ECE 445

SENIOR DESIGN LABORATORY

FINAL REPORT

Automated guided vehicle for cargo delivery in factories

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May 18, 2025

Abstract

Cargo delivery in large factories faces challenges such as low efficiency and safety risks associated with manual labor. To address these issues, we design an automated guided vehicle (AGV) to reduce labor costs and improve safety in the delivery process. Our AGV system comprises the following components: a navigation system, an obstacle avoidance system, a communication subsystem, and a mechanical and electrical control system.

Contents

1 Introduction

1.1 Problem

Cargo delivery in large factories has long been a problem due to the low efficiency, restricted working period, and high safety risks caused by manual labor. Human-operated systems, such as forklifts, often results in delays, errors, and accidents, as evaluated by injuries linked to forklifts in the U.S[1]. Human-operated vehicles or manual transport methods often result in delays, errors, and inconsistent performance, especially in complex factory surroundings. Workers' working hours are limited and therefore cannot maintain a 24/7 operation. Additionally, heavy machinery, narrow transporting channels, and dynamic obstacles increase the risk of accidents and injuries. To solve these problems, factory owners and researchers want to design a kind of automated guided vehicle that performs better than manual labor. These challenges call for the rising demand of automated guided vehicles (AGVs), which will eliminate human error, reduce labor costs by 20–30% [2], and operate continuously day and night.

1.2 Solution

An automated guided vehicle needs to be designed and assembled. The vehicle needs to deliver cargo within a large factory. The vehicle needs to be equipped with a control/navigation and obstacle avoidance system. This system ensures that the vehicle can move to the ordered destination by itself safely. Moreover, the vehicle needs to lift goods weighted at least 10kg. This AGV frees workers from moving the goods from point to point, and the only job they need to do is to place the goods in the correct position when the AGV reaches its destination. To accomplish these functions, five parts will be built and assembled onto a manual forklift to transform the cart into an AGV. The main system is a Raspberry Pi, serving as a core processor of any signals. Users can access the AGV from a distance, and the order assigned by the user will be transferred to the main system through the instruction subsystem, which contains database to provide the user with the available positions the AGV can go to. Once the AGV is in motion, another two subsystems will start functioning. The navigation subsystem employs laser radar and SLAM reconstruction positioning to navigate the route, and the obstacle avoidance subsystem uses ultrasonic sensor to detect any possible obstacles and give instant signal to avoid them. These subsystems communicate with the main system, and after processing, the Raspberry Pi will send signals to the mechanical and electrical subsystems to adjust the power supply of each motion part, controlling the motion of the cart.

1.3 Visual Aid

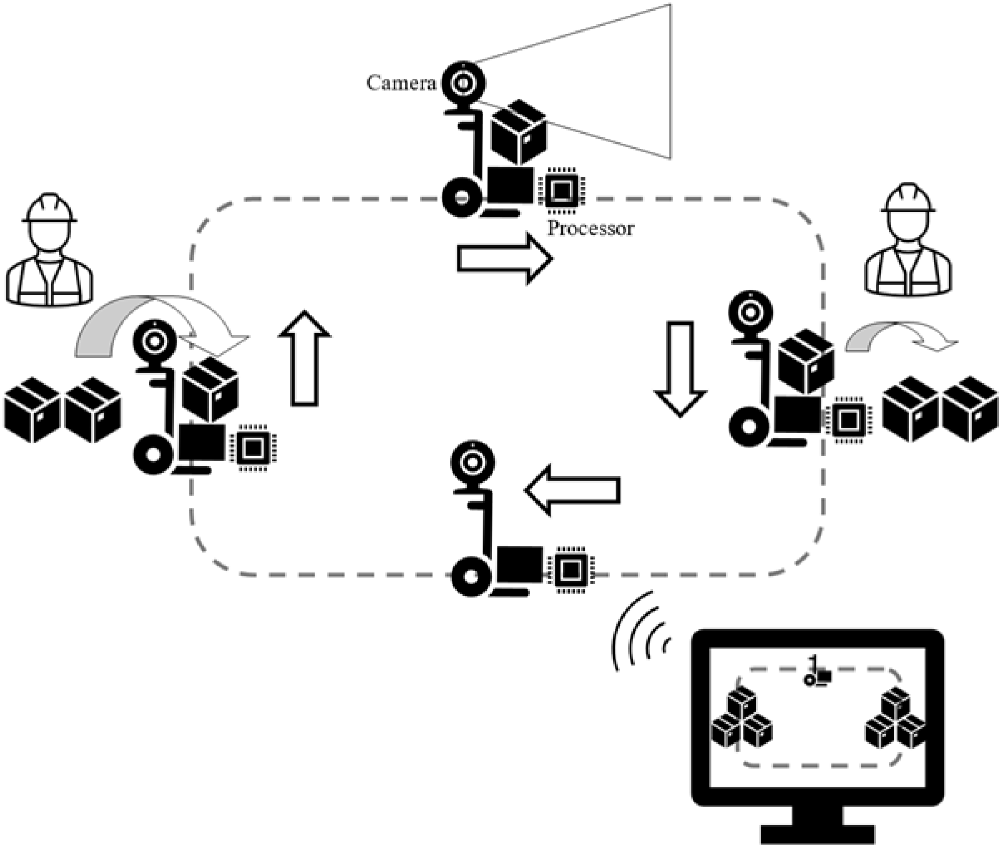
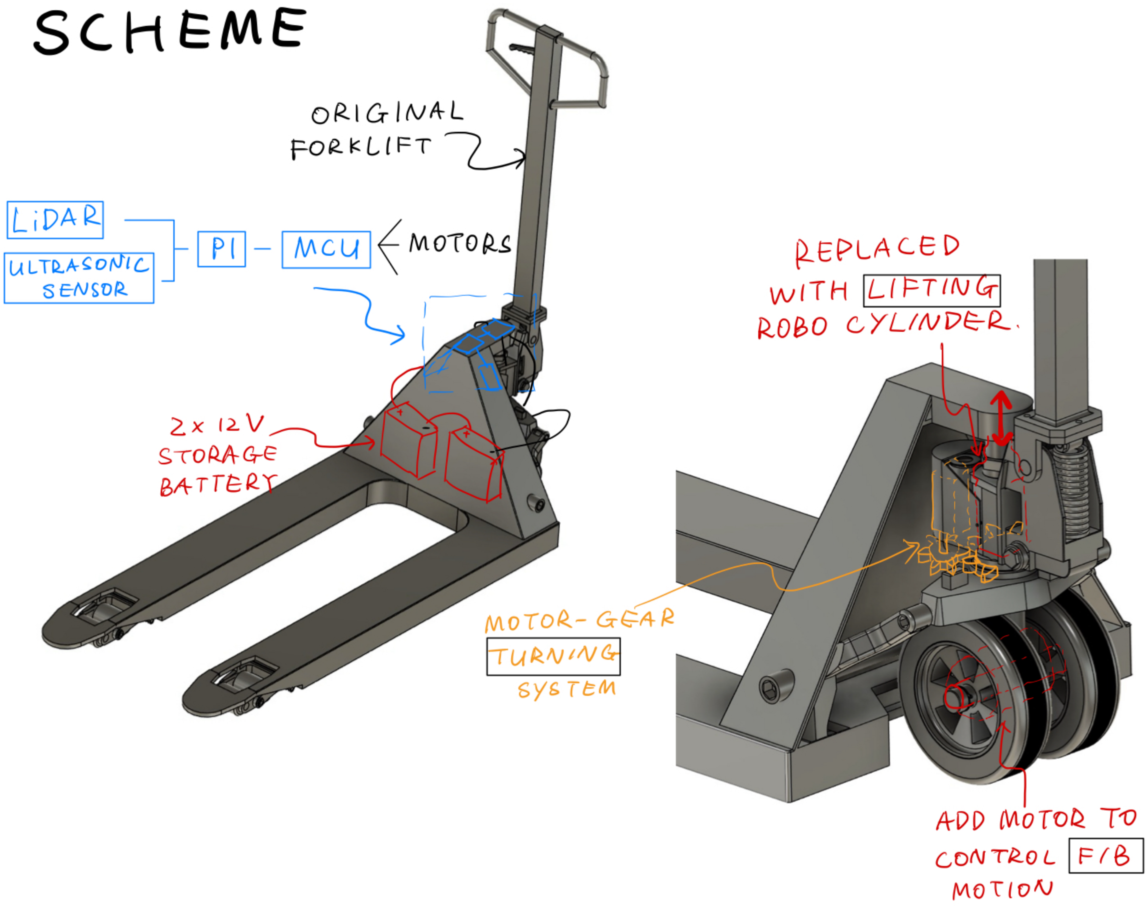


Figure 1: AGV System Overview

The application scenarios and functionality of our AGV are illustrated in Figure 1. In factory environments requiring cargo transportation, the AGV can be deployed to reduce manual labor and minimize workforce requirements. When a cargo transportation task is initiated, the computer sends a command to the AGV, prompting it to follow a route generated by the AGV's main system.



SCHEME
ORIGINAL FORKLIFT
LiDAR
ULTRASONIC SENSOR
PI
MCU
MOTORS
2x 12V STORAGE BATTERY
REPLACED WITH LIFTING ROBO CYLINDER.
MOTOR-GEAR TURNING SYSTEM
ADD MOTOR TO CONTROL F/B MOTION

Figure 2: AGV Scheme

The design schematic of our redesigned forklift is shown in Figure 2. For mechanical modifications, three motors were added to automate motions such as moving, turning, and lifting, which previously required manual operation. A gearbox was also installed adjacent to the turning shaft to transmit motion. All motors are powered by two 12V rechargeable batteries.

1.4 High-level requirements list

- The AGV should move along the route generated by itself from the start point to the destination.
- The communication system should be able to subscribe the navigation topic and transfer the high-level data to motor data and send it to the mechanical system.
- While moving, the AGV must continuously scan for obstacles and stop immediately if one is detected.

- The mechanical system should provide smooth motion, which means that the motion transmission and change should be continuously processed without interruption by the mechanism itself.
- When handling cargo, the AGV must properly align its fork before lifting or lowering the load.

2 Design

2.1 Block Diagram

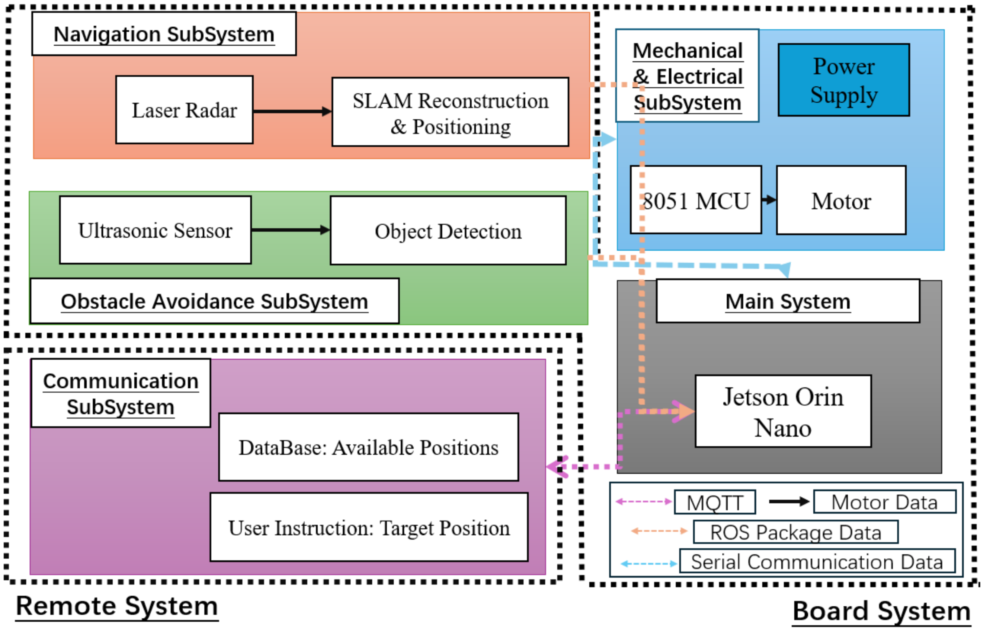


Figure 3: AGV System Block Diagram

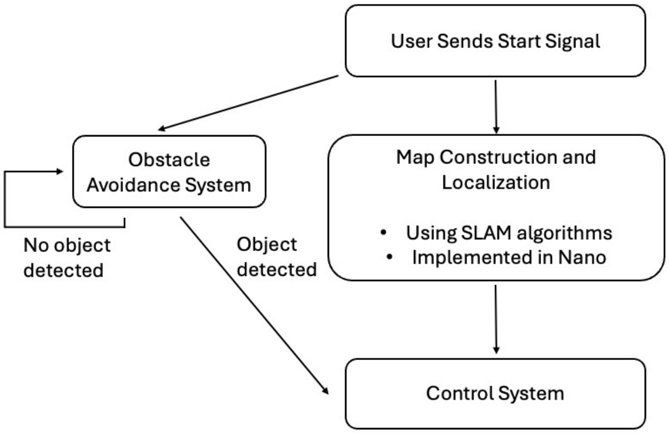


Figure 4: AGV System Overview

2.2 Subsystem Overview

The AGV consists of four modular interconnected subsystems (as shown in Figure 3): Navigation Subsystem, Obstacle Avoidance Subsystem, Communication Subsystem and

Mechanical Electrical Subsystem. Each subsystem is essential to ensuring the AGV operates efficiently, safely, and autonomously within the factory environment. Together, these subsystems work in harmony to create an AGV capable of reliable and efficient cargo transport.

2.2.1 Navigation Subsystem

The SLAM (Simultaneous Localization and Mapping) [3] algorithm is responsible for constructing a real-time map of the factory environment while simultaneously tracking the vehicle's position within it. It integrates data from the laser radar to estimate the vehicle's position and update the environmental map. This subsystem provides critical spatial information for path planning. By maintaining accurate localization, it ensures the forklift operates autonomously in the factory scenarios. When it is close enough to the target point (within the threshold), it will stop immediately. The workflow is shown in Figure 5.

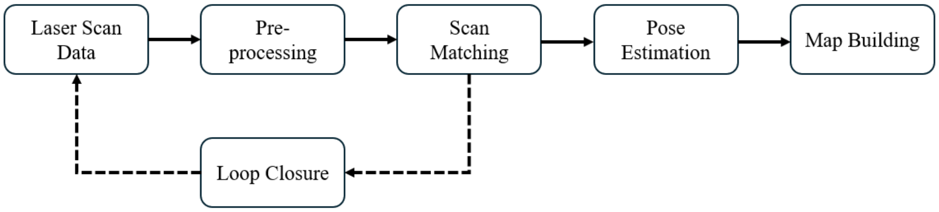


Figure 5: SLAM Scene Construction Block Diagram

2.2.2 Obstacle Avoidance Subsystem

The obstacle avoidance subsystem ensures that the AGV can safely navigate through the factory environment by detecting both static and dynamic obstacles in real time. It employs three ultrasonic sensors mounted at the front, front-left, and front-right of the vehicle. These sensors continuously emit high-frequency sound waves and listen for echoes to determine whether there are nearby obstacles.

The distance to an object is calculated using the time-of-flight principle and the speed of sound at room temperature (assumed to be 20°C). The following formula is used to compute the distance:

$$d = \frac{v \cdot \Delta t}{2} \tag{1}$$

where $v = 331.5 + 0.6T$ (in m/s) is the speed of sound at temperature $T = 20°C$, and Δt is the measured round-trip time. Substituting $T = 20$, we obtain $v = 343\,\text{m/s}$ or equivalently $0.0343\,\text{cm}/\mu s$, resulting in:

$$d \approx 0.0343 \cdot \Delta t \,\text{(in cm)} \tag{2}$$

The detection logic considers a threshold: 200 cm. If any reading falls below this threshold, the system immediately sends a stop signal to the AGV controller. This mechanism allows the vehicle to halt before a collision occurs.

A known limitation of ultrasonic sensors is their dependence on receiving a reflected echo. In certain conditions, such as irregular surfaces or high-absorption materials, the sensor may not receive a valid echo. To handle such cases, the system includes a timeout mechanism. If no echo is detected within a predefined time window, the sensor returns a ‘None‘ value, and the system conservatively assumes the path is clear. This design choice favors avoiding false positives that could disrupt AGV movement due to phantom obstacles.

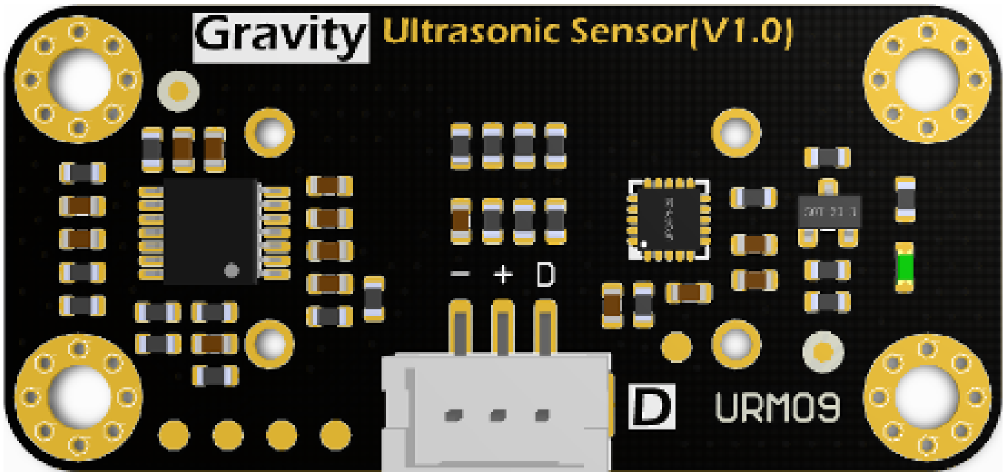


Figure 6: Ultrasonic sensor

2.2.3 Communication Subsystem

The Communication Subsystem is responsible for managing both external and internal communication related to AGV task execution. It enables data exchange between the AGV and the control center. The overall structure is illustrated in Figure 8.

The external communication is built upon the Message Queuing Telemetry Transport (MQTT) protocol [4], a lightweight and efficient publish-subscribe messaging system. An MQTT broker receives all messages from clients and routes them to subscribers. The control server, connected to the broker, maintains a lightweight SQLite database that stores relevant metadata—such as the status of cargo shelves. When a user issues a delivery command through the control interface, the server publishes a start signal to the broker. The AGV, subscribed to the relevant topic, receives this message and initiates the corresponding delivery task by navigating to the specified destination.

The internal communication layer is designed to ensure integration between the AGV's functional modules. The main control program receives data from both the navigation and obstacle avoidance subsystems. Operating at a control frequency of 100 Hz, the main loop receives updates including linear and angular velocities from the navigation system. These inputs are parsed and processed into motion commands such as forward, left, right, or stop, which are then encoded in hexadecimal format. The encoded commands are transmitted via the ttyTHS0 serial interface to the lower-level motion controller.

This communication architecture ensures low-latency real-time feedback within the AGV. Although the current system only performs basic verification of MQTT communication and database access, the communication framework is designed to support future extensions involving more sophisticated external systems such as databases, brokers, and user interfaces. It forms a critical foundation for safe, flexible, and autonomous AGV operation in dynamic industrial environments.

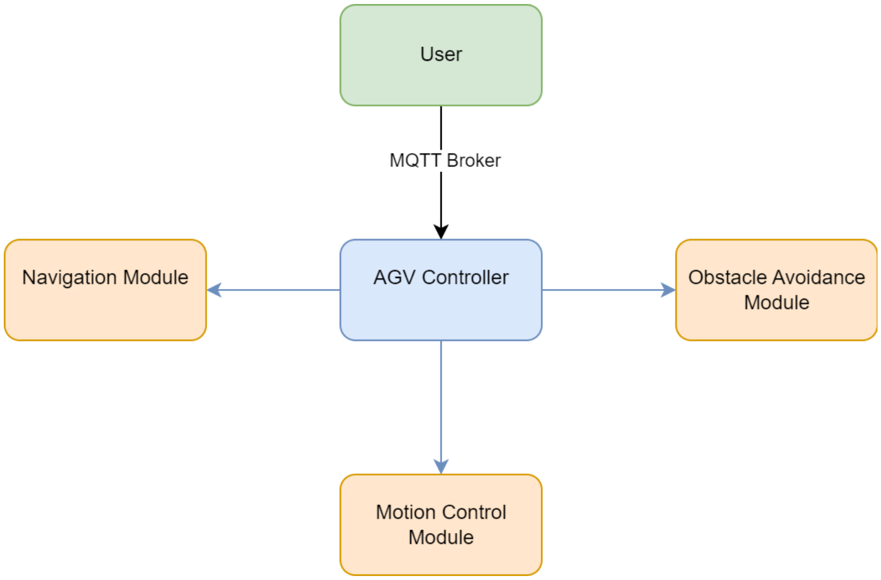


Figure 7: AGV Communication System

2.2.4 Mechanical & Electrical Subsystem

The mechanical and electrical subsystem incorporates three electrical motors, controlling the motion of lifting, turning, and accelerating. The three motors are connected to an STC89C52-RC microcontroller, sharing signals from the main system. Digital and analog signals are transferred and assigned to each of these motors, controlling the motion of the AGV to accomplish the order given by the user or the algorithm in the processor. Detailed schematic diagram is shown in Figure 8.

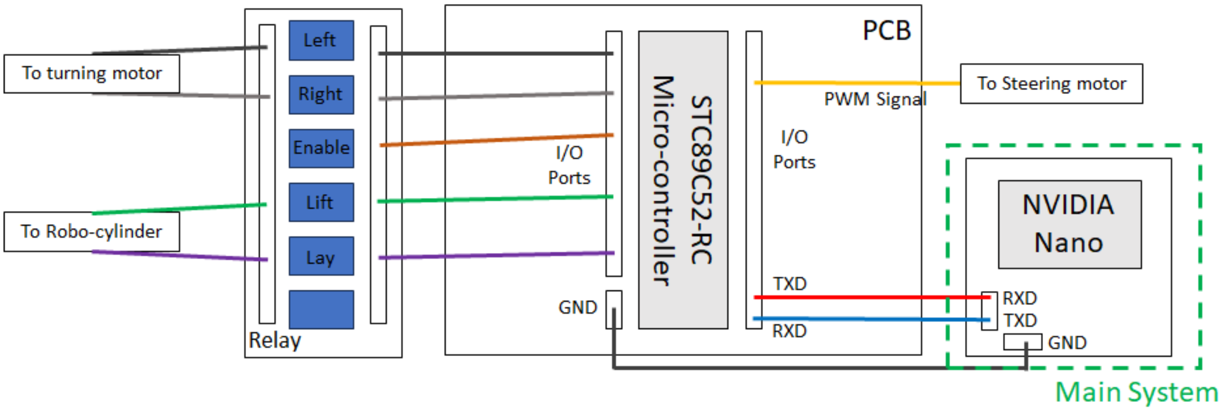


Figure 8: Electric control subsystem scheme

2.3 Subsystem Requirements and Verification

2.3.1 Navigation SubSystem

The navigation subsystem must generate a real-time map with an accuracy of ±10 cm and maintain localization drift under 2% over a 10-meter trajectory. It must process data from laser radar with a refresh rate of at least 10 Hz to ensure efficient responsiveness and store the data locally. The subsystem will provide continuous position updates and map data for route planning. If the system fails to maintain accurate localization and map updates, the vehicle will not be able to navigate autonomously within the factory.

Requirement	**Verification Method**
The SLAM system must be able to build a map of a 5m × 10m indoor environment within 5 minutes, with localization accuracy within ±10 cm at 5 test points.	A. Place the robot in a known 5 m × 10 m indoor area with measured reference points. B. Start the SLAM system and allow it to build the map. C. Export the map and compare key landmarks to ground truth. D. Move the robot to 5 reference points and compare estimated position with ground truth.
The robot must complete autonomous navigation to several random target points on the pre-built map with a 90% success rate, and must detect and avoid static obstacles with 90% success rate.	A. Set 5 navigation goals and let the robot follow planned paths; log success/failure and arrival accuracy for 20 total runs. B. Place static obstacles along the path in at least 10 trials. C. Verify that successful arrivals 90% and obstacle avoidance success 90% in all applicable trials.
Translate high-level velocity commands into motor control actions	Verify the mapping by commanding turns for specific durations and measuring the actual angular change, ensuring it matches the predicted values within an acceptable tolerance.

2.3.2 Obstacle Avoidance Subsystem

The Obstacle Avoidance Subsystem is responsible for detecting and avoiding both static and dynamic obstacles to ensure safe AGV operation. It continuously scans the surroundings using multiple ultrasonic sensors, which emit high-frequency sound waves and measure the time taken for echoes to return, allowing precise distance estimation. This data is processed to identify obstacles and determine their location relative to the AGV. Requirement 1: The system must detect obstacles within a minimum range of 3 meters Requirement 2: The Obstacle Avoidance Subsystem interfaces with the Mechanical Electrical Subsystem by transmitting stop signals when an obstacle is detected within a 200 cm range.

Requirement	Verification Method
1. Ultrasonic Sensor can operate properly. 2. Ultrasonic Sensor can communicate with the control system properly.	1. Place known obstacles at distances of 10, 20, ..., 100 cm and compare sensor readings. 2. Connect the ultrasonic sensor to GPIO pins of the Raspberry Pi and verify signal and echo reception.

2.3.3 Communication SubSystem

The communication subsystem ensures the data exchange between the AGV and the control center. When a cargo needs to be transferred to its final destination, the control center sends an instruction to the AGV to ensure that it first moves to the starting point, and then proceeds to the final destination and the correct cargo shelf. MQTT is used as the communication protocol between the AGV and the control center. It is a lightweight and low-consumption protocol. Its Quality of Service guarantees reliable message delivery, making it suitable for the AGV system.

Requirement	Verification Method
The communication system should enable the information flow between the vehicle and the central control. This module makes use of an MQTT broker to transfer information.	1. Input a command in the central control system on the computer; the vehicle should receive the start signal and print the information out, which demonstrates its communication ability. 2. The main control logic of the vehicle should receive information from the SLAM algorithm and send a control signal to the control unit. This can be verified by checking whether the received values are correctly printed out in the main control logic.

2.3.4 Mechanical & Electrical SubSystem

The lifting motion's electrical motor, as well as the lifting plate's strength, should be able to provide a force that can at least lift goods of 10 kilograms. The turning part is designed to make a 90-degree turn within a 3 meters radius. The accelerating motor should provide a minimum operating speed of 1 m/s when unloaded, and 0.5 m/s when fully loaded.

Requirement	**Verification Method**
The motion motors should be controlled by the main control system, where signals from the upper computer (Nano) are received.	An STC89C52RC MCU is mounted on the AGV. It receives signals from the upper computer through serial communication, and then an 8-digit binary number will be received and used to determine which switch should be turned on. Forward/backward motion is controlled by a small steering engine, which uses PWM signals to set the rotation angles. Turning and lifting motions are controlled by a relay that serves as a switch to enable or disable the respective motion.
The automated guided vehicle should be powered by a stable power source that supports both the motion of motors and the power supply of MCUs.	Two storage batteries are connected in series to provide a 24 V DC voltage for both motors and MCUs. The large capacity of the storage batteries ensures constant and smooth operation for a long time.

2.4 Tolerance Analysis

A critical risk in using ultrasonic sensors for obstacle detection is measurement accuracy and response time, particularly in a dynamic factory environment where reflective surfaces, environmental noise, and sensor blind spots could affect performance. The system relies on three ultrasonic sensors positioned at the front, front-left, and front-right of the AGV to detect obstacles in multiple directions. This configuration allows the AGV to identify obstacles in its path and react accordingly by stopping when an object is detected within a 50 cm range. However, ultrasonic sensors may suffer from signal reflection and absorption issues, especially in environments with metallic surfaces or irregularly shaped objects. Reflections from highly smooth surfaces can cause false detections, while soft materials may absorb the sound waves, leading to undetected obstacles. Additionally, cross-interference between the three ultrasonic sensors could result in inaccurate readings, especially if they operate at similar frequencies.

To mitigate these risks:

- The sensors should operate at slightly different frequencies or incorporate sequential triggering to minimize interference.
- Signal filtering techniques, such as median filtering, should be implemented to discard outlier readings caused by reflections.
- The system should integrate redundant checks where an obstacle is only confirmed if detected by at least two consecutive reads within 50 ms to reduce false positives.

3 Cost and Schedule

3.1 Cost analysis

3.1.1 Labor Cost

For this project, we assume each team member is compensated at a rate of **$35/hour**, which aligns with typical internship or early career salaries for ECE graduates at the University of Illinois.

Each member works **15 hours/week** over **14 weeks**, and a multiplier of **2.5** is applied to account for meetings, documentation, testing, and project management.

$$\text{Cost}_{\text{individual}} = \$35\ /\text{hr} \times 15\ \text{hrs/week} \times 14\ \text{weeks} \times 2.5 = \textbf{\$18,375}$$

There are four members in the team, so:

$$\text{Total Labor Cost} = 18,375 \times 4 = \textbf{\$73,500}$$

Table 1: Personnel Cost Table

Name	**$/Hour**	**Hours/Week**	**Weeks #**	**Multiplier**	**Cost ($)**
Xuhong	35	15	14	2.5	18375
Qiqian	35	15	14	2.5	18375
Yuyi	35	15	14	2.5	18375
Zhengjie	35	15	14	2.5	18375
Total	35	60	14	2.5	**73500**

3.1.2 Manufacturing Prototype Costs

The following parts are used in our project and are critical to implementing the AGV control system, SLAM-based localization communication system and sensor feedback systems:

Table 2: Equipment Cost Table

Name	Description	Quantity	Price ($)	Cost ($)
NVidia Jetson Orin Nano	The CPU that is used for the whole system	1	273.97	273.97
RPLIDAR-C1	The laser radar that can be used for SLAM[3] algorithm	1	58.90	58.90
URM09-Trig	The ultrasonic sensors that can be used for obstacle detection	3	8.22	24.66
STC89C52 MCU development board	The MCU used in the main control system	2	10.96	21.92
DS3230 steering engine	The engine used to control the forward/backward motion	1	14.80	14.80

3.2 Schedule

As shown in Tables 3 and 4, we provide a detailed timetable showing when each step of the design will be completed by week. It also includes information about how the tasks are shared among team members.

Table 3: Weekly Schedule: Xuhong He and Qiqian Fu

Date	Xuhong He	Qiqian Fu
2/24/2025	Study ROS and set up the execution environment	Study the concept of ROS
3/3/2025	Study SLAM[3] algorithm and corresponding package	Study deep learning
3/10/2025	Set up the workspace of the whole project	Study concept of cloud point and relevant models
3/17/2025	Start programming on scene construction using SLAM[3]	Testing how well the laser radar perform using Point Pillar model
3/24/2025	Finish programming on scene construction part using the simulator.	Thinking of other ways to implement obstacle avoidance

3/31/2025	Finish programming on vehicle localization part using the simulator.	Study how ultrasonic sensor works
4/7/2025	Finish programming on route planning part using the simulator.	Writing the code for using ultrasonic sensor to test distance
4/14/2025	Use laser radar to test the scene construction functionality in the real scenario.	Test ultrasonic sensor on Raspberry Pi
4/21/2025	Test the functionality of localization in a real-world scenario.	Study how to run ROS code
4/28/2025	Integrate the whole SLAM system into the main function.	Integrate the obstacle avoidance logit to the whole system
5/5/2025	Test AGV system in real scenario	Mapping the relationship between angular velocity and turning time
5/12/2025	Prepare final demo	Prepare final demo

Table 4: Weekly Schedule: Yuyi Ao and Zhengjie Wang

Date	Yuyi Ao	Zhengjie Wang
2/24/2025	Study basic knowledge about ROS	Studying the mechanism of original forklift
3/3/2025	Set up workspace on Raspberry Pi	Set forklift 3D model in Autodesk Fusion
3/10/2025	Test MQTT system on computer	Prepare for motion connection remodel
3/17/2025	Connect Raspberry Pi to computer with SSH and start testing MQTT.	Set motion connection remodel to the forklift and test
3/24/2025	Finish programming the server-side and vehicle-side code for the communication system	Adjust motion connection remodel to the forklift and test
3/31/2025	Testing communication between the vehicle and computer	Install the MCU to the forklift and test basic functions
4/7/2025	Coding the main logic function framework of AGV.	Set the main control program to the MCU
4/14/2025	Coding for the function for information communication inside AGV: Gathering movement information in main logic function from SLAM algorithm.	Adjust the main control program of the MCU, with the adjustment of connection remodel part
4/21/2025	Coding for the function: Sending control signal in main logic function to control unit.	Combine the MCU with upper computer to test the control
4/28/2025	Integrate the whole communication system into the main function.	Integrate the whole communication system into the main function.
5/5/2025	Test AGV system in real scenario	Test AGV system in real scenario
5/12/2025	Prepare final demo	Prepare final demo

4 Ethics and Safety

The development and deployment of AGVs for industrial use may raise ethical and safety considerations.

4.1 Ethical Considerations

4.1.1 Public Welfare and Safety

Human safety has a higher importance than AGVs, especially in shared workspaces. This is most important during the whole development process, and should follow the IEEE Code of Ethics, and ACM Code of Ethics and Professional Conduct [5][6]. A breach could lead to accidents or harm due to system failures or inadequate collision avoidance. To avoid this, it is possible to implement safety mechanisms (e.g., LiDAR, emergency stop systems) and evaluate them through limit tests like accelerated scenario-based evaluation.

4.1.2 Data Privacy

AGVs' motion is partly based on collecting operational data (e.g., worker movements), and may have risks in violating privacy if mishandled. A possible solution can be aligning with the client and employer best interests principle [7] and to mitigate such risks by encrypting sensitive data and complying with GDPR or equivalent regulations.

4.2 Safety Standards and Regulatory Compliance

During development, it is significant to note the restrictions published by the local government. Some relative regulations are listed here. ISO 3691-4 specifies AGV safety requirements, including obstacle detection and emergency braking[8]. The National Electrical Safety Code (NESC) ensures safe electrical infrastructure for AGVs, particularly in high-risk environments [9]. ISO 34502 outlines scenario-based safety evaluations for autonomous systems[10].

4.3 Potential Safety Risks

Potential safety risks in this AGV development are mostly about the risk of physical harm, system failures, and environmental hazards. For instance, in the deployment of an autonomous mobile device, there is a significant risk of collisions with humans, particularly vulnerable people such as children and the old, leading to injuries. Similarly, in industrial environments, the use of AGVs may also cause collision risks due to sensor failures or algorithmic errors. Additionally, in high-temperature factory environments, such as those involving heat-treating furnaces, the lack of proper protective gear like heat-resistant gloves can lead to burns or other injuries.

4.4 Implementation Verification

All safety systems undergo validation through accelerated scenario testing that simulates edge cases including sensor failures, high-traffic environments, and extreme operating conditions. Compliance documentation includes ISO standard checklists, encryption audit logs, and training records that collectively demonstrate adherence to the highest safety standards throughout the product lifecycle. This comprehensive safety framework not only protects users and developers but also establishes a model for ethical AGV deployment in complex industrial settings.

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