http://www.doi.org/10.62341/macm0758

Received	**2025/10/08**	**تم استلام الورقة العلمية في**
Accepted	**2025/11/03**	**تم قبول الورقة العلمية في**
Published	**2025/11/05**	**تم نشر الورقة العلمية في**

Cost-effective Line-Following Robot (LFR) Design and Implementation with Analog Multiplexed Keypad Input and IR Barcode-Based Station Recognition

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Abstract

This study presents the design and implementation of a cost-effective Line Following Robot (LFR) capable of autonomous navigation and station recognition. The system utilizes infrared (IR) sensors for line detection and barcode-based encoding for identifying designated stations, allowing the robot to stop, wait, or return based on predefined tasks. An Arduino Uno microcontroller with an analog multiplexed keypad provides efficient input handling while reducing pin usage. Experimental results demonstrate reliable performance at moderate speeds under stable indoor lighting, though challenges were observed at higher speeds due to sensor and control limitations. To address these issues, future improvements such as advanced sensors and PID-based control algorithms are suggested. Overall, the proposed design achieves a balance between simplicity, low cost, and functionality, making it suitable for applications in education, industrial automation, and hobbyist projects.

Keywords: Line Following Robot(LFR), Arduino, IR Sensors, Analog Multiplexing, Barcode Recognition, Low-Cost Design.

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تصميم وتنفيذ روبوت متتبع للخط منخفض التكلفة باستخدام لوحة مفاتيح تماثلية متعددة الإرسال والتعرف على المحطات عبر رموز شريطية بالأشعة تحت الحمراء (IR)

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قسم الهندسة الكهربائية و الالكترونية – كلية العلوم التقنية – درنة – ليبيا

الملخص

تقدّم هذه الدراسة تصميمًا وتنفيذًا لروبوت متتبع للخط منخفض التكلفة قادر على الملاحة الذاتية والتعرف على المحطات. يعتمد النظام على حساسات الأشعة تحت الحمراء (IR) لاكتشاف الخطوط، وعلى ترميز يعتمد على الرموز الشريطية (الباركود) للتعرف على المحطات المحددة، مما يسمح للروبوت بالتوقف أو الانتظار أو العودة وفقًا للمهام المبرمجة مسبقًا. يستخدم النظام متحكمًا دقيقًا من نوع **Arduino Uno** مع لوحة مفاتيح تماثلية متعددة الإرسال لتوفير إدخال فعال وتقليل عدد الأرجل المستخدمة. أظهرت النتائج التجريبية أداءً موثوقًا عند السرعات المتوسطة وتحت إضاءة داخلية مستقرة، في حين ظهرت بعض التحديات عند السرعات العالية نتيجة محدودية الحساسات ونظام التحكم. وللتغلب على هذه القيود، تُقترح تحسينات مستقبلية تشمل استخدام حساسات متقدمة وخوارزميات تحكم تعتمد على **.PID**

بشكل عام، يحقق التصميم المقترح توازنًا بين البساطة وانخفاض التكلفة والوظائف العملية، مما يجعله مناسبًا للتطبيقات التعليمية والأتمتة الصناعية والمشاريع الهواياتية.

الكلمات المفتاحية : روبوت متتبع للخط(LFR) ، أردوينو، حساسات الأشعة تحت الحمراء، تعدد الإرسال التماثلي، التعرف على الرموز الشريطية، التصميم منخفض التكلفة.

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1. . Introduction

Since the Industrial Revolution in Europe, technological development has advanced at an unprecedented pace, fundamentally transforming societies and industries worldwide. This rapid evolution has been driven by human curiosity and the desire to innovate, particularly in fields such as robotics[1][2]. Over the decades, robotics has emerged as one of the most dynamic and rapidly growing technological domains, attracting significant attention from researchers and engineers alike[3][4].

The continuous advancements in robotics have led to remarkable changes in the size, design, and functionality of robots, enabling them to perform increasingly complex tasks[4][5]. Today, robots are widely deployed across various sectors, from manufacturing and logistics to healthcare and education, demonstrating their potential to enhance productivity and support human labor[6][7]. These technological innovations not only contribute to scientific progress but also provide tangible benefits to society by simplifying tasks and improving the speed and efficiency of operations. As robotics continues to evolve, its applications are becoming more integrated into daily life, shaping the future of work and human-technology interaction[8].

In the advancement of robotics, the incorporation of automation technologies is a significant factor in enhancing the efficiency and precision of different applications. The line tracking robot (LTR) is a highly significant robot designed for autonomous navigation due to its ability to follow predetermined paths using an entrance. Robots play a significant role in a variety of areas, including production and educational demonstrations, and demonstrate the intersection of engineering principles and practical applications. AVR microcontrollers are remarkable for their balance between performance and energy efficiency in real-time process tasks in robot systems [9]. By taking advantage of their abilities, designers can develop more sophisticated algorithms that enable the robot to adapt to the dynamic environment effectively. Understanding LTR's complexes not only makes technological advances, but also emphasizes the importance of microcontroller -based systems in modern robotics [10].

In this paper, the design and implementation of a cost-effective Line Following Robot (LFR) with IR barcode-based station detection and an analog multiplexed keypad are presented. The methodology involves developing a circuit schematic using Cirkit Designer IDE,

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selecting low-cost hardware components such as IR sensors and a DC motor driver, and programming the microcontroller to perform line detection, station recognition, and task execution. The proposed approach combines both hardware and software design, supported by experimental validation on different tracks to evaluate performance under varying conditions.

2. Literature Review

The field of robotics has shown significant interest in line-tracking robots (LTRs), particularly in integrating AVR microcontrollers to enhance their performance [11]. Previous studies have explored various approaches combining sensor technologies and algorithmic strategies to improve the accuracy and efficiency of autonomous navigation. For example, the use of infrared sensors paired with PID control algorithms has demonstrated notable improvements in tracking precision compared to earlier models [12][13]. Furthermore, innovations in microcontroller programming have enabled more advanced adaptations to changing environmental conditions, leading to faster response times and better maneuverability [14]. Recent research has expanded on these foundations, with studies demonstrating enhanced line-following performance using Arduino-based PID controllers tailored for industrial automation [15]. Adaptive control strategies have also been proposed to improve robot responsiveness in dynamic environments, allowing for more robust navigation [16]. Additionally, integrating wireless monitoring systems with AVR microcontrollers has introduced smart features that facilitate real-time supervision and control of line-following robots [17]. These advancements illustrate the versatility of AVR microcontrollers and highlight the ongoing need to refine line-tracking algorithms to address current challenges. Consequently, this research provides a foundation for developing more advanced LTR systems applicable in areas such as industrial automation and hobbyist projects [18][19].

3. System Design

The block diagram of the line-following robot system is presented in Figure 1. This robot is designed to operate autonomously by following a predetermined path—typically a black line on a light-colored surface or vice versa—to ensure sufficient contrast for reliable detection. The system comprises several main components: an input unit (a keypad for entering the target station number), a set

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of sensors for line detection, a processing and control unit based on an Arduino microcontroller, an output unit consisting of motor and actuator driver circuits, and a main power supply provided by a rechargeable battery.

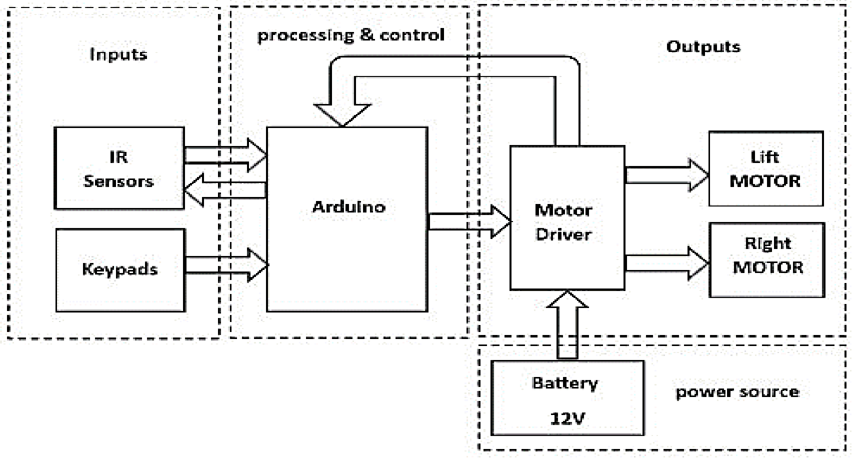

Figure 1. block diagram of LFR system

The detection mechanism is based on the reflective properties of surfaces. Light-colored areas reflect a greater amount of light, while dark-colored areas reflect less. Infrared sensors, consisting of an emitter (infrared LED) and a receiver (photodiode), exploit this difference for line detection. When the photodiode detects a high level of reflected light from a light-colored surface, its resistance decreases; conversely, resistance increases when reflecting from a dark surface. This principle enables the robot to differentiate between the track and the surrounding surface, as illustrated in Figure 2.

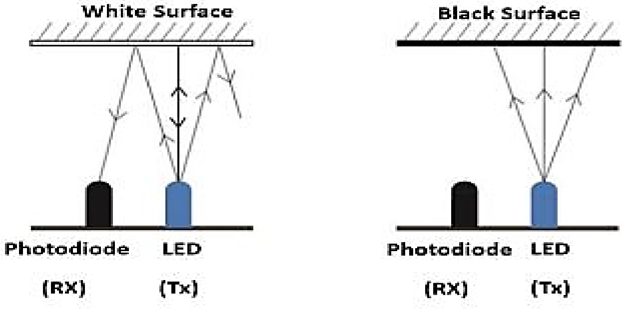

Figure 2. The Principle of Operation of IR Sensors

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Sensor readings are transmitted to the Arduino microcontroller, which processes the data and generates control signals for the driver circuit. The driver circuit then powers the DC motors, enabling directional movements—forward, left, or right—based on the robot's position relative to the line.

4. Movement of the proposed LFR robot

- **Forward Movement:**

When both sensors detect a white surface, indicating that the black line lies between them, the robot proceeds forward. In this mode, both motors rotate in the same direction to propel the robot straight ahead. While the physical configuration of the motors may involve opposite rotation directions due to their placement, for simplicity, this motion is considered forward.

- **Left Turn:**

A left turn occurs when the left sensor detects the black line while the right sensor remains over the white surface. The detection signal prompts the microcontroller to adjust motor behavior. To execute the turn, the left motor rotates in reverse while the right motor rotates forward, causing the robot to pivot left and realign with the line.

- **Right Turn:**

This condition mirrors the left-turn scenario, except that the right sensor detects the black line while the left sensor is over the white surface. In response, the microcontroller commands the left motor to move forward and the right motor to rotate in reverse, enabling the robot to pivot right and maintain its path along the line, as shown in Figure 3.

- **Stop**:

The stop condition is managed by barcode sensors, which detect a station-specific barcode placed on the floor. When the barcode matches the destination entered via the keypad at the start of the operation, the robot halts at the designated station. The keypad allows the user to select the desired delivery station. The robot identifies each station using three additional sensors mounted at the front of the cart. These sensors read a simple barcode placed at each station. Upon detecting the correct barcode, the robot halts at the designated station. With three barcode-reading sensors, the system can support a maximum of seven stations, as illustrated in Figure 4.

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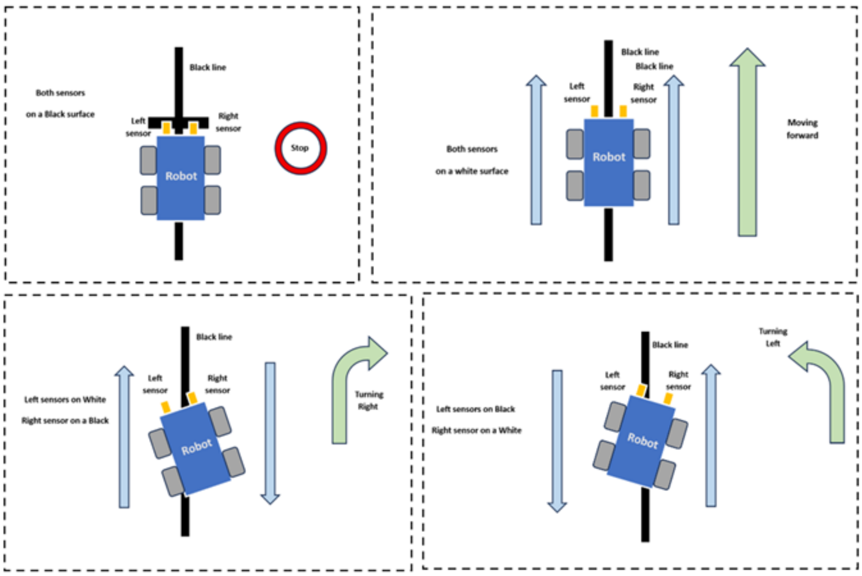

Figure 3. Directional Control Mechanism of the LFR

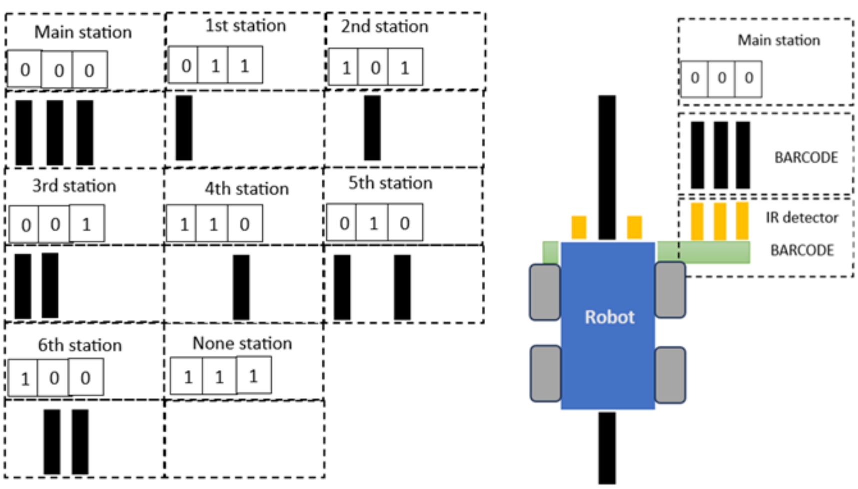

Figure 4. Station Identification Using Barcodes

- **IR Barcode Patterns**

In this project, station identification is achieved through a simple yet effective technique using three infrared (IR) sensors placed away from the main tracking line. Alongside the path, a barcode pattern composed of three horizontal segments (either black or white) is printed in alignment with the three sensors. As the robot moves forward, each segment passes under its corresponding sensor, producing a binary code where 0 represents black and 1 represents

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white. Following this, the binary code is converted into a decimal value representing the station code. This method provides a scalable and cost-effective approach for station detection without the need for complex communication modules or encoding systems. It is particularly well-suited for educational and industrial robotic applications involving predefined paths and autonomous navigation. Table 1 summarizes the barcode pattern configurations and their corresponding station identifiers.

Table 1: Barcode Patterns and Corresponding Station Identifiers

Visual Pattern (Right → Left)	Binary Code	Decimal Value	Station Code
Black – Black – Black	000	0	Main Station
Black – Black – White	001	1	Station 1
Black – White – Black	010	2	Station 2
Black – White – White	011	3	Station 3
White – Black – Black	100	4	Station 4
White – Black – White	101	5	Station 5
White – White – Black	110	6	Station 6
White – White – White	111	7	NON-STATION

- **Sensor States and Robot Control Logic**

The line-following robot operates based on ten distinct states detected using an Arduino microcontroller. The system employs two line-detection sensors (left and right) to determine the position of the line relative to the robot. Additionally, three barcode-reading sensors provide digital signals to identify station markers along the path.

By analyzing the combined inputs from these five sensors, the robot determines its current state and adjusts its behavior accordingly. The ten possible states include scenarios such as: when only the left sensor detects the line, when only the right sensor detects the line, when neither sensor detects the line, and when specific barcode patterns are recognized.

The Arduino continuously monitors these sensor states to control the motors, ensuring precise directional adjustments for accurate line tracking. Furthermore, upon detecting the predefined barcode corresponding to the user-selected destination, the robot halts at the designated station. The detailed mapping of sensor states and corresponding robot actions is summarized in Table 2.

Table 2: Mapping of Sensor States to Corresponding Robot Actions

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Input					Output				Movement Of Robot	Stations
Left Sensor	Right Sensor	BARCODE Sensors			Left Motor		Right Motor			
0	1	1	1	1	1	0	0	0	Turn Right	NON-STATION
1	0	1	1	1	0	0	1	0	Turn Left	NON-STATION
1	1	1	1	1	1	0	1	0	Forward	NON-STATION
1	1	0	0	0	0	0	0	0	Stop	Main station
1	1	0	1	1	0	0	0	0	Stop	1st station
1	1	1	0	1	0	0	0	0	Stop	2nd station
1	1	0	0	1	0	0	0	0	Stop	3rd station
1	1	1	1	0	0	0	0	0	Stop	4th station
1	1	0	1	0	0	0	0	0	Stop	5th station
1	1	1	0	0	0	0	0	0	stop	6th station

5. Implementation

The line-following robot was constructed using two central infrared sensors to reliably track a predefined black line. In addition, three side-mounted sensors were employed to detect barcode patterns representing station codes. These barcodes, composed of alternating black and white segments, were processed and converted into binary values. The robot then compared these values against the destination code entered by the user via a 4×4 keypad. The keypad was integrated through analog multiplexing, which effectively overcame the limited number of digital input pins on the Arduino Uno.

- **Required Components**

To build a line-following robot using an Arduino, several essential components are required. These include one Arduino Uno microcontroller, one L293D motor driver to control the motors, and five IR sensor modules for line detection. The robot is powered by a 12V battery that supplies energy to two small DC motors connected to four wheels, enabling movement. All components are mounted on a hobby robot chassis that serves as the robot’s frame. Additionally, connecting wires and mounting screws are used as needed to establish electrical connections and securely assemble the parts.

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- **Analog Interface for Keypad Input**

Due to the limited number of I/O pins on the Arduino, an analog keypad reading technique was utilized. Multiple buttons were connected through separate resistors in a voltage divider network (as illustrated in Figure 7) to a single analog input pin. This method allows identification of button presses via distinct voltage levels, significantly reducing the required digital pins and preserving critical microcontroller resources for sensors and motor drivers, thereby maintaining overall system functionality with minimal hardware complexity.

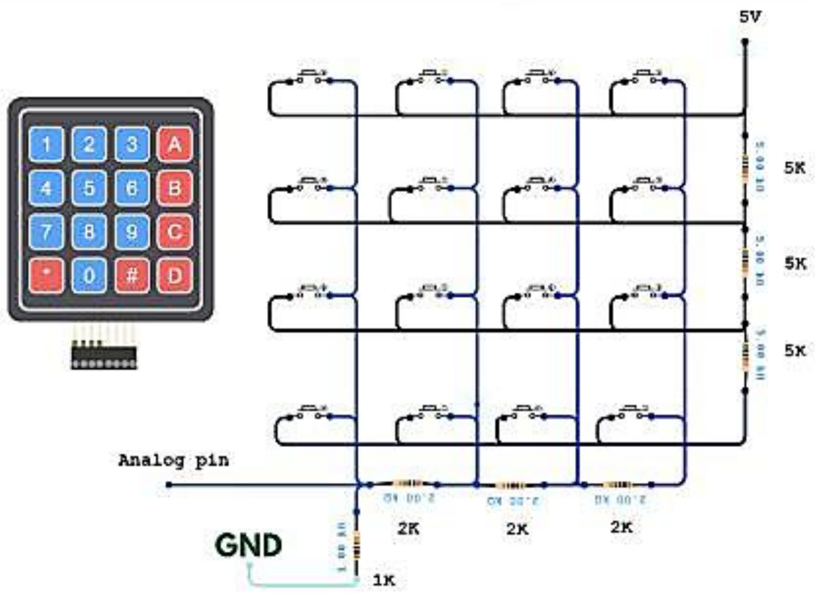

Figure 5. Keypad Analog Input Circuit

- **Overview of the Circuit Diagram**

The presented circuit diagram depicts the fundamental structure of the Line Following Robot (LFR), illustrating the principal components and their connections in a clear and organized approach. The schematic diagram of the proposed robot, drawn using Cirkit Designer IDE, is shown in Figure 5.

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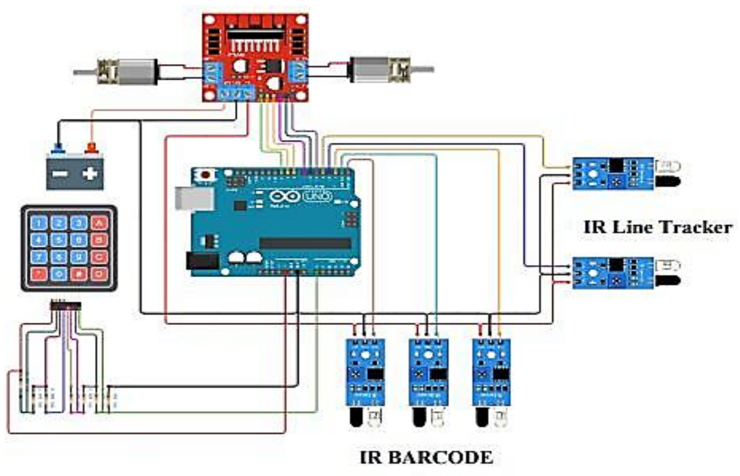

Figure 6: Schematic Diagram of the Circuit of the proposed LFR

- **Flowchart for the Line Following Robot**

The robot's line-following system processes sensor inputs to navigate the path and identifies stations by detecting barcodes placed alongside the line. Operational decisions are then made at each station accordingly. Figure 6 presents the robot's flowchart.

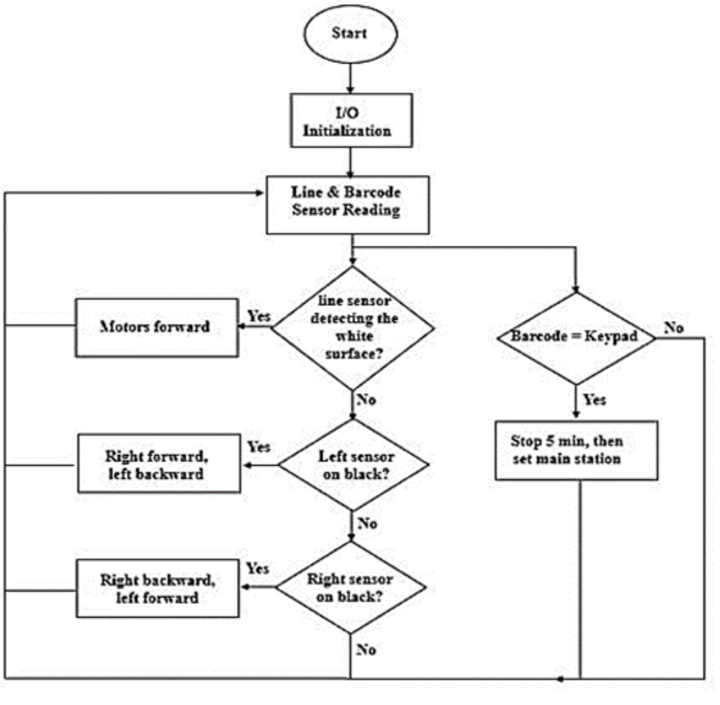

Figure 7: Flowchart of the Line-Tracking Robot (LTR) System

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6. Results and Discussion

Tests on different tracks showed that the robot, moving at moderate speeds of 120 to 150 RPM, successfully recognized all designated stations, including the main station. It responded correctly by stopping, waiting, or returning as needed. The system worked well under steady indoor lighting, but at higher speeds (above 180 RPM), it struggled to stay on track. Using analog multiplexing for the keypad proved to be a practical way to increase input capacity without needing extra digital pins.

Overall, the system strikes a good balance between simplicity and reliability. Using basic infrared sensors alongside an analog multiplexed keypad made the design straightforward but effective. However, the robot's performance drops at higher speeds, mainly because the sensors and control algorithm can't respond quickly enough. This means we need to improve both the sensors and the control system for faster operation. Also, the binary barcode system limits how many stations can be uniquely identified. To handle more stations, more advanced coding methods would be necessary. The analog multiplexing solution solved the problem of limited Arduino inputs, but it adds some complexity when processing signals. Figure 8 shows a prototype of the LTR design, which was validated through construction and testing.

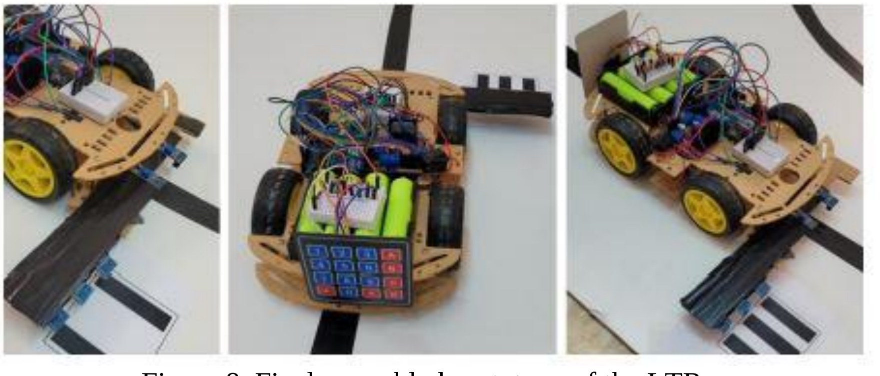

Figure 8. Final assembled prototype of the LTR

7. Conclusion and Future Work

This project shows that it's possible to build a functional line-following robot with station detection using low-cost and simple parts like IR sensors and a multiplexed keypad. The system worked well at moderate speeds and stable lighting, allowing the robot to perform tasks based on predefined codes. Still, higher speeds revealed weaknesses, highlighting the need for better sensors and

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control algorithms. The binary barcode method is straightforward and effective, but for wider applications, more sophisticated coding or wireless communication might be needed. For future improvements, we plan to use faster sensors and more advanced control methods to keep the robot stable at higher speeds. We also want to explore more complex coding schemes to increase the number of stations the robot can recognize. Using microcontrollers with more inputs or specialized multiplexing chips could simplify the keypad wiring. Additionally, expanding the robot's use to outdoor or more variable environments will require better sensor calibration, adjustments for changing lighting, and possibly machine learning to improve its adaptability.

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