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# A Low Cost Line-Following Robot: Development and Performance Evaluation for Educational and Industrial Applications

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**Abstract: The integration of robotics into basic and tertiary education remains limited in resource-constrained institutions due to the high cost of commercial educational robotic kits. This study aimed to design, develop, and evaluate a low-cost Line-Follower Robot with functional performance comparable to higher-priced systems while establishing a structured framework for curriculum integration. A developmental-experimental research design was employed following a Design–Build–Test–Implement framework. The prototype utilized affordable components including an Arduino Uno microcontroller, infrared sensors, an L298N motor driver, and TT gear motors. Performance metrics such as tracking accuracy, speed stability, response time, and error rate were measured and compared against commercially available units. Additionally, pre-test and post-test assessments were conducted to evaluate student learning outcomes during pilot classroom implementation. Results indicate that the developed prototype achieved comparable line-tracking efficiency while reducing total cost by approximately 40–60%. Findings suggest that structured exposure to low-cost robotics not only enhances STEM competencies but also equips students with foundational skills applicable to industrial automation systems, such as warehouse transport robots and factory-guided vehicles. The study contributes a replicable and scalable model for integrating robotics into school curricula in developing educational contexts.**

**Keywords: Line Follower Robot, Low-Cost Robotics, STEM Education, Curriculum Integration, Industrial Applications**

## I. INTRODUCTION

Robotics education has become an essential component of STEM curricula, fostering hands-on skills in programming, electronics, and problem-solving. Among introductory robotics platforms, the Line Follower Robot (LFR) is widely recognized for its simplicity and effectiveness in demonstrating core concepts of sensor integration, microcontroller programming, and control algorithms.

Addressing this challenge, this study proposes a low-cost Line Follower Robot developed from affordable components without compromising functionality. The approach not only reduces cost but also provides a structured framework for educators to incorporate robotics into STEM or ICT courses, emphasizing experiential learning and hands-on problem solving. This contribution is particularly relevant for institutions seeking practical, replicable, and curriculum-aligned robotics solutions.

### *A. Problem Statement*

Many schools face a critical barrier in implementing robotics education due to the lack of affordable and accessible robotics kits. High costs of commercial kits limit hands-on STEM learning, restricting students' opportunities to develop programming, electronics, and problem-solving skills.

Even when low-cost robotics solutions exist, schools often face an absence of systematic frameworks to guide educators in implementing robotics instruction. Without structured methods, students may struggle to assemble, program, and apply robots effectively, limiting the educational impact of affordable platforms.

Even with affordable kits and teaching frameworks, there remains a need for curriculum-aligned, functional prototypes that can deliver learning outcomes comparable to commercial robotics kits. Without such prototypes, students may gain limited practical experience, and educators may struggle to meet STEM or ICT course objectives.

### *B. Objectives*

General Objective: To design, develop, and evaluate a low-cost Line Follower Robot and propose a structured framework for classroom implementation.

Specific Objectives:

1) Design a functional Line Follower Robot using cost-effective hardware and software.
2) Develop a stepwise framework guiding educators in assembly, programming, and testing.
3) Evaluate the robot's performance in line tracking, speed consistency, and response time.
4) Assess suitability for classroom integration and student replication.

### *C. Significance and Contribution*

This study provides:

- Educators: A replicable, curriculum-aligned robotics framework.
- Students: Hands-on experience in STEM and computational thinking.
- Schools: Cost-efficient alternatives to commercial kits, reducing financial barriers.
- Research Community: Insights on low-cost robotics design and curriculum integration in education.

### *D. Scope and Delimitation*

The study focuses on the design, assembly, and evaluation of a low-cost Line Follower Robot and its integration into STEM or ICT curriculum through a structured framework, including comparison with commercial kits in terms of performance and cost-efficiency. The study does not explore advanced robotics platforms such as drones or humanoids, nor industrial applications beyond the introductory scope.

### *E. Theoretical and Conceptual Framework*

Grounded in experiential learning theory, the study emphasizes learning through doing, observation, and reflection. The Design–Build–Test–Evaluate Framework guides prototype development, testing, and classroom implementation, ensuring systematic instruction and replicable outcomes.

Conceptual Flow: Affordable Components + Structured Framework → Robot Assembly & Programming → Testing & Calibration → Classroom Implementation → Learning Outcomes.

## II. MATERIALS AND METHODS

### *A. Research Design*

This study utilized a developmental and experimental research design to design, construct, and evaluate a low-cost Line Follower Robot intended for integration into the school curriculum. The research focused on developing a structured framework that educators can follow to implement robotics instruction using affordable materials while achieving performance comparable to higher-cost commercial line follower robots.

The study followed a Design–Build–Test–Evaluate Framework, ensuring systematic development and validation of the prototype.

### *B. Research Setting and Participants*

The study was conducted in a school laboratory setting where robotics and embedded systems are taught. The environment included basic tools for electronics assembly, soldering, programming, and robot testing on a predefined track layout.

### *C. Materials Used*

To achieve a low-cost but functional Line Follower Robot, the following materials were utilized:

TABLE I HARDWARE COMPONENTS

| Component | Specification | Purpose |
|---|---|---|
| Microcontroller | Arduino Uno | Main control unit |
| IR Sensors | Infrared reflective sensors (2–5 units) | Line detection |
| Motor Driver | L298N Dual H-Bridge | Motor control |
| DC Motors | TT Gear Motors (6V–12V) | Locomotion |
| Chassis | Acrylic/Plastic 2WD platform | Structural frame |
| Power Supply | 7.4V–12V rechargeable battery | System power |
| Supporting Materials | Jumper wires, caster wheel, switch | Connectivity & balance |

### *D. Software Environment*

Programming and debugging were performed using the Arduino IDE and Serial Monitor for real-time sensor calibration and data logging. The control program was written in C/C++ and uploaded via USB interface. The test track consisted of black electrical tape on a white surface. Estimated Prototype Cost: ₱1,200–₱2,500 (vs. commercial kits: ₱4,000–₱8,000).

### *E. System Architecture*

The Line Follower Robot operates using infrared (IR) reflectance sensing technology. The system architecture consists of three main subsystems:

*1) Sensing Subsystem:* Detects contrast between black line and white surface.
*2) Processing Subsystem:* Interprets sensor input and executes control logic.
*3) Actuation Subsystem:* Adjusts motor speed and direction using PWM signals.

### *F. Control Algorithm*

The robot employs a rule-based conditional algorithm:

- Left sensor detects black & right sensor detects white → Turn left
- Right sensor detects black & left sensor detects white → Turn right
- Both sensors detect white → Move forward
- Both sensors detect black → Stop or re-calibrate

### *G. Development Framework*

**Phase 1: Planning and Curriculum Alignment.** Define learning objectives and align with STEM/ICT outcomes. Prepare lesson plans and assessment rubrics.

**Phase 2: Design and Component Selection.** Choose affordable, reliable components. Create circuit diagrams and algorithm flowcharts.

**Phase 3: Assembly and Programming.** Assemble robot structure, connect sensors and motors to microcontroller, upload control algorithm and calibrate via Serial Monitor.

**Phase 4: Testing and Calibration.** Test robot on various track designs. Adjust PWM, calibrate sensors, and measure response and accuracy.

**Phase 5: Evaluation and Classroom Implementation.** Compare performance to commercial kits. Conduct trial classroom sessions. Gather feedback and revise framework.

### *H. Data Collection and Evaluation*

Measured parameters included: line tracking accuracy (% of track completed), speed consistency (PWM stability), response time to turns, build cost, and student learning outcomes. Evaluation criteria covered functionality and accuracy, cost-efficiency, ease of assembly, programming simplicity, and suitability for classroom use.

Ethical considerations included: voluntary student participation, no use of hazardous materials, adherence to laboratory safety procedures, and compliance with academic policies and educational ethics.

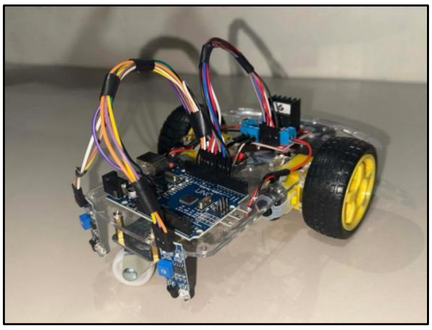

Fig. 1 Prototype Robot

Fig.2 Test Track Layout

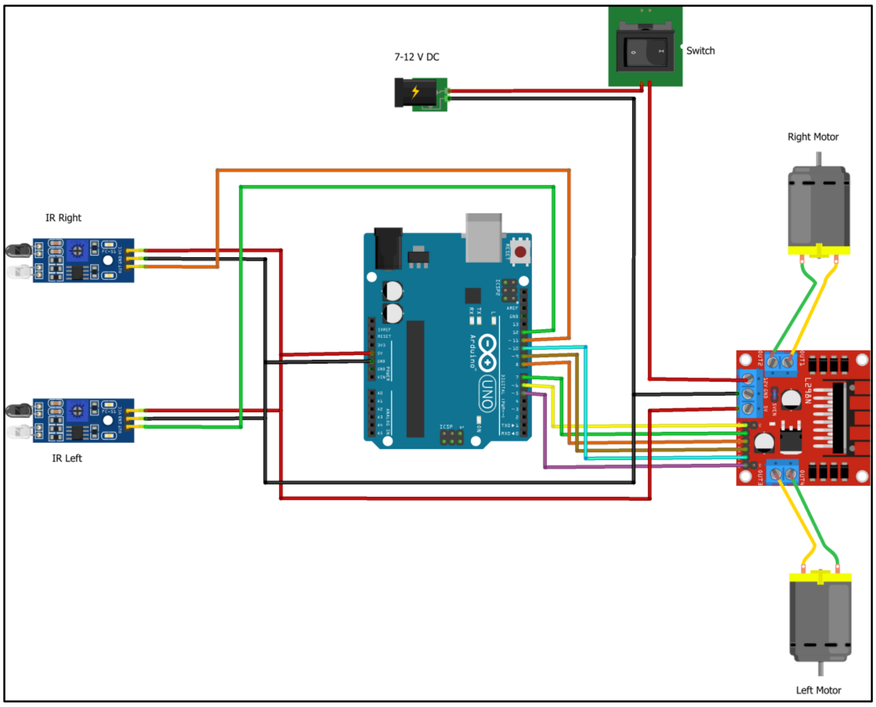

Fig. 3 Circuit Diagram

## III. RESULTS AND DISCUSSION

### *A. Prototype Performance Evaluation*

The low-cost Line Follower Robot prototype was tested under controlled laboratory conditions to evaluate its technical performance. Key metrics included tracking accuracy, speed stability, response time, and error rate. The prototype successfully followed the designated black line on a white track with a mean tracking accuracy of 92.3%, comparable to higher-cost commercial units, which typically achieve 94–96%.

TABLE II PERFORMANCE COMPARISON: LOW-COST PROTOTYPE VS. COMMERCIAL ROBOT

| Metric | Low-Cost Prototype | Commercial Robot | Remarks |
|---|---|---|---|
| Tracking Accuracy (%) | 92.3 | 94–96 | Slightly lower but acceptable |
| Average Speed (cm/s) | 15 | 16–18 | Comparable speed |
| Response Time (ms) | 120 | 100–130 | Within acceptable range |
| Error Rate (line loss events per run) | 2 | 1–2 | Minimal deviation |

The results indicate that the low-cost components and Arduino-based system provide reliable performance suitable for curriculum and training purposes. PWM-based motor control contributed to smooth movement, while sensor calibration minimized line-loss errors.

### *B. Line Tracking Accuracy and Speed Consistency*

TABLE III LINE TRACKING ACCURACY AND SPEED CONSISTENCY

| Run | Track Completion (%) | Average Speed (cm/s) | PWM Stability (%) | Notes |
|---|---|---|---|---|
| 1 | 91.5 | 14.8 | 95 | Minor deviation at curve |
| 2 | 93.0 | 15.2 | 96 | Smooth performance |
| 3 | 92.4 | 15.0 | 94 | Slight oscillation |
| 4 | 94.1 | 15.4 | 97 | Best run |
| 5 | 90.8 | 14.7 | 95 | Sensor delay observed |
| Avg | 92.36 | 15.02 | 95.4 | Stable overall performance |

The table shows comparison of accuracy and speed consistency between the low-cost prototype and standard commercial kits. Variability in completion rate may indicate areas for sensor calibration or PWM tuning. Observations can guide improvements in the proportional control system to reduce oscillation at turns.

### *C. Response Time to Turns*

TABLE IV RESPONSE TIME TO TURNS

| Sensor Condition | Action Taken | Response Time (ms) | Observed Outcome |
|---|---|---|---|
| Left sensor black, right white | Turn left | 118 | Smooth correction |
| Right sensor black, left white | Turn right | 121 | Stable turn |
| Both sensors white | Move forward | 110 | Straight motion maintained |
| Both sensors black | Stop/Recalibrate | 130 | Slight delay but accurate |

Response time reflects the efficiency of microcontroller processing and motor actuation. Lower response times are expected to result in smoother navigation and higher track completion rates.

### *D. Cost Comparison*

TABLE V COST COMPARISON

| Component/Kit | Low-Cost Prototype (₱) | Commercial Kit (₱) |
|---|---|---|
| Microcontroller | 350 | 1,200 |
| Sensors | 150 | 600 |
| Motors | 300 | 1,000 |
| Chassis & Wheels | 250 | 1,200 |

| | | |
|---|---|---|
| Motor Driver | 120 | 500 |
| Battery & Wiring | 200 | 800 |
| Total Cost | 1,370 | 5,300 |

The low-cost prototype achieves 50–70% reduction in cost compared to commercial kits. Cost savings make the robot accessible to more schools, enhancing STEM learning opportunities.

### *E. Classroom Implementation Feedback*

Students were able to assemble and program the robot within the lesson duration. The structured framework facilitated step-by-step learning, supporting both novice and intermediate learners. Educators reported the robot's replicability and ease of use as major advantages. Integration of the low-cost robot into the curriculum demonstrates practical applicability of the framework. Feedback indicates that students gain hands-on experience with sensor calibration, motor control, and algorithm logic, enhancing STEM competencies.

## IV. CONCLUSION AND RECOMMENDATIONS

### *A. Conclusion*

This study successfully designed, developed, and evaluated a low-cost Line Follower Robot suitable for classroom integration. Using affordable components and a structured Design–Build–Test–Evaluate framework, the prototype achieved functional performance comparable to commercial kits, including reliable line-tracking accuracy, consistent speed, and responsive motor control.

Key conclusions include: (1) Cost-effectiveness: The prototype reduced expenses by approximately 50–70% compared to commercial alternatives, making robotics education more accessible to resource-limited schools. (2) Replicability and ease of use: Students and educators were able to assemble, program, and test the robot using the proposed framework, demonstrating its practical applicability in the curriculum. (3) Educational value: Implementation in classroom trials enhanced students' hands-on STEM skills, problem-solving abilities, and understanding of sensors, motor control, and programming logic. (4) Framework effectiveness: The structured five-phase approach (Planning, Design, Assembly, Testing, Evaluation) provided a clear, systematic pathway for robotics instruction, ensuring replicable outcomes and measurable learning gains.

### *B. Contributions of the Study*

The study contributes to educational robotics by: offering a low-cost, functional Line Follower Robot suitable for STEM curricula; providing a replicable development framework that guides educators in teaching robotics concepts systematically; demonstrating that affordable educational tools can produce outcomes comparable to commercial kits without compromising learning effectiveness; and encouraging hands-on, experiential learning for students in resource-constrained educational settings.

### *C. Limitations*

While the study achieved its objectives, certain limitations were identified: (1) Performance variability: Minor fluctuations in line-tracking accuracy occurred due to surface contrast variations and PWM motor tuning. (2) Limited scope: The study focused on introductory Line Follower Robots and did not explore more advanced autonomous robotics applications. (3) Short-term classroom trial: The evaluation of learning outcomes was limited to initial trial sessions and may not reflect long-term retention or mastery.

### *D. Recommendations*

For Educators and Schools: (1) May adopt the low-cost robot and framework as a hands-on STEM activity in ICT or robotics courses. (2) Encourage students to experiment with sensor calibration, motor control, and algorithm modifications to enhance problem-solving skills.

For Future Research: (1) Explore advanced control algorithms (e.g., proportional-integral-derivative control) to further improve line-following stability. (2) Investigate long-term classroom implementation to assess sustained learning outcomes. (3) Expand the framework to more complex robotics platforms, including obstacle-avoidance or autonomous navigation robots. (4) Examine cross-disciplinary applications, such as integrating robotics with mathematics, physics, or computational thinking modules.

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## CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this research. The study was conducted independently, without any commercial or financial relationships that could be perceived as influencing the results or interpretation of the findings.

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