operation in dynamic environments with seamless sensor integration and precise motor control.

Power Supply Unit (PSU)

The Power Supply Unit (PSU) uses two LM2596-based step-down regulators to convert a 12V input into two stable DC outputs:

5V Output: Using the LM2596T-5.0 regulator, this output powers components requiring 5V.

3.3V Output: Using the LM2596T-3.3 regulator, this output powers components requiring 3.3V.

These designs prioritize efficiency, stability, and thermal management, ensuring the proper functioning of embedded systems and other sensitive electronics. Below are the schematic and PCB layout designs for the PSU, prepared using Altium Designer, showing component placement and connections. This setup provides efficient power to the system with minimal ripple, high stability, and low thermal impact.

LM2596T-5.0:

Model Description

The PSU design features the LM2596T-5.0, a fixed-output buck converter that steps down a 12V input to 5V with minimal ripple and noise, supporting up to a 3A load. Operating at a fixed switching frequency of 52 kHz, it ensures compact and efficient filtering while incorporating fault protection mechanisms such as thermal shutdown and overcurrent limits.

Electrical Characteristics

The LM2596T-5.0 offers the following electrical parameters for the PSU:

- Output Voltage: Stable at 5V, with typical tolerances of ±4% across load and line conditions.

- Oscillator Frequency: Fixed at 52 kHz, which maintains switching frequency consistency and improves voltage regulation​ allowing compact and efficient filter designs.

- Current Limit: 5.8A peak, preventing excessive current flow and protecting against faults.

- Input Voltage Range: Operates with a wide range of input voltages.

Thermal Management and Power Dissipation

- Thermal Shutdown: Built-in thermal shutdown ensures safe operation by automatically disabling the IC if temperatures exceed safe limits​.

- Thermal Resistance: With θJA at 65°C/W (TO-220 package) and junction temperature max at 125°C, the power dissipation under normal operation is within safe ranges with limited or no additional heat sink requirement.

- Power Dissipation Equation: Power dissipation (PD) can be calculated using:

VSAT

where VIN is 12V, IQ (quiescent current) is 5 mA, VO is 5V, and VSAT is approximately 1.4V for the LM2596T-5.0.

Performance Under Load and Temperature Tolerances

Graphs from the datasheet show:

- Efficiency vs Load Current: At 3A, efficiency reaches around 77%.

A diagram of a voltage

Description automatically generated

- Ripple Voltage: The output ripple can be managed with the 1000 µF output capacitor, achieving smooth operation and low noise at approximately 1% of the output voltage​.

~~I~~mplementation Design

The LM2596T-5.0 PSU is designed to efficiently convert a 12V DC input to a stable 5V DC output, ideal for powering embedded systems.

i. Input Power and Filtering: The 12V input, provided through a power jack and SPST switch, is stabilized by capacitors (100 µF and 10 nF) to filter high-frequency noise, reducing oscillations for smooth regulator operation.

ii. Voltage Regulator Module: The LM2596T-5.0 regulator steps down the input to a steady 5V, chosen for its efficiency and ability to manage higher input voltages with minimal power loss.

iii. Inductor (100 µH): The 100 µH inductor supports energy storage and smooths the current, minimizing ripple crucial for stable applications.

iv. Output Capacitor (1000 µF): Positioned as the primary output filter, the 1000 µF capacitor smooths residual ripple, enhancing stability. Its voltage rating is selected above 5V to ensure durability against minor surges.

v. Catch Diode (1N5822): This Schottky diode, with fast switching and low forward voltage drop, prevents current backflow, protecting the circuit during off cycles.

vi. Indicator LED and Resistor: An LED and 330-ohm resistor signal the output status, providing a simple verification tool.

vii. Output Connector: A 2-pin connector offers easy 5V access for external devices, creating a reliable, efficient PSU for systems requiring stable power.

LM2596T-3.3:

Model Description

The LM2596T-3.3 regulator steps down a 12V input to a stable 3.3V output. It supports up to 3A load and includes the same thermal and overcurrent protection as the LM2596T-5.0.

Electrical Characteristics

* Output Voltage: Nominal output is 3.3V, with ±4% tolerance.
* Oscillator Frequency: Fixed at 52 kHz, enabling efficient filtering.
* Current Limit: Peak current limit of 5.8A.
* Input Voltage Range: Accepts input voltages of 12V in this PSU design.

Thermal Management and Power Dissipation

* Thermal Shutdown: Automatically disables the IC in case of overheating.
* Thermal Resistance: θJA: 65°C/W for the TO-220 package. Maximum junction temperature: 125°C.
* Power Dissipation: Calculated similarly to LM2596T-5.0, using:

VSAT

where VIN is 12V, IQ (quiescent current) is 5 mA, VO is 3.3V, and VSAT is approximately ~1.4V.

Performance Under Load and Ripple Voltage

* Efficiency: Efficiency can reach 78% under typical load conditions.
* Ripple Voltage: Ripple is minimized using a 330 µF output capacitor, maintaining noise at around 1% of output voltage.

Implementation Design

The LM2596T-3.3 PSU is designed to efficiently convert a 12V DC input to a stable 3.3V DC output, ideal for powering embedded systems.

i. Input Power and Filtering: The 12V input is filtered using a 330 µF capacitor to suppress high-frequency noise.

ii. Voltage Regulator Module: The LM2596T-3.3 steps down 12V to 3.3V, ensuring stability and low noise.

iii. Inductor: A 33 µH inductor smooths current flow, reducing ripple.

iv. Output Capacitor: A 330 µF capacitor filters the output voltage, ensuring a stable 3.3V output.

v. Catch Diode: A 1N5822 Schottky diode prevents reverse current flow.

vi. Indicator LED and Resistor: An LED and 330-ohm resistor signal the presence of the 3.3V output.

vii. Output Connector: A 2-pin connector provides access to the regulated 3.3V output.

Below is the Schematic and PCB diagram showing the connection of the Power Supply Unit (PSU):

A diagram of a machine

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Fig. 1a The schematic diagram of the PSU (Power Supply Unit

A computer screen shot of a computer scheme

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Fig 1b. The Printed Circuit Board (PCB) of the PSU (Power Supply Unit

USB Control Unit (UCU)

The UCU is the USB interface used to establish bidirectional communication with the PC over a USB-to-Serial protocol. Using the FT232RL functions as the USB-to-serial UART interface. The design can include the following essential elements:

- VCCIO: Configured based on the voltage requirement (1.8V to 5.25V). This can be set to interface with other components in the circuit.

- USB Data Lines (USBDP and USBDM): Connected to the USB connector with internal pull-up resistors for proper USB 2.0 full-speed communication.

- CBUS Pins: Configurable GPIO pins (CBUS0-4) set in the EEPROM to control additional functions like LEDs for data indication or to manage power settings via PWREN.

FT232RL Configuration and Analysis

The FT232RL integrates critical functions needed for USB communication and UART interfacing:

Electrical Characteristics:

- Operating Voltage: 3.3V to 5V nominal operating voltage; the internal LDO provides a regulated 3.3V output.

- Current Requirements: Operating at approximately 15mA in normal mode and 70µA in USB suspend mode, supporting low-power applications​.

Thermal Characteristics:

- Suitable for a temperature range of -40°C to 85°C, making it versatile for embedded applications.

- The IC includes an internal power-on-reset (POR) and a 3.3V LDO, reducing the need for additional thermal management components like heat sinks for moderate power applications​.

Performance Specifications:

- Data Rate: Capable of up to 3 Mbaud for serial communication, with a baud rate generator allowing non-standard rates via internal prescaler adjustments.

- Integrated EEPROM: Stores device descriptors, VID, PID, and custom configurations for the CBUS pins​(FT232R).

FT232RL Key Functional:

- USB Protocol Engine: Manages USB control endpoint data flow and low-level protocol requests from the host.

- UART Controller: Converts data between USB and UART formats, with support for signal inversion and a configurable drive strength to interface efficiently with various UART levels.

The baud rate equation for the FT232RL is calculated using:

Baud Rate = 3,000,000 / 𝑛 + 𝑥

where n is an integer between 2 to 16,384 and x a fractional divisor (0, 0.125, etc.), giving a wide range of achievable baud rates from 183.1 baud to 3,000,000 baud​.

Implementation Design

The FT232RL chip serves as the primary USB interface in the USB Control Unit (UCU), facilitating bidirectional data communication between a PC and an embedded system by converting USB signals to UART protocol.

1. USB Data Lines (USBDP, USBDM): The differential data lines, D+ (USBDP) and D- (USBDM), are directly connected to the USB port. These lines manage data transmission to and from the PC, enabling communication via USB.

2. Power Supply (VCCIO): VCCIO pin supplies the logic level for UART and CBUS pins, configured to either 3.3V or 5V depending on the MCU’s interfacing requirements. This ensures the chip communicates at the proper voltage level.

3. UART Interface Pins (TXD, RXD): The TXD (Transmit) and RXD (Receive) pins handle serial data exchange with the ATmega128-16AU, providing full-duplex communication capability.

4. CBUS I/O Pins (CBUS0-4): Configurable through the integrated EEPROM, CBUS pins can be assigned to auxiliary functions like TX and RX LED indicators or used as general-purpose I/O pins.

5. EEPROM: The FT232RL’s internal EEPROM holds USB descriptors (e.g., Vendor ID and Product ID) and the configuration settings for CBUS pins, allowing easy customization and integration with USB host systems.

6. PCB Layout and Design Considerations:

- USB and Power Routing: The D+ and D- lines are routed as differential pairs with controlled impedance to maintain signal integrity. Power traces are designed short and wide to handle current demands efficiently.

- LED Indicator Circuit: LEDs, each with a 330-ohm resistor (R33 for RX, R34 for TX), indicate the operational status of data transmission, providing a visual check for communication activity.

- The VBUS signal is directly connected to 2OE (Pin 4) of the multiplexer (Z2).

7. Connector Configuration:

- USB Connector: The USB-B connector interfaces with the PC, allowing standard USB connectivity.

Below is the Schematic and PCB diagram showing the connection of the USB Control Unit (UCU):

A diagram of a computer

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A computer circuit board with many wires

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Fig. 2a The schematic diagram of the USB Control Unit (UCU)

Fig. 2b The Printed Circuit Board (PCB) of the USB Control Unit (UCU)

Motor Driver Unit (MDU)

The Motor Driver Unit (MDU) uses the L6205 full-bridge motor driver IC, designed for driving DC motors efficiently while ensuring reliability and robust protection. The L6205 supports a dual full-bridge configuration, making it ideal for driving two independent DC motors. With built-in features like overcurrent protection, thermal shutdown, and undervoltage lockout, the MDU ensures safe and stable operation for embedded motor control systems.

Features of the MDU

* Dual Full-Bridge Motor Driver: Supports two independent motors with separate control signals.
* High Voltage and Current Capability:

i. Supply Voltage (VSA/VSB): Up to 52V.

ii. Output Current (IOUT): 2.8A RMS per channel.

* Integrated Protection Mechanisms:

i. Overcurrent Protection: Prevents damage due to motor stall or excessive load.

ii. Thermal Shutdown: Disables operation when IC temperature exceeds the threshold.

iii. Undervoltage Lockout: Ensures the motor operates only within safe voltage levels.

* Low RDS(on): MOSFET switches integrated into the driver reduce heat dissipation.

Circuit Implementation and Connections

The MDU design consists of two identical motor driver circuits, each built around an L6205 IC. The following sections describe the critical components and their functions:

1. Input Power Supply

i. Voltage Source (VS): The motors are powered by a 12V DC input.

ii. Capacitors (C13, C14, C15, C16):

- 100 µF capacitors filter noise and smooth voltage input.

- 220 nF bootstrap capacitor (CBOOT): Ensures high-side MOSFETs can switch correctly.

2. Control and Logic Inputs

i. Enable Pins (EN\_A, EN\_B): Used to enable or disable each motor. Controlled by microcontroller logic.

ii. Input Pins (IN1, IN2): Determine the motor's rotation direction based on logic levels:

- IN1 High, IN2 Low: Forward rotation.

- IN1 Low, IN2 High: Reverse rotation.

- Both Low: Motor brakes.

iii. Resistors (M\_RENA,B and M\_CENA,B): Pull-up and pull-down resistors stabilize input signals, minimizing noise.

3. Output Stage

i. The driver outputs (OUT1a, OUT2a, OUT1b, OUT2b) connect to the motor terminals via a 2-pin connector (J4, J5).

ii. Each channel provides a full-bridge output, allowing bidirectional control of motors.

4. Bootstrap Circuit

Diodes (1N4148): Fast recovery diodes ensure proper charging of the bootstrap capacitors during switching cycles.

5. Sensing and Protection

Sense Resistors (SENSE\_A, SENSE\_B): Connect to the ground for overcurrent sensing. These are crucial for triggering protective mechanisms within the IC.

Thermal Management and Power Dissipation

i. Thermal Shutdown: The L6205 has an internal thermal sensor that disables operation when the junction temperature exceeds safe limits.

ii. Power Dissipation (PD): Power dissipation for each channel can be calculated using:

PD = I2 × RDS (on) × Duty Cycle

With the low RDS (on) value of the L6205, power loss is minimal, enhancing efficiency and reducing the need for large heat sinks.

Performance Characteristics

* Efficiency: The low RDS(on) and optimized switching characteristics result in high efficiency across various loads.
* Current Control: Peak current control prevents overheating or motor damage during stall conditions.
* Motor Speed Control: Achieved through Pulse Width Modulation (PWM) applied to the enable pins, allowing smooth speed variations.

Implementation Benefits

The MDU, designed with the L6205 IC, provides the following advantages:

1. Compact Design: Integration of MOSFETs and protection features reduces the need for external components.
2. High Reliability: Built-in protections ensure long-term stability, even under demanding conditions.
3. Easy Integration: Compatibility with standard microcontrollers simplifies control logic implementation.

Below is the Schematic and PCB diagram showing the connection of the Motor Driver Unit (MDU):

A diagram of a computer circuit

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Fig. 3a The schematic diagram of the Motor Driver Unit (MDU)

A computer screen shot of a circuit board

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Fig. 3b The Printed Circuit Board (PCB) of the Motor Driver Unit (MDU)

Microcontroller Unit (MCU)

Micro-Controller Unit (MCU): The MCU is based on the ATmega128, a versatile and widely-used microcontroller from Atmel’s AVR family, known for its high performance and efficient power consumption. It operates on the Harvard architecture with a RISC-based instruction set, enabling efficient execution of embedded applications.

- Core Functionality: The ATmega128 serves as the central processing unit for the system, executing the programmed instructions to control connected sensors, peripherals, and communication modules.

- Integration with Peripherals: As evident in the provided schematic, the MCU interfaces with various components such as Ultrasonic sensors (CON1), a RPLidar (CON2), a Camera (CON3), an I2C LCD (CON4), and an ADC (CON5). These connections highlight the MCU's ability to manage multiple inputs and outputs effectively.

Key Features of the ATmega128 in This Design

1. High Pin Count and I/O Flexibility:

The ATmega128 features 53 programmable I/O lines, enabling connectivity with a wide range of devices. For example, in the schematic:

- PORTB, PORTC, and PORTD are used for communication with peripherals like the ultrasonic sensor and camera module.

- PORTF is leveraged for ADC operations, allowing analog signals to be processed digitally.

2. Communication Protocols:

The microcontroller supports several communication protocols, such as SPI, I2C, and USART:

i. SPI communication is used for high-speed data exchange such as with the OV2640 camera module.

ii. I2C is used to connect the I2C-based LCD for efficient data transfer with minimal pin usage.

iii. USART facilitates communication with the ESP32-WROOM-32D module for wireless data exchange.

To ensure proper functionality, careful pin management has been implemented. For instance, the PB1/SCK line is shared between the ISP header and the camera module, with programming only possible when the camera is inactive.

3. Analog and Digital Conversions:

Equipped with a 10-bit ADC (on PORTF pins), the ATmega128 can convert analog signals from sensors into digital data for processing.

4. Timers and PWM:

The ATmega128 includes four timers (8-bit and 16-bit) to handle tasks like event counting, signal generation, and control. PWM outputs are also used for applications requiring precise modulation, such as motor control.

5. Programming and Debugging:

An In-System Programming (ISP) header is connected to PB1-SCK, PB2-MISO, PB3-MOSI, and the RESET pin, enabling programming and debugging of the microcontroller during development.

6. Crystal Oscillator:

The design includes a 16 MHz crystal oscillator with 18 pF capacitors (C5 and C6), providing the clock signal necessary for stable MCU operation.

Detailed Component Connections

1.Power Supply Connections:

- The ATmega128 is powered by a stable 5V supply regulated by the LM2596T-5.0.

- AVCC powers the ADC module, and AREF sets the reference voltage for analog-to-digital conversions.

- Decoupling capacitors stabilize the power supply and filter noise for reliable operation.

2. Clock Signal:

A 16 MHz external crystal oscillator provides the clock source for the MCU, ensuring precise timing and synchronization of internal processes.

3. Peripheral Connections:

- Ultrasonic Sensor (CON1):

Connected to PORTD (PD0-PD7) for transmitting trigger signals and receiving echo pulses for distance measurement.

- Camera Module (CON3):

The OV2640 camera module is linked to PORTC (PC0-PC7) for transferring image data to the MCU. SPI is used for communication.

- LCD Module (CON4):

An I2C-based LCD is connected via SCL and SDA pins on PORTC, enabling simple and efficient data display.

- ADC Inputs (CON5):

Analog sensors are connected to PORTF (PF0-PF7) for conversion of analog signals to digital data.

4. Wireless Communication Module (ESP32-WROOM-32D):

The MCU communicates with the ESP32 module via the USART interface on PD0 (TXD) and PD1 (RXD), enabling wireless communication over Wi-Fi.

5. Multiplexer:

The design utilizes two multiplexers (Z1 and Z2) for UART switching on the ATmega128.

Z1 connects CON2 (RPLidar) and the ISP to UART1 (PD2/PD3), controlled by the RESET signal. When RESET is HIGH, the ISP connects to UART1; when LOW, RPLidar is active.

Z2 handles UART0 (PE0/PE1), switching between the ESP32 and USB (FT232RL), controlled by the USB’s VBUS signal. When VBUS is HIGH, USB is active; when LOW, the ESP32 is connected. Pull-down resistors ensure stable signal transitions. This configuration enables automatic peripheral switching, optimizing UART usage without manual intervention.

6. ISP Programming Header (CON6):

Provides access to SPI pins (PB1-SCK, PB2-MISO, PB3-MOSI) and the RESET line for programming and debugging.

7. Status Indicator:

A status LED is connected to one of the I/O pins through a resistor, offering visual feedback about the system's operational status.

Below is the Schematic and PCB diagram showing the connection of the Motor Driver Unit (MDU):

A diagram of a computer

Description automatically generated

Fig. 4a The schematic diagram of the Microcontroller Unit (MCU)

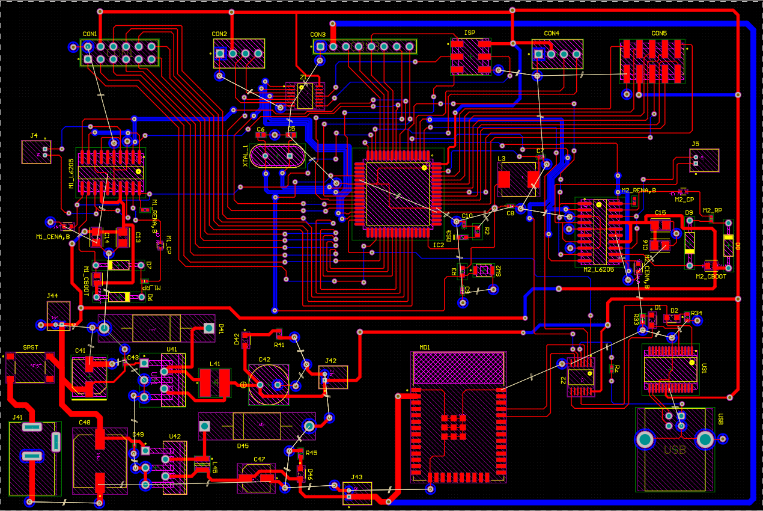


Fig. 4b The Printed Circuit Board (PCB) of the whole connection to the Microcontroller Unit (MCU)

1. Results/ Experiments:

This section presents the outcomes and insights derived from the design and implementation of the embedded control system for an autonomous cleaning robot. Utilizing Altium Designer’s Design Rule Check (DRC), the schematic and PCB designs for critical subsystems were meticulously developed and rigorously validated. These results are supported by detailed analyses, 3D renderings, and rule-checking to ensure compliance with professional and industry standards.

The DRC was performed based on the following rule categories:

* Electrical
* Routing
* Surface-Mount Technology (SMT)
* Manufacturing
* High-Speed Design
* Placement

Upon executing the DRC, the Verification Report indicated that all circuit connections were correctly established with zero warnings. The only rule violation identified was related to the Silk to Solder Mask clearance.

The Silk to Solder Mask rule pertains to the required spacing between the silkscreen layer and the solder mask layer on the PCB. The identified violation occurred because the clearance did not meet the 10-mil threshold between the silkscreen and pad areas. This issue arises from the specific components and their placement on the PCB, as their designs do not fully conform to Altium’s default design rules. However, the violation does not compromise the general electrical functionality of the circuit and can therefore be safely disregarded in this context. The Altium Designer Design Rule Verification Report can be found in the link in the Appendices section below.

After performing the DRC, the PCB was properly grounded using the Polygon Pour. The Polygon Pour is referred to as the large area on a printed circuit board (PCB) that is filled with copper. It is often used for grounding, power distribution, or thermal management.

The polygon pours are typically categorized into: Solid and Hatched.

Solid Pour: A solid pour fills the entire defined area with a continuous layer of copper.

Hatched pour: It uses a grid or mesh-like pattern of copper to fill the area, leaving spaces between the copper lines.

In this design, a hatched polygon pour is applied to the bottom layer to connect all components to the ground (GND) net. The hatched pour effectively serves two critical functions:

- Heat Dissipation: The hatched pattern aids in spreading heat generated by components, minimizing the risk of overheating.

- Cost Efficiency: By reducing the amount of copper used compared to a solid pour, the design maintains cost-effectiveness while fulfilling thermal and grounding requirements.

The hatched pour ensures mechanical flexibility, making it suitable for applications where stress and bending may occur. This approach reflects a balanced consideration of performance, cost, and reliability.

Below show the full PCB circuit below:

A blue circuit board with red and blue lines

Description automatically generated

Fig. 5a 2d PCB Layout mode

A computer chip with many components

Description automatically generated

Fig. 5b 3d PCB Layout mode

1. Conclusions

This project successfully developed a robust electronic control system for an autonomous cleaning robot, integrating a Power Supply Unit (PSU), USB Control Unit (UCU), Microcontroller Unit (MCU), and Motor Driver Unit (MDU). This design adheres to professional and industry standards using Altium Designer for schematic and PCB layout development. The key results highlight:

* Efficient Power Management: The PSU efficiently converts a 12V input to stable 5V and 3.3V outputs, ensuring minimal ripple and optimized thermal management.
* Reliable Control System: The MCU based architecture effectively will manage the robot's cleaning functions, including navigation, obstacle avoidance, and recharging.
* Motor Driver Optimization: The MDU, based on the L6205 IC, provides smooth, bidirectional motor control with integrated overcurrent and thermal protection.
* Seamless Communication: The UCU's USB-to-Serial interface facilitates efficient data exchange between the robot and external systems.

The experimental results validated the functionality of these subsystems, ensuring seamless integration for effective robot operation.

Contributions

The design introduces several innovations that enhance functionality and efficiency.

- Power Management Optimization: The PSU uses a hatched polygon pour for grounding, providing improved heat dissipation and cost-effective thermal management.

- Enhanced Motor Control: The L6205 IC optimizes motor driver performance, ensuring smooth, reliable operations under various conditions.

- Integration of Multiplexers: The multiplexers (Z1, Z2) dynamically manage UART interfaces, allowing seamless switching between devices like the ESP32, USB, and RPLidar. This reduces hardware complexity, simplifies microcontroller pin allocation, and enables simultaneous multi-device communication without manual reconfiguration.

- ESP32 for Wireless Connectivity: The ESP32 module facilitates remote operation and real-time monitoring via Wi-Fi. It gives room for support of IoT functionalities such as scheduling, cloud data storage, and voice assistant integration, offering a powerful, cost-effective connectivity solution.

These innovations emphasize modularity, adaptability, and efficiency, setting a new standard for robotic cleaning system design and enhancing user convenience.

Future Developments

To enhance the electronic control system of the autonomous cleaning robot, several advancements are proposed:

- Heat Dissipation: Integrating a small, energy-efficient cooling fan or heat sinks on the PSU and Motor Driver Unit will mitigate heat buildup, ensuring consistent thermal performance during prolonged use.

- Power Management: Adaptive power management, including dynamic voltage scaling, can optimize energy usage based on workload, while a backup power mechanism (e.g., supercapacitor) ensures reliability during power transitions.

- Motor Control: Adding current-sensing circuits for dynamic load adjustments and upgrading to brushless DC motors will increase energy efficiency and durability.

- Diagnostics: Real-time power monitoring and status indicators for key subsystems will simplify maintenance and improve user feedback.

These developments aim to enhance reliability, energy efficiency, and scalability for future applications.

Overall Impact

The project demonstrates how an efficient, scalable control system can enhance the functionality and reliability of autonomous cleaning robots, contributing significantly to the field of household and industrial automation.

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Appendices

Mechatronics Files: [Mechatronics](https://testlivesalfordac-my.sharepoint.com/:f:/r/personal/i_e_oke_edu_salford_ac_uk/Documents/Mechatronics?csf=1&web=1&e=piFIP0)