ROBOTICS

Autonomous Mobile Robot for Warehouse Logistics

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Abstract

Warehouses move large volumes of goods between receiving, storage and dispatch areas. Manual trolleys and forklifts are slow, labour intensive and carry accident risk, while conveyors, automated guided vehicles (AGVs) and commercial autonomous mobile robots (AMRs) need fixed infrastructure or an investment that small warehouses cannot justify. This paper presents the design of a low-cost, remotely commanded mobile robot for load transport that protects itself with onboard obstacle sensing. An ESP32 controller receives movement commands (forward, reverse, left, right, stop and five speed levels) wirelessly from a mobile device, measures the distance ahead with an HC-SR04 ultrasonic sensor, and drives two DC geared motors through an L293D dual H-bridge driver. A three-zone safety rule allows normal driving at 40 cm or more, reduces speed and beeps between 20 cm and 40 cm, and stops the motors with a continuous buzzer and an LCD warning at 20 cm or less. The robot also stops automatically when no command is received for 1 s. Design calculations for a 2 kg payload on a 1.5 kg chassis give a speed of about 0.34 m/s, a required torque of about 0.46 kgf·cm against 1–2 kgf·cm available per motor, a stopping distance of about 6 cm against the 20 cm limit, and a continuous driving time of about 2.3 h. Prototype testing and measured results are planned as the next phase.

Keywords: Autonomous Mobile Robot; Warehouse Logistics; ESP32; Ultrasonic Obstacle Detection; L293D Motor Driver; Link-loss Failsafe; Load Transport; Wireless Control; Low-cost Automation

1 Introduction

1.1 Research context

Warehouses move large volumes of goods between receiving, storage and dispatch areas, and this internal transport is repetitive, time-consuming and a large share of handling cost. Manual trolleys and forklifts are flexible but slow, labour intensive and a source of accidents. Conveyors and automated guided vehicles (AGVs) reduce manual effort but need fixed infrastructure such as belts, magnetic tape or guide wires, which makes layout changes costly [1, 2].

Autonomous mobile robots (AMRs) carry their own sensors and controller and need no change to the building, so they are the natural step beyond fixed automation [3, 4]. Commercial AMR fleets, however, are costly, and small and medium warehouses need a simple, low-cost alternative. Low-cost microcontrollers with built-in wireless links, cheap ultrasonic range sensors and small motor drivers now make such a robot practical to build. The block diagram of the proposed robot is shown in Figure 1.

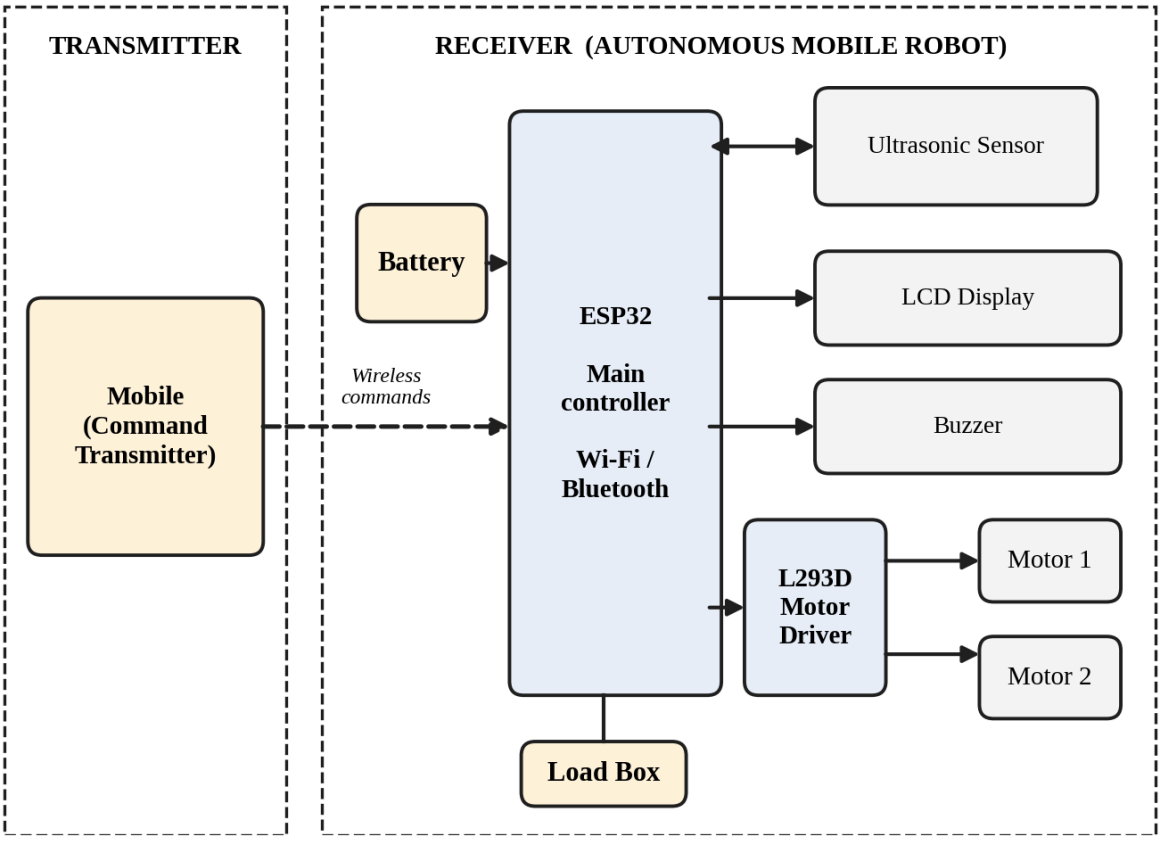


Figure 1. Block diagram of the proposed warehouse logistics robot (transmitter and receiver).

1.2 Problem statement

Conventional load transport in small warehouses depends heavily on manual labour for repetitive movement. The work carries a risk of collision with racks, pallets, people and equipment. Operators and supervisors get no real-time local feedback of the robot status or the distance to an obstacle. Commercial AGV and AMR systems answer these problems but at a high cost and with infrastructure needs.

A simple hobby robot is not a solution either, because it only follows commands: it keeps moving if the operator misjudges a distance or if the wireless link is lost. There is therefore a need for a remotely commanded robot that carries a load and protects itself with onboard obstacle sensing, audible and visible warnings, and automatic stopping.

1.3 Research gap

Table 1 summarises the existing approaches to load transport and their limitations.

Table 1. Existing approaches and limitations.

Approach	Advantages	Limitations
Manual trolley / forklift	Flexible, no investment	Slow, labour intensive, accident risk
Conveyor / AGV	Reliable, repeatable	Needs belts, tape or guide wires
Commercial AMR fleet	Navigates freely, scalable	High cost, complex set-up

Approach	Advantages	Limitations
Hobby remote robot	Low cost, simple	No self-protection; moves on if link is lost

Existing work addresses either large-scale fleet automation or simple remote-controlled vehicles. Few low-cost designs join remote commanding, load carrying, onboard obstacle override and a link-loss failsafe in one small platform, with local feedback on a display. The contribution of this work is the design of such a robot, with an analytical check of its drive, safety and battery parameters. The objectives are to:

- design an ESP32-controlled, battery-powered receiver robot;
- send movement commands wirelessly from a mobile device;
- detect obstacles in the path using an ultrasonic sensor;
- drive two DC motors through an L293D driver for forward, reverse and turning;
- show status and distance on an LCD and warn with a buzzer; and
- carry goods in a load box and evaluate safe load transport.

2 Literature survey

2.1 Warehouse automation

Material handling in warehouses has moved from manual carts to fixed automation and then to free-roaming vehicles. AGV systems follow guide wires, magnetic tape or similar fixed paths and are described in detail in the AGV literature [1], and surveys of AGV design and control cover layout, routing and dispatching [2]. Large mobile-robot fleets have been shown to work in warehouses at scale [4], but they are built for high-volume operations.

2.2 AMR planning and control

A review of AMR planning and control for intralogistics classifies the work on navigation, task allocation and fleet management [3], and a survey of AGV control algorithms covers the techniques used for guidance and motion control [5]. Textbook treatments of mobile robots describe locomotion, kinematics and sensing [6], which form the basis of the two-motor drive used here.

2.3 Ultrasonic obstacle detection

Ultrasonic range sensors are widely used on small robots because they are cheap and give distance directly from the echo time. Their limits are also well known: a wide beam, specular reflection from angled surfaces, and poor return from soft materials [7]. Distance-based stopping and slow-down rules are therefore common on low-cost platforms, with the limits of the sensor taken into account in the choice of thresholds.

2.4 Embedded platform and components

The ESP32 integrates a dual-core processor with Wi-Fi and Bluetooth on 3.3 V logic [8]. The HC-SR04 module measures distance from 2 cm to 400 cm using 40 kHz bursts [9], and the L293D is a dual H-bridge driver that can supply 600 mA per channel and accepts PWM for speed control [10].

2.5 Safety requirements

Safety standards for driverless industrial trucks require detection of obstacles and people and a safe stop [11]. These standards are written for full-size industrial vehicles, but the principle of detecting an obstacle and stopping before contact is applied here at a small scale.

2.6 Research gap analysis

The literature gives mature solutions for large AGV and AMR systems and well-documented components for small robots. What is missing is a documented low-cost design that combines remote commanding with a sensor-based override and a link-loss failsafe, together with a calculation of its drive and safety margins. The proposed robot addresses this gap.

3 Proposed system

The proposed robot has a transmitter side and a receiver side. The transmitter is a mobile device that sends movement commands. The receiver is the robot itself, built around an ESP32 DevKit with a battery, an ultrasonic sensor, an LCD, a buzzer, an L293D driver, two DC motors and a load box. The ESP32 overrides the operator's command whenever an obstacle is too close. The system has five functional layers.

3.1 Command layer

A mobile device acts as the command transmitter. It sends the commands F (forward), B (backward), L (left), R (right), S (stop) and a speed level from 1 to 5 over the wireless link (Bluetooth or Wi-Fi) of the ESP32.

3.2 Control layer

The ESP32 validates each received command, measures the obstacle distance in every cycle, decides whether to drive, slow down or stop, and updates the motors, LCD and buzzer. Safety decisions take priority over operator commands.

3.3 Sensing layer

An HC-SR04 ultrasonic sensor faces forward and measures the distance to the nearest object in the path. Its echo output is at 5 V and is reduced to the 3.3 V logic level of the ESP32 by a resistor divider.

3.4 Actuation layer

Two DC geared motors (6 V, about 100 RPM, 65 mm wheels) are driven through the L293D. Direction is set by the input pins IN1 to IN4 and speed by PWM on the enable pins. Turning is obtained by driving the two wheels in different directions or at different speeds.

3.5 Indication and Power layer

A 16×2 I2C LCD shows the current command, the measured distance and warnings. A buzzer, switched through a transistor, gives audible alerts. A 7.4 V, 2200 mAh 2S Li-ion battery supplies the system; a buck converter makes the 5 V logic rail, and the motors are fed from the battery through the L293D. The hardware components and their specifications are listed in Table 2.

Table 2. Hardware components and specifications.

Component	Role and key specification
ESP32 DevKit	Main controller; dual core, Bluetooth and Wi-Fi, 3.3 V logic
Battery	7.4 V, 2S Li-ion, 2200 mAh
HC-SR04 sensor	Distance 2 to 400 cm, 40 kHz, 5 V
16×2 LCD (I2C)	Shows command, distance and warnings
Buzzer	Audible alerts, driven through a transistor
L293D driver	Dual H-bridge, 600 mA per channel, PWM speed control
DC geared motors (2)	6 V, about 100 RPM, 65 mm wheels
Load box	Design payload 2 kg; chassis about 1.5 kg

4 System architecture

The architecture connects the mobile transmitter to the ESP32 receiver, which in turn connects to the sensor, display, buzzer and motor driver, as shown in Figure 1. The electrical interconnection and the power paths are shown in Figure 2.

4.1 Interconnection and Power

Each module has its own GPIO pins, listed in Table 3. The L293D direction inputs IN1 to IN4 use GPIO 26, 27, 32 and 33, and its PWM enable inputs use GPIO 25 and 13. The battery feeds a buck converter that gives the 5 V logic rail, the motor supply of the L293D is taken directly from the battery, and all modules share a common ground. Keeping the motor current away from the logic rail reduces the risk of controller resets when the motors start.

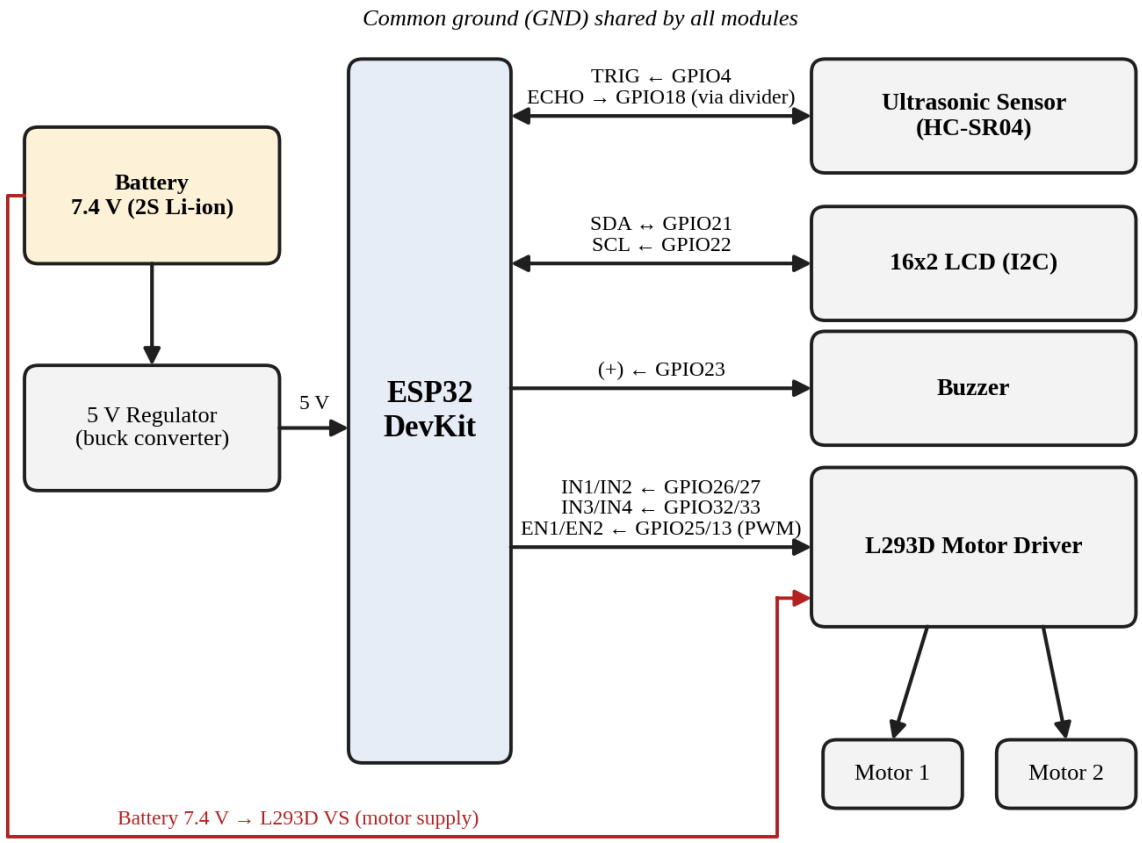


Figure 2. Interconnection and power distribution of the receiver robot.

Table 3. Pin assignment.

Module	Signal	ESP32 GPIO
HC-SR04	TRIG	4
HC-SR04	ECHO (via divider)	18
I2C LCD	SDA / SCL	21 / 22
Buzzer	Control (+)	23
L293D	IN1 / IN2	26 / 27
L293D	IN3 / IN4	32 / 33
L293D	EN1 / EN2 (PWM)	25 / 13

4.2 Operational workflow

The operational workflow is given in Figure 3 and runs as follows:

- On power-up the GPIO pins, LCD, sensor, driver and buzzer are initialised and the motors are kept stopped.
- The wireless link with the mobile device is established.
- A command is received and checked as valid (F, B, L, R, S or speed 1 to 5); invalid commands are ignored.
- The ultrasonic distance is measured in every cycle.

- The safety decision is made: stop, slow down or drive.
- The motors are driven through the L293D and the LCD is updated.

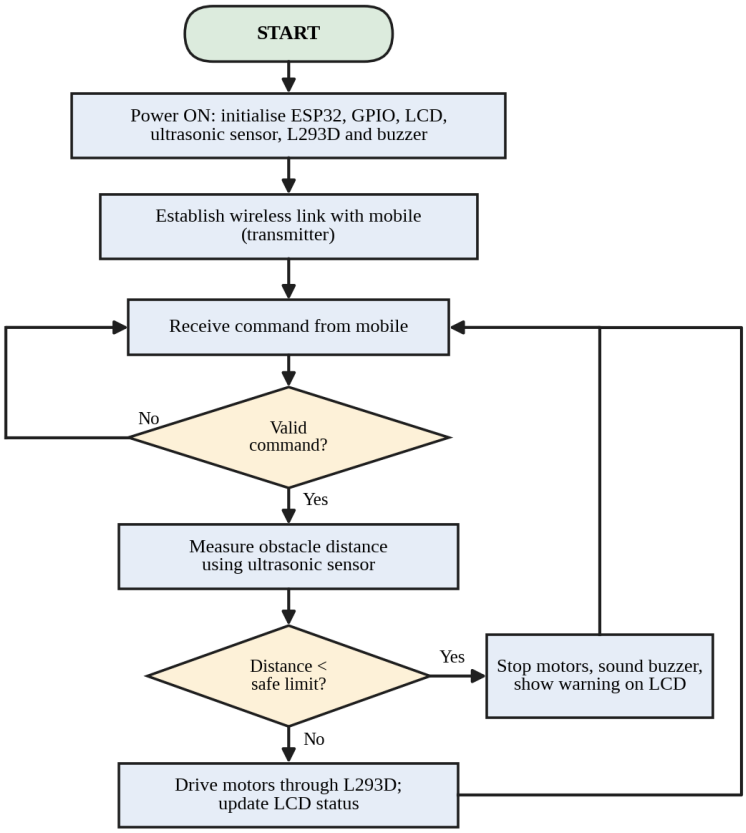


Figure 3. Operational workflow of the robot.

5 Methodology

5.1 Obstacle detection

$$d = \frac{t}{58}\left(\text{cm}\right) \tag{1}$$

@EQ

which is evaluated in every control cycle.

5.2 Three-zone safety rule

The measured distance selects one of three responses, summarised in Table 4 and shown as a loop in Figure 4. Above 40 cm the robot drives at the commanded speed. Between 20 cm and 40 cm it reduces the PWM speed and sounds an intermittent beep, which warns people nearby and gives the operator time to react. At 20 cm or less the motors are switched off, the buzzer sounds continuously and the LCD displays an obstacle warning.

Table 4. Obstacle detection and safety response.

Distance	Robot response
40 cm or more	Normal drive at the set speed
20 to 40 cm	Reduced speed, intermittent beep
20 cm or less	Motors off, continuous buzzer, LCD warning
No command for 1 s	Automatic stop (link-loss failsafe)

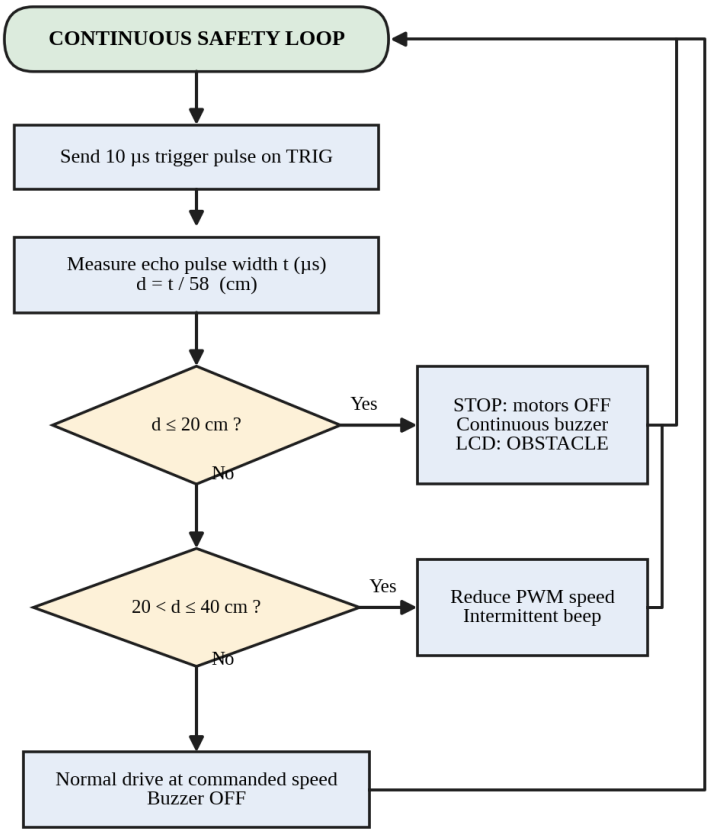


Figure 4. Continuous safety loop of the robot.

5.3 Link-loss failsafe

The controller expects commands from the mobile device at regular intervals. If no command is received for 1 s, the controller treats the link as lost and stops the motors. This prevents the robot from continuing to move after a wireless dropout or when the operator releases control.

5.4 Design calculation method

The mechanical and electrical parameters are checked by calculation before the prototype is built. The drive speed, motor torque, stopping distance and battery run time are calculated in Section 6 from the component specifications in Table 2.

6 Design analysis and results

The values in this section are calculated from the component ratings and the design assumptions and are summarised in Table 5. They are design values, not measurements, and will be compared with test results in Phase 2.

6.1 Robot speed

$$v = \frac{\pi D N}{60} \approx 0.34\text{m/s} \tag{2}$$

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6.2 Torque requirement

$$\tau = \frac{F \cdot r}{2} \approx 0.46\,\text{kgf} \cdot \text{cm} \tag{3}$$

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A typical geared motor of this class gives 1 to 2 kgf·cm, so the available torque is about 2.2 to 4.3 times the requirement. The margin covers floor friction, small slopes and starting torque.

6.3 Stopping distance

$$d_{\text{stop}} = v \cdot t_{\text{delay}} + \frac{v^2}{2a_{\text{b}}} \tag{4}$$

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At 0.34 m/s this is about 6 cm, which is well inside the 20 cm stop limit. The robot therefore halts about 14 cm before the obstacle even when the stop command is issued at the limit.

6.4 Battery run time

$$t_{\text{run}} = \frac{0.8C}{I} \approx 2.3\text{h} \tag{5}$$

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Table 5. Design analysis (calculated values).

Parameter	Value
Robot speed (65 mm wheel, 100 RPM)	about 0.34 m/s
Torque needed per motor (3.5 kg, 0.5 m/s^2)	about 0.46 kgf·cm
Motor capability (typical)	1 to 2 kgf·cm
Stopping distance at 0.34 m/s	about 6 cm (limit 20 cm)
Total battery current	about 0.76 A
Continuous driving time	about 2.3 hours

6.5 Discussion

The torque margin of more than two times shows that the selected motors can carry the 2 kg design payload with reserve. The stopping distance is about 30% of the 20 cm stop limit, so the limit leaves

room for sensor noise and for the tolerance of the ultrasonic reading. The warning zone from 20 cm to 40 cm lets the robot slow down before the stop zone is reached, and the run time of about 2.3 h covers a typical working session between charges. Table 6 compares the proposed robot with manual handling and a simple hobby robot.

Table 6. Comparison of approaches.

Parameter	Manual / hobby robot	Proposed robot
Load carrying	Manual effort / none	2 kg load box
Obstacle response	Operator only	Slow down, then automatic stop
Link loss	Keeps moving	Stops after 1 s
Local feedback	None	LCD distance and status, buzzer
Infrastructure	None	None

6.6 Limitations

The robot has a single front ultrasonic sensor, so the reverse direction and the sides are not protected. Ultrasonic sensing may miss soft or angled surfaces. The wireless range of the mobile link is limited. The values in Table 5 are calculated, and the voltage drop in the L293D output stage will lower the motor voltage, so the measured speed may be somewhat below 0.34 m/s. Wheel slip, floor type and payload placement are not modelled.

7 Experimental validation plan

The prototype will be tested in Phase 2 with the tests in Table 7. Each test records the measured value and compares it with the design value of Section 6.

Table 7. Phase 2 test plan.

Test	Purpose
Wireless link and motion commands	Check that every command gives the correct motion
Speed levels and load test (2 kg)	Measure speed at levels 1 to 5, with and without load
Obstacle stop and warning zone	Verify the 40 cm and 20 cm thresholds and the stopping distance
Link-loss failsafe	Confirm the stop after 1 s without a command
Battery run-time test	Measure continuous driving time against 2.3 h

8 Novelty and advantages

The novelty of this work lies in joining remote commanding, a distance-based speed and stop rule, a link-loss failsafe and local feedback in a low-cost ESP32 platform that needs no change to the building. The sensor decision overrides the operator command, so the robot protects itself and its surroundings even when the operator misjudges a distance.

The main advantages are low cost, no infrastructure, reduced manual effort for repetitive load transport, safer operation through obstacle stopping and the failsafe, and clear feedback through the

LCD and buzzer. The platform is suited to small and medium warehouses, stores and workshops, and can be extended with further sensors and navigation functions.

9 Conclusion and future work

This paper presented the design of a low-cost warehouse logistics robot. A complete architecture was developed from the block diagram: a mobile transmitter and an ESP32-based receiver with ultrasonic sensing, an LCD, a buzzer, an L293D driver, two motors and a load box. Calculations show a torque margin of more than two times for a 2 kg payload, a stopping distance of about 6 cm against a 20 cm stop limit, and about 2.3 h of driving. Obstacle stopping, speed reduction, warnings and the link-loss stop support safe use in a warehouse. The next step is to build the prototype and record measured results. Future work will focus on:

- rear and side ultrasonic sensors;
- wheel encoders for speed feedback;
- Wi-Fi control and monitoring;
- battery voltage display on the LCD; and
- path following between fixed points.

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