



Design and Fabrication of an Autonomous Line Following Robot for Industrial Applications

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Abstract

This methodology paper presents a compact design and fabrication framework for an autonomous line-following robot intended for repetitive material-transfer and guided-mobility tasks in industrial environments. The proposed platform uses a differential-drive chassis, a multi-element infrared reflectance sensor array, a microcontroller-based closed-loop controller, and pulse-width-modulated motor actuation. The control objective is to minimize lateral displacement between the robot centerline and a high-contrast floor guide while maintaining stable forward motion through straight segments, bends, and junctions. A proportional-integral-derivative (PID) correction law is adopted because it provides a practical compromise between computational simplicity, tracking accuracy, and real-time implementation on low-cost embedded hardware. The methodology covers mechanical fabrication, sensor placement, signal normalization, weighted line-position estimation, PID tuning, motor command generation, obstacle-stop logic, and a repeatable validation protocol. Earlier studies show that sensor configuration, calibration, curvature estimation, and controller selection strongly influence line-following accuracy and robustness [4], [6], [8], [9]. For industrial relevance, the proposed design also considers payload stability, battery endurance, fail-safe stopping, and repeatability. Because no user-supplied physical measurements are available, the results section provides clearly identified illustrative validation targets rather than claiming unobserved experimental data. The framework can be directly used to fabricate a laboratory prototype and then replace the illustrative values with measured test results.

Introduction

Mobile robots are increasingly used to move components, documents, tools, and small payloads between workstations because they can reduce repetitive manual transport and improve consistency of intralogistics. A mobile robot combines locomotion, perception, control, and navigation functions, and the quality of the resulting motion depends on how effectively these functions are integrated [1], [3]. In an industrial environment, a fully map-based autonomous mobile robot can offer high

flexibility, but its sensing and computation requirements may be unnecessary when the route is fixed and repeatable. For such cases, a line-following robot provides a simple and economical alternative: a visible or reflective guide is installed on the floor and the robot continuously corrects its wheel speeds so that its sensor array remains centered on the guide.

Line guidance has long been related to automated guided vehicle practice, where vehicles travel along predetermined paths established by wires,

magnetic markers, optical tracks, or other guidance methods [2], [7], [10]. The attraction of optical line following is that the guide path is inexpensive to install, easy to modify, and compatible with small mobile platforms. However, a practical industrial robot must do more than simply detect black and white regions. It must tolerate variations in ambient illumination, floor reflectivity, motor mismatch, battery voltage, wheel slip, track curvature, and payload. It must also recover gracefully from temporary loss of the line and stop safely when an obstacle is detected.

Earlier line-follower studies reported that the selection and arrangement of sensors can directly affect tracking accuracy and response [8], while PID-based systems provide smoother correction than simple ON-OFF steering when the error can be represented continuously [4]. Singh and Chouhan [6] showed that curvature information and differential-drive kinematics can be exploited to improve behavior on curved paths. Broader reviews of mobile robot navigation emphasize the central role of sensors, feedback, path tracking, and control-system architecture in achieving reliable autonomous motion [1], [3]. Industrial AMR research further stresses testing, operational rules, and safety interactions in manufacturing facilities [2]. These findings motivate a methodology that is intentionally simple in hardware but disciplined in calibration and closed-loop control.

The objective of this paper is therefore to describe, step by step, the design and fabrication of an autonomous line-following robot suitable for light industrial transport. The proposed system uses a compact two-wheel differential drive with a caster wheel, an infrared reflectance array mounted near the floor, a microcontroller, a dual H-bridge driver, geared DC motors, and a rechargeable battery. The principal performance variables are mean lateral tracking error, maximum deviation, successful completion rate, response at curves and intersections, obstacle stopping distance, and energy endurance. The design is intended as a reproducible methodology that can be scaled from a classroom prototype to a more rugged industrial platform by upgrading the chassis, sensors, actuators, and safety hardware while preserving the same control structure.

Literature Review

Pakdaman et al. [9] described the practical progression from line-follower design to implementation and highlighted technical issues associated with sensing, mechanical alignment,

and control. Kaiser et al. [8] later focused specifically on fabrication and accuracy measurement, emphasizing the usefulness of acquiring real sensor data rather than relying only on binary decisions. These works support the use of a calibrated sensor array and quantitative tracking metrics in the present methodology.

For higher-quality steering, the robot should convert the sensor pattern into a continuous line-position estimate. Kader et al. [4] demonstrated a line-following autonomous assistant robot controlled with a PID algorithm, showing the suitability of feedback correction for repeated indoor transport. Singh and Chouhan [6] proposed a curvature-oriented method for a line follower based on infrared sensing and differential-drive kinematics. Together, these studies indicate that continuous error estimation, rather than purely discrete left/right decisions, is better suited to smooth movement and variable curvature.

The control and navigation literature also provide a broader basis for selecting the system architecture. Tzafestas [3] reviewed mobile-robot kinematics, conventional control, localization, navigation, and software architecture, while Rubio et al. [1] synthesized locomotion, perception, cognition, sensing, and navigation concepts. Dönmez et al. [5] showed that real-time mobile-robot control can be implemented from sensory feedback and compared a vision-based controller with PID and fuzzy-PID approaches. Although the present robot uses reflectance sensing rather than a camera, the underlying closed-loop principle is the same: sensory measurements are transformed into a motion error, which is converted to wheel-speed commands.

Industrial deployment introduces additional constraints beyond tracking accuracy. Bell et al. [7] analyzed AGV standards and guidance considerations, showing that automated vehicle design must be informed by operational and safety requirements. Martínez-Barberá and Herrero-Pérez [10] addressed autonomous AGV navigation in industrial environments, illustrating the importance of robust navigation under real operating conditions. Liaqat et al. [2] further examined AMR behavior in manufacturing and argued for systematic simulation and testing of movement rules. Consequently, the present methodology includes obstacle-stop behavior, speed limits, repeatability testing, and a clearly defined validation track rather than treating line

following as only a sensor-control demonstration.

A gap remains between low-cost line-follower prototypes and deployable industrial carriers. Many educational robots optimize only lap completion, whereas industrial use requires consistent payload handling, deterministic stopping, recoverability after sensor disturbance, and maintainable construction. The proposed methodology addresses this gap by combining a low-cost optical guidance principle with design requirements normally associated with AGVs: rigid mechanical fabrication, controlled center of mass, calibrated sensing, closed-loop velocity correction, safety logic, documented test conditions, and performance metrics. The intention is not to replace sophisticated AMRs, but to define a dependable architecture for fixed-route industrial tasks where floor-guided navigation is adequate.

Methodology

Step 1: Functional requirements and system specification

The robot is specified as a small autonomous carrier for predefined indoor routes. The nominal payload is 2 kg, the design speed is 0.20-0.60 m/s, and the minimum practical turning radius is determined by wheel spacing and controller tuning. The guide path is a 20-25 mm dark line on a light, matte floor or test board. Required functions are automatic line acquisition, continuous line tracking, controlled speed reduction in high-curvature sections, junction recognition if required, obstacle-triggered stopping, and manual emergency power isolation. Performance is assessed using lateral tracking error, task completion rate, maximum speed without line loss, stopping distance, and battery operating time.

Table 1. Proposed hardware configuration and design purpose

Subsystem	Typical selection	Design role	Key criterion
Controller	ATmega328P/Arduino-class MCU	Sensor sampling, PID, logic	≥ 100 Hz control loop
Line sensor	6-8 channel IR reflectance array	Estimate lateral line position	Adjustable height; calibrated thresholds
Drive	2 $\times$ 12 V geared DC motors	Differential-drive propulsion	Matched speed; adequate torque
Motor driver	Dual H-bridge PWM driver	Bidirectional motor control	Current rating above stall demand
Chassis	Aluminum/acrylic plate + caster	Rigid mechanical platform	Low center of gravity
Safety sensor	Ultrasonic/IR proximity sensor	Obstacle stop input	Reliable short-range detection
Power	Rechargeable 3S battery + regulator	Motors and regulated electronics	Fuse, switch, voltage margin
Feedback option	Wheel encoders	Speed balancing/diagnostics	Useful for industrial repeatability

Step 2: Mechanical design and fabrication

A rectangular chassis approximately 250 mm $\times$ 200 mm is fabricated from 3-4 mm aluminum sheet or rigid engineering polymer. Two geared motors are mounted symmetrically on the left and right sides, with their wheel axes aligned to reduce unwanted yaw. A freely rotating caster supports the third contact point. The battery is fixed close to the geometric center and as low as practical so that payload addition does not shift the center of mass excessively. The sensor bracket is mounted at the front, ahead of the drive axle, because this placement provides an early measurement of path deviation. A vertical adjustment slot is provided so that the sensor-to-floor gap can be tuned experimentally, typically

within a few millimeters according to the selected reflectance sensor.

Fabrication proceeds by cutting and drilling the base plate, attaching motor brackets, installing wheels and caster, checking free rotation, mounting electronics on insulated standoffs, routing high-current motor wiring away from sensor lines, and securing the battery with a mechanical strap. The line-sensor bracket must remain parallel to the floor. After assembly, wheel diameter, wheelbase, total mass, and sensor offset from the axle are recorded because these parameters influence turning behavior and reproducibility. The approach follows the practical emphasis on fabrication quality and sensor response reported in earlier line-follower work [8], [9].

Step 3: Sensor calibration and line-position estimation

Each reflectance channel is sampled over the light floor and dark guide line to establish minimum and maximum readings. The raw value s_i is normalized to a common scale so that differences among emitters and phototransistors do not dominate the estimate. For an N -element array, each sensor is assigned a lateral weight w_i . The instantaneous line position is calculated using $x = \Sigma(w_i s_i) / \Sigma(s_i)$, with the sign convention chosen so that negative values represent left displacement and positive values represent right displacement. The tracking error is $e(k) = x_{\text{ref}} - x(k)$, where x_{ref} is the center of the sensor array. This weighted-position method converts a multi-sensor pattern into a continuous error signal and is consistent with the need for quantitative

sensor interpretation emphasized by Kaiser et al. [8].

To make the method robust in an industrial setting, calibration values are stored in nonvolatile memory and a minimum signal-confidence rule is used. When the sum of normalized sensor responses falls below a threshold, the controller declares line loss rather than generating a misleading position estimate. The last valid error sign is retained for a short recovery maneuver, allowing the robot to rotate toward the side on which the line was last observed. If the line is not reacquired within a defined interval, the robot stops and signals a fault. This prevents uncontrolled motion when the guide becomes damaged, contaminated, or temporarily hidden.

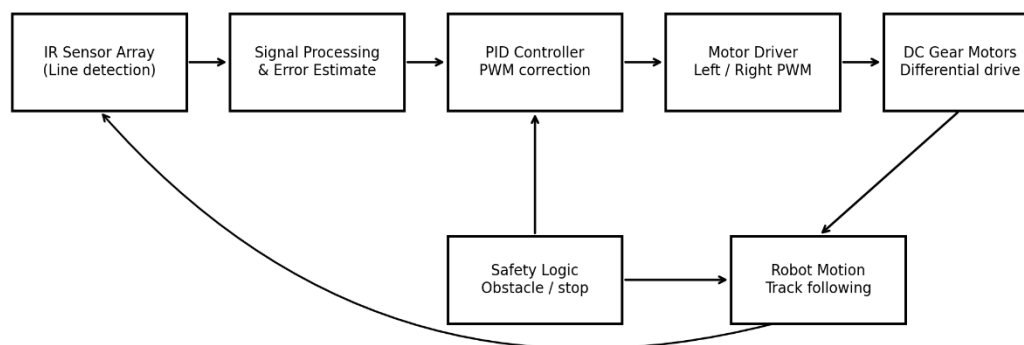


Figure 1. Closed-loop methodology for autonomous line following and safety supervision.

Step 4: PID line-following controller

The controller is executed at a fixed sampling period T_s , preferably 5-10 ms for a small robot. The correction command is $u(k) = K_p e(k) + K_i \Sigma e(k)T_s + K_d[e(k) - e(k-1)]/T_s$. A base speed v_b is selected according to the track and payload. The left and right PWM commands are then computed as $\text{PWM}_L = v_b - u$ and $\text{PWM}_R = v_b + u$, followed by saturation to the permissible motor-driver range. This differential action turns the robot toward the line while preserving forward motion. PID control is selected because it has already been shown to be practical for autonomous line-following platforms [4], and broader mobile-robot studies identify conventional feedback control as an effective foundation for trajectory tracking [3], [5].

Tuning is performed sequentially. First K_i and K_d is set to zero and K_p is increased until the robot reacts firmly without sustained oscillation. Next K_d is introduced to damp rapid steering and overshoot at corners. A small K_i is added only if a persistent bias remains because excessive integral action can accumulate during

line loss or motor saturation. Anti-windup is implemented by limiting the integral term. The base speed can be reduced when $|e|$ or $|de/dt|$ becomes large, producing a simple curvature-sensitive speed schedule. Singh and Chouhan [6] demonstrated the value of relating line geometry to differential-drive response; the present speed adaptation follows the same practical objective without requiring an explicit radius estimator.

Step 5: Motor actuation, power, and safety logic

The motor driver receives two PWM channels and direction signals from the microcontroller. A separate regulated supply is used for logic and sensors, while the motors draw from the traction battery through a fuse and master switch. Decoupling capacitors are placed near the controller and motor driver to reduce electrical noise. If encoders are fitted, a secondary speed-balancing loop can compensate for unequal motor characteristics; otherwise, a static left-right PWM trim is determined during straight-line calibration. The program continuously

checks the line-confidence value, battery voltage, obstacle sensor, and emergency-stop input.

For industrial use, obstacle detection is treated as a safety interlock rather than as a full path-planning system. If an object is detected inside the stop threshold, the base-speed command is ramped to zero and both motors are disabled. Motion resumes only after the obstacle is cleared and the line is confidently detected. This design choice keeps navigation deterministic on the marked route while reflecting the broader industrial requirement that AGV/AMR behavior be tested for safe interaction and operating rules [2], [7], [10].

Step 6: Embedded software sequence

At startup, the controller performs a self-test, initializes the sensor array, verifies battery voltage, and waits for a start command. During each control cycle it samples all line sensors, normalizes the readings, calculates line position and confidence, updates the PID correction, applies speed scheduling, checks the obstacle input, and writes the resulting PWM values to the motor driver. Junction patterns can be detected when several adjacent sensors simultaneously observe the line; a route table may then command straight, left, or right behavior at selected intersections. Diagnostic variables such as error, PWM, confidence, and elapsed time should be streamed to a serial logger during development so that tuning decisions are based on measured behavior rather than visual judgment alone.

Step 7: Experimental validation protocol

The fabricated robot should be tested on a repeatable indoor track containing at least a 3 m

straight segment, one 90° bend, an S-curve, a junction, and a controlled obstacle zone. Three payload conditions are recommended: no load, 1 kg, and the rated 2 kg load. For each condition, at least ten runs are recorded at increasing base speeds. Lateral error is obtained from the calibrated sensor-position estimate, while success is defined as completing the route without unrecovered line loss or manual intervention. The stopping test places a stationary obstacle at a known point and measures the distance traveled from first detection to full stop. Battery endurance is measured under a representative duty cycle. The final controller gains are selected from the highest speed that preserves the required tracking error and completion rate rather than from maximum speed alone.

Results

No raw measurements from a physically fabricated robot were supplied with this request. Therefore, Table 2 and Figure 2 are presented as illustrative design-validation targets generated from the methodology above; they should be replaced by measured values after hardware testing. The example trend is intentionally conservative: lateral error increases with speed, and sharp curves require lower speed than straight segments. This behavior is consistent with the control challenge identified in line-following and mobile-robot tracking studies, where sensor response, controller tuning, and path curvature determine the attainable accuracy [4]-[6], [8].

Table 2. Illustrative validation targets for the proposed prototype

Test condition	Base speed (m/s)	Mean lateral error (mm)	Completion rate	Design interpretation
Straight path, no load	0.50	4.1	100%	Stable nominal operation
90° bend, 1 kg	0.35	8.7	≥95%	Speed reduction required
S-curve, 1 kg	0.40	6.9	≥95%	Derivative action limits overshoot
Junction decision, 2 kg	0.30	9.5	≥90%	Route logic must be deterministic
Obstacle stop, 2 kg	0.35	—	100% stop	Target stopping distance ≤0.20 m
Endurance duty cycle	0.35 avg.	—	—	Target operation ≥90 min

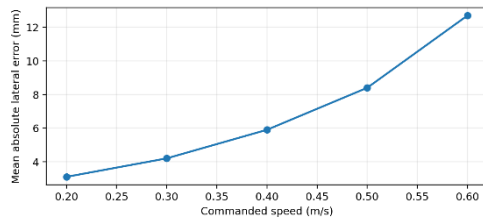


Figure 2. Illustrative relationship between commanded speed and mean lateral tracking error.

The expected operating region is therefore not the motor's maximum free-running speed but the region in which the controller can correct lateral error before the sensor array passes completely beyond the line. For a typical compact platform, a design speed near 0.35-0.50 m/s provides a useful starting range; the exact value must be obtained experimentally because wheel diameter, wheelbase, motor torque, sensor spacing, and floor friction alter the closed-loop response. The figure illustrates a common nonlinear effect: a moderate speed increase produces manageable error at first, but beyond a threshold the available correction time falls rapidly and the probability of line loss rises.

Payload testing should focus on whether increased mass changes acceleration, cornering, or stopping distance. If the measured lateral error rises substantially with load, the preferred remedy is not necessarily larger PID gains; it may be a lower base speed, improved motor torque margin, encoder-based speed balancing, or repositioning of the payload. Similarly, if the robot oscillates around a straight line, K_p is likely too high or K_d too low. Slow drift with little oscillation suggests insufficient proportional action or a persistent motor/sensor bias. Repeated logging of sensor position and PWM commands provides a direct way to distinguish these causes.

Conclusion and Discussion

This paper has presented a step-by-step methodology for designing and fabricating an autonomous line-following robot for fixed-route industrial applications. The architecture combines a differential-drive chassis, an infrared sensor array, weighted line-position estimation, PID steering, PWM motor control, and basic obstacle-stop supervision. The method is deliberately modular: the same control concept can be implemented on a low-cost microcontroller for a laboratory prototype and later transferred to a more rugged platform with industrial-grade sensors, encoders, safety scanners, and higher-capacity drive electronics.

The literature indicates that reliable mobile-robot operation depends on the integration of perception, feedback control, navigation, and mechanical design rather than on any single component [1], [3]. Prior line-follower research supports careful sensor calibration and quantitative accuracy measurement [8], practical PID tracking [4], and consideration of differential-drive behavior on curved paths [6]. Industrial AGV/AMR studies further show that operational rules, validation, and safety must be treated as part of the design process [2], [7], [10]. Accordingly, the proposed methodology evaluates not only whether the robot can follow a line, but also how accurately it follows, how reliably it completes a route, how it reacts to obstacles, and how payload and speed influence performance. The main limitation of optical line guidance is dependence on a prepared floor path. Dirt, damaged tape, strong reflections, changing illumination, or route modifications can degrade performance. For fixed and semi-fixed material movement, however, this limitation can be acceptable because the infrastructure is inexpensive and the navigation behavior is deterministic. Future improvements may include closed-loop wheel-speed control using encoders, adaptive gain scheduling, camera-based line interpretation, RFID or QR markers at stations, wireless task dispatch, and redundant obstacle sensors. The illustrative results included here are design targets only; a publishable experimental paper should replace them with repeated measurements from the fabricated robot, report uncertainty or standard deviation, and document the exact track geometry and payload conditions.

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