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A Greener Approach to Industrial Automation: Solar-Assisted Wireless Chargeable Line Follower

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***Abstract*— This work investigates the development and implementation of a solar-powered wireless chargeable line follower for industrial applications. Traditional line-following robots often face significant challenges due to their reliance on wired charging systems and the frequent need for battery replacements. These limitations can lead to operational inefficiencies, increased maintenance demands, and downtime, as the robots need to be manually connected to charging stations or have their batteries swapped. This work proposes an approach that combines solar power technology with wireless charging capabilities. The proposed line follower utilizes colour sensor to accurately detect and follow a predetermined path. A solar-powered charging platform equipped with a transmitter module is strategically integrated into the line follower's route. While the line follower can bypass the charging platform when its battery level is sufficient, it is designed to automatically halt at the platform when the battery falls below a predefined threshold of 25%. This intelligent diversion mechanism ensures that the line follower receives timely charging without compromising its operational efficiency. The transmitter module on the charging platform directly transmits power to the line follower's wireless receiver module, which is then stored in a rechargeable battery mounted on the line follower. By harnessing solar energy and implementing wireless charging, it is aimed to create a more sustainable, efficient, and reliable line follower solution for industrial applications.**

***Keywords*— Industrial automation, Autonomous charging, Operational sustainability, Color-based navigation, Photovoltaic smart power systems.**

I. INTRODUCTION

Automation has transformed industries worldwide, increasing efficiency, reducing operational costs, and enabling continuous, precise operations that were once impossible with manual processes. From assembly lines in manufacturing to complex logistics systems, automation has been pivotal in enhancing productivity and reducing human error. One prominent example of automation's impact is in the automotive industry. Ford's assembly line innovation, for instance, drastically reduced the time required to build a car, enabling mass production that fuelled the growth of the automobile industry [1]. Today, industrial automation continues to evolve, integrating advanced technologies such as robotics, artificial intelligence (AI), and autonomous systems to further optimize operations. In recent years, the integration of autonomous systems like line-following robots has revolutionized industries such as warehousing, manufacturing, and logistics [2].

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These robots, designed to follow predetermined paths, streamline the process of material handling, transporting goods along factory floors or between warehouses without the need for human intervention. By doing so, they enhance productivity, reduce labour costs, and minimize errors. For example, in Amazon's fulfilment centres, autonomous mobile robots (AMRs) like Kiva systems have significantly improved operational efficiency [3]. These robots move shelves of products to human pickers, allowing for faster and more accurate order fulfilment. The use of such robots has cut down warehouse operating costs by as much as 20-40%, while improving speed and reducing errors in the order-picking process. Line-following robots are particularly suited for industries where repetitive tasks and precise navigation are required [4]. These robots use sensors to detect and follow a visible or invisible path, typically a line drawn or embedded on the factory floor. In industries such as manufacturing and logistics, line-followers are used to transport raw materials, semi-finished goods, or finished products along a predetermined route, ensuring that production lines operate smoothly and efficiently [5]. For instance, in automotive manufacturing plants, Automated Guided Vehicles (AGVs) and line-following robots transport vehicle parts between assembly stations. This reduces the need for human workers to manually move heavy materials, thereby minimizing the risk of injury and enhancing workflow efficiency. In pharmaceutical industries, line-following robots are employed to deliver sensitive materials and products across different stages of production and packaging, ensuring high precision and safety in handling. In warehousing and logistics, they help speed up the movement of goods between storage and dispatch areas, ensuring timely delivery while optimizing storage space.

Despite the advantages of line-following robots, one significant challenge is power management. Traditionally, these robots rely on wired charging systems or require frequent battery replacements, leading to operational inefficiencies. Robots must periodically stop for charging or battery replacements, which interrupts their workflow and increases downtime. This not only slows down production but also adds to labour costs, as personnel must oversee the charging or battery replacement process. To address this challenge, wireless charging has emerged as an effective solution. Wireless charging systems eliminate the need for manual intervention, allowing robots to recharge autonomously whenever required, thereby reducing operational downtime. This is achieved through Wireless Power Transfer (WPT) technology [6-9], in which electrical energy is transferred from a transmitter to a receiver using electromagnetic induction. In the proposed system, the robot navigates to a designated charging station and recharges wirelessly before resuming its assigned tasks. The concept of dynamic charging is borrowed from advancements in electric vehicle (EV) technology. In the automotive industry, dynamic wireless charging systems enable EVs to be charged while driving. This technology significantly reduces the need for large battery capacities, making vehicles lighter, more reliable, and economical [10-11]. By charging vehicles at regular intervals during their operation, EVs can maintain optimal power levels without the need for frequent stops, which enhances their range and efficiency. A similar approach can be applied to industrial line-following robots, allowing them to charge as they move along their designated routes, thereby ensuring continuous operation and reducing downtime. To make wireless charging more sustainable, solar energy presents an ideal solution. Solar power is a clean and renewable energy source, harnessing the energy from the sun to generate electricity. On average, the Earth receives about 173,000 terawatts of energy from the sun, more than 10,000 times the world's total energy use. Despite the vast potential of solar energy, only a small fraction is currently harnessed, with the global solar power generation capacity reaching over 1,000 gigawatts as of 2023 [12-13].

II. Literature Survey

Sivakumar et al. [1] have proposed an innovative system for charging electric vehicle (EV) batteries both while stationary and in motion. Their approach leverages inductive power transfer technology, which traditionally suffers from low power ratings, to achieve high-power wireless charging. The system integrates multiple power sources, including solar cells, to ensure continuous charging even in congested areas or during emergencies. The authors developed a mathematical model and conducted simulations using MATLAB/Simulink to validate their design. The hardware setup includes a digital signal controller, high-frequency MOSFETs, and other components to facilitate efficient power transfer. Their method aims to reduce reliance on fossil fuels, lower maintenance costs, and provide a pollution-free charging solution. The proposed system also offers the potential for EVs to serve as emergency power sources for homes and businesses during outages. Overall, this work addresses key challenges in EV charging, such as power efficiency and charging time, by providing a robust and scalable solution.

Chen et al. [2] have developed a dynamic wireless power transfer (DWPT) system aimed at enhancing the efficiency and reliability of electric vehicle (EV) charging. Their research addresses key challenges such as unstable coupling, limited system efficiency, and low system stability. By focusing on ferrite structure optimization, compensation network design, and adaptive control methods, they have proposed solutions to improve the dynamic performance of DWPT systems. This work also explores sensing technology to reduce system complexity and enhance performance. Their findings include the development of a universally-applicable ferrite optimization algorithm and adaptive control methods, which significantly improve the system's dynamic performance without the need for position sensors or communication units. Their work contributes to making EV transportation more efficient and reliable by enabling continuous on-road powering, thus alleviating concerns about being stranded due to battery depletion.

Deepak V. Prasad et al. [3] have developed a System (DWCS) for electric vehicles (EVs) to address the limitations of traditional fixed charging infrastructure. Their system utilizes advanced wireless power transfer technologies to enable EV charging while in motion, enhancing the convenience and scalability of EV charging infrastructure. The DWCS dynamically adjusts to the vehicle's location and speed, ensuring seamless and uninterrupted charging. This innovative approach aims to reduce range anxiety and promote the widespread adoption of EVs by improving the accessibility and flexibility of charging. The study details the system's key components, such as charging pads, compensation networks, and power modulators, and highlights the potential of DWCS to revolutionize the future of EV charging infrastructure. Through rigorous experimental analysis and real-time implementation, the authors demonstrate the system's effectiveness and scalability, paving the way for a more sustainable and user-friendly electric transportation ecosystem.

Anitha et al. [4] present an innovative dynamic wireless charging system for electric vehicles powered by solar energy. Their system aims to reduce fuel consumption and pollution by enabling electric vehicles to charge while in motion, eliminating the need for wires, external power supplies, and frequent stops for charging. The system incorporates components such as batteries, transformers, Atmega controllers, LCD displays, regulatory circuits, solar panels, copper coils, and AC to DC converters. By embedding copper coils in the road, the system allows for continuous charging of electric vehicles, enhancing their range and reliability. This ntegrates IoT technology with renewable solar energy, utilizing a Node MCU microcontroller to monitor and display battery voltage. The dynamic wireless charging system is designed to be cost-effective, environmentally friendly, and efficient, addressing the challenges of EV recharge-related issues and contributing to a sustainable transportation system. The authors highlight the potential of this technology to extend driving range, reduce battery size, and promote the widespread adoption of electric vehicles.

Ahmad et al. [5] conducted a comprehensive study on the design and interoperability of a quadruple pad structure for wireless charging applications in electric vehicles. They focused on optimizing the power pad coil design to enhance efficiency and reliability. The research involved analyzing various coil configurations, including rectangular, double D (DD), and double D quadrature (DDQ) structures, and comparing them with the quadruple coil structure. Through finite-element analysis (FEA) using ANSYS Maxwell, they verified the optimized design, shape, size, and current directions in the quadruple pad structure. The study demonstrated that the quadruple coil structure is compatible with other coil designs and offers improved misalignment tolerance and higher coupling coefficients. The results showed that the quadruple coil structure achieved a coupling coefficient of 0.210, making it a viable option for dynamic wireless charging applications. The research also highlighted the importance of optimizing coil dimensions and current directions to maximize performance and efficiency. Sarala T et al. [6] have designed and implemented a wireless power transmission (WPT) system for electric vehicles (EVs) using magnetic coils in parking areas and roads. Their work focuses on the mutual inductance principle to transmit power via resonant coupling, aiming to replace traditional conductive charging methods. The system comprises a transmitter and receiver module, where the transmitter generates an oscillating magnetic field that induces power in the receiver coil. This method eliminates the need for physical connectors, enhancing convenience and safety. The authors have demonstrated that WPT can achieve an overall transfer efficiency of 60-75%, significantly reducing range anxiety for EV users by enabling dynamic charging while driving. Their work highlights the potential of WPT technology to improve energy performance, reduce environmental impact, and increase the operational safety and convenience of EVs.

In the paper [7], Abu Shufian et al. present a wireless power transmission system that utilizes solar energy to charge batteries. The system employs magnetic resonant coupling to transfer power wirelessly from a solar panel to a receiver circuit. The transmitter coil, driven at the resonant frequency of the receiver coil, ensures efficient energy transfe. Despite achieving only 11% efficiency due to power losses in the transmission process, the system demonstrates the potential for future applications in charging electric cars, drones, hospital equipment, and smartphones without the need for physical connections. The authors highlight the environmental benefits of using solar energy and the convenience of wireless charging, especially in remote areas where electricity is scarce. The study underscores the importance of renewable energy sources and innovative charging solutions in modern technology. Mude et al. [8] conducted a comprehensive review and analysis of two-element resonant compensation topologies for wireless inductive power transfer (WIPT) systems. Their study focused on the efficiency and performance of various compensation techniques under different operating conditions. They evaluated the behavior of performance factors such as efficiency, power transfer capability, and voltage regulation across different topologies, including series-series (SS), series-parallel (SP), parallel-series (PS), and parallel-parallel (PP). The authors highlighted the importance of compensation capacitors in reducing system losses and improving efficiency. They also discussed the impact of load variations, coupling coefficients, frequency mismatches, and component tolerances on system performance. The paper concluded with a detailed comparison of the topologies, emphasizing the advantages and limitations of each, and provided guidelines for selecting appropriate compensation methods for specific applications. This work is significant for advancing the design and optimization of WIPT systems, particularly for applications like electric vehicle charging and biomedical implants. Kavin et al. [9] have developed a WPT system for electric vehicles using solar energy. Their work focuses on enhancing the efficiency of power transfer between coils by employing MOSFET switches in the inverter, which allows for high-frequency charging. This system aims to address the challenges of charging time, range, and cost associated with electric vehicles. By integrating WPT with solar energy, this provides a sustainable and efficient solution for EV charging. The authors have designed a system that includes a solar panel, rechargeable battery, charge controller, and voltage regulator, along with an Arduino controller to manage the switching pulses to the MOSFET inverter. The energy is transferred via inductive coupling, and the system is validated through simulation using Proteus software. This work demonstrates the potential of WPT to revolutionize EV charging by reducing reliance on cables, minimizing energy losses, and promoting the use of renewable energy sources. Karthi et al. [10] have developed a wireless charging technology for electric vehicles, which eliminates the need for physical cables by using electromagnetic induction. The system comprises a transmitter coil embedded in the ground and a receiver coil mounted on the vehicle. They explored three types of wireless charging: static, dynamic, and quasi-dynamic, each suited for different scenarios. The study highlights the convenience, safety, and efficiency of wireless charging compared to traditional plug-in methods. However, challenges such as standardization, low power transfer, electromagnetic interference, and high costs were also identified. The authors conducted both theoretical and experimental analyses, demonstrating that the efficiency of power transfer increases as the distance between the coils decreases. They proposed a system using Arduino for managing the power transfer and included safety features like temperature sensors to prevent overheating. The research underscores the potential of wireless charging to enhance the adoption of electric vehicles by making the charging process more user-friendly and integrated into everyday infrastructure. Razu et al. [11] conducted a study on the wireless charging for EVs while movement, focusing on the dynamic wireless power transfer (WPT) system. They designed and simulated a system using two Archimedean coils of copper to evaluate the impact of vertical and horizontal misalignment on WPT efficiency. The study achieved a transfer power of 3.74 kW and an efficiency of up to 92.4% for a 150 mm air gap. Additionally, they designed a charging lane for dynamic charging and calculated the power transfer from mutual inductance when an EV is driven over it. The results indicated that the system could significantly extend the driving range of EVs by enabling continuous charging while in motion, potentially eliminating the need for large batteries. This research provides a foundation for future developments in dynamic WPT systems, aiming to overcome challenges such as misalignment and air-gap variations to enhance the efficiency and practicality of wireless EV charging. Ashwini V. et al. [12] have developed a novel wireless power transfer system for EVs using a Tesla coil and a photovoltaic (PV) generator. This system aims to provide a more efficient, durable, and safe alternative to traditional cable charging methods. The WPT system utilizes inductive coupling between primary (transmitter) and secondary (receiver) coils to transfer power wirelessly. The authors have modeled a PV source and integrated it with the WPT system to ensure optimal power generation. They have addressed the challenge of power fluctuations by introducing a complex vehicle assembly with three overlapped coils, enhancing the stability of power transfer. The system's efficiency was tested through simulations and hardware models, demonstrating its potential for deployment in public spaces like railway stations and urban centers. This innovative approach not only reduces the dependency on fossil fuels but also offers a cost-effective and environmentally friendly solution for EV charging, making it a significant contribution to the advancement of EV technology. Kashani et al. [13] conducted a comprehensive review on the integration of solar energy with wireless charging systems for electric vehicles (EVs). Their research addresses the increasing demand for renewable energy sources and the need for efficient EV charging solutions. They explored various types of solar-powered EV charging stations, focusing on wireless power transfer (WPT) technologies. The study delves into the components of WPT systems, such as compensators and coil structures, and evaluates their efficiency. Additionally, the authors examined the role of artificial intelligence (AI) in optimizing WPT frameworks. They highlighted the advantages of using AI to enhance computation speed, fault detection, and overall system efficiency. The review also discusses the challenges and potential solutions for maximizing power output from solar panels under varying environmental conditions. By integrating solar energy with WPT, the study aims to reduce the reliance on fossil fuels and minimize air pollution, contributing to a more sustainable future for electric mobility. Bugatha Ram Vara Prasad et al. [14] have developed a solar-powered wireless charging system for EV aimed at addressing the limitations of traditional fuel-based vehicles and the challenges of EV charging infrastructure. Their innovative solution enables EVs to be charged wirelessly while in motion, eliminating the need for stops to recharge. The system utilizes a combination of solar panels, batteries, transformers, regulator circuitry, copper coils, AC to DC converters, and an Atmega microcontroller. The solar panels charge the batteries, which then convert DC power to AC for transmission through copper coils embedded in the road. As the vehicle passes over these coils, energy is wirelessly transferred to the vehicle's onboard coil, converted back to DC, and used to charge the EV battery. This approach not only leverages renewable energy but also enhances the convenience and efficiency of EV charging, potentially reducing reliance on external power supplies and contributing to a more sustainable transportation system. This work demonstrates a practical application of embedded systems and renewable energy technologies in modern transportation. Tummapudi et al. [15] have developed a charging station for electric vehicles (EVs), addressing the limitations of prolonged charging times and lack of power in rural areas. Their system utilizes solar panels to generate electricity, which is then stored in batteries and converted from DC to AC using an inverter. This AC power is transmitted wirelessly through copper coils embedded in the road, allowing EVs to charge while in motion. Their primary goal is to create an efficient, eco-friendly charging solution that reduces greenhouse gas emissions and noise pollution. The prototype demonstrated successful wireless energy transfer, although power fluctuations were noted, suggesting areas for future improvement. Their innovative approach highlights the potential for integrating renewable energy sources with advanced charging technologies to enhance the practicality and sustainability of EVs. Kandasamy et al. [16] have developed an on road charging station for electric vehicles which is solar-based, aiming to enhance the efficiency and sustainability of EV charging. Their work integrates solar panels to create an autonomous power source, minimizing reliance on conventional energy resources. The system employs inductive coupling for wireless power transfer, where energy from photovoltaic cells is transmitted to the EV battery through electromagnetic waves. This method allows for dynamic charging while the vehicle is in motion, eliminating the need for stationary charging stops. The proposed system includes a comprehensive setup involving a transmitter circuit that converts DC supply to high-frequency AC output, which is then wirelessly transmitted and converted back to DC for battery charging. The authors have demonstrated the effectiveness of this system through simulations, highlighting its potential for high efficiency, fast charging, and reduced power losses compared to traditional wired methods. This innovative approach promises to significantly improve the practicality and convenience of electric vehicle usage, contributing to sustainable transportation solutions. In this work [17], Rahul Kumar Reddy Chaganti et al. have developed a wireless charging system for electric vehicles using inductive coupling and RFID technology. The system aims to address the challenges associated with conventional wired charging, such as the need for human intervention and the messiness of cables. By implementing a wireless charging mechanism, the user can charge their vehicle simply by parking it in a designated spot equipped with a transmitter coil. The RFID tags attached to the vehicles are used to authenticate and initiate the charging process. The system comprises a transmitter side with an RFID reader interfaced with an Arduino, which controls the power transmission to the receiver coil attached to the vehicle. The receiver coil then transmits the power to the vehicle's battery. This work demonstrates the efficiency and convenience of wireless charging, eliminating the need for manual cable connections and enabling a seamless charging experience. The results show that the system can effectively charge electric vehicles wirelessly, providing a practical solution for the growing demand for electric vehicle charging infrastructure. In the review article [18] by Vishnuram et al., the authors explore the advancements and challenges in wirelesss charging systems for electric vehicles (EVs). They focus on the use of magnetic materials and coil configurations to enhance the efficiency and safety of wireless power transfer (WPT) technology. The study provides a comprehensive overview of the current state of WPT, highlighting the selection of materials for designing coils, various electromagnetic shielding techniques, and different inductive pad architectures. The authors also discuss the sustainability and social impacts of wireless charging systems, emphasizing the potential for environmentally responsible mobility. They identify research limitations and propose future directions for improving WPT technology, aiming to facilitate the widespread adoption of EVs by addressing issues related to charging infrastructure and vehicle performance. This review serves as a valuable resource for researchers and engineers working on developing more efficient and sustainable wireless charging solutions for electric vehicles. Fujita et al. [19] have developed a dynamic wireless power transfer (DWPT) system aimed at enhancing the charging efficiency and safety of electric vehicles (EVs). The proposed system uniquely allows the vehicle-side assembly to control the load current independently, addressing the challenge of limited communication between the ground and vehicle sides. By employing a one-pulsewidth modulation (PWM) control method and a feed-forward control approach, the system effectively manages the load current even as the coupling coefficient varies during vehicle motion. The researchers designed and tested a bench system to validate their method, demonstrating that the proposed control method outperforms traditional proportional-integral (PI) control in both static and dynamic conditions. The system maintained stable load current in high coupling coefficient areas and effectively controlled current in other regions, showcasing its potential for practical application in EV charging infrastructure.

We developed a solar-powered, wireless chargeable line-following robot designed for industrial automation. The robot utilizes a TCS3200 color sensor to differentiate blue, green, and red lines, enabling it to follow a predefined path while intelligently managing its energy. When the battery level drops below 25%, the robot diverts to a charging station using the green line and initiates wireless charging upon detecting the red line. Once fully charged, it resumes its operation, ensuring uninterrupted functionality. This system combines sustainable energy solutions with efficient automation to address traditional challenges like wired charging and frequent battery replacements.

III. METHODOLOGY

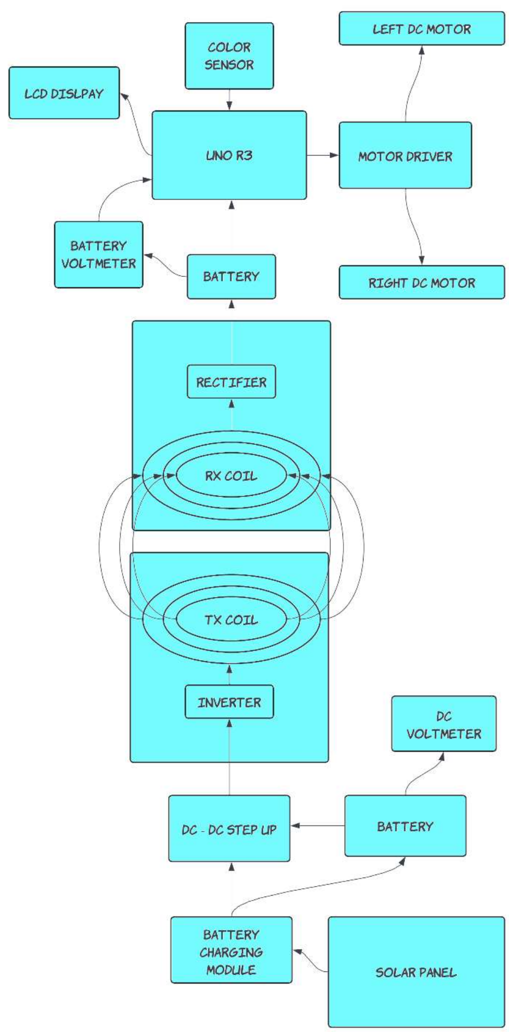

Fig.1.Block diagram of the implemented system

Fig. 1 shows an optimized industrial automation processes using a solar-powered, wireless chargeable line-following robot. At the core of this system lies an Arduino Uno R3 microcontroller, which functions as the central control unit coordinating the robot's movement, power management, and decision-making based on sensor inputs. The robot is built to navigate along predefined colored paths, marked with blue, green, and red tape, which dictate its operational flow and charging patterns. A TCS3200 color sensor is mounted on the robot to detect these color-coded paths, allowing the robot to differentiate between its work path (blue), the path to the charging station (green), and the charging station itself (red). This color-based navigation system ensures that the robot autonomously follows the correct route while dynamically adapting to its battery status. The robot's path is marked with a blue line, indicating the main work route where tasks are conducted. The Arduino continuously processes data from the color sensor to maintain the robot's position on this blue line. If the battery level drops below a critical threshold, for instance, 25%, the system triggers a transition to the green path. This transition ensures that the robot searches for the nearest charging route while still following the blue path to prevent abrupt halts in its workflow. Upon detecting the green line, the Arduino redirects the robot to follow this path, which leads to the designated charging station. This approach allows the robot to intelligently prioritize energy conservation by redirecting to a charging station before reaching a critical power failure state, thereby enhancing reliability in continuous industrial tasks. The charging station is identified by a red line that intersects with the green path, signaling the robot to stop and initiate charging. The charging process is facilitated through wireless power transfer, which is achieved using resonant magnetic coupling between two coils – a transmitting coil (TX) located at the charging station and a receiving coil (RX) installed on the robot. This setup allows for efficient energy transfer without the need for physical connectors, which is advantageous in industrial environments where durability and maintenance are crucial. The power transfer module uses an inverter to convert the DC input from an external power source into AC, which is then transmitted wirelessly via the TX coil. Upon reception by the RX coil, the AC is converted back to DC through a rectifier circuit, making it suitable for charging the robot's onboard battery.

The robot is powered by a combination of solar and wireless charging sources to ensure continuous operation in different environments. A polycrystalline solar panel, measuring 70mm x 70mm, is integrated into the system to provide supplementary charging during active tasks, especially in daylight conditions. With an output voltage of 6V and a power rating of 0.6W, the solar panel generates a stable energy supply that can either directly power the robot or charge the battery incrementally. The DC output from the solar panel is connected to a battery charging module equipped with a constant current/constant voltage (CC/CV) charging mechanism. This module is capable of charging a variety of battery types through both wired and wireless connections, with multiple protections in place, including overcharge, over-discharge, and overcurrent protection. These safeguards enhance battery longevity and ensure reliable performance over extended periods. The system employs a DC-DC step-up converter module (MT3608) to regulate and boost the voltage output to meet the operating requirements of different components in the robot. The step-up converter receives input from both the battery and the solar panel, with an adjustable output range between 5V to 28V and an efficiency rating of up to 93%. This component is particularly crucial when the battery voltage is below the desired operating voltage for the Arduino and other peripherals, as it allows the robot to sustain functionality by adjusting voltage levels dynamically. The ability to source a maximum current of 2A ensures that the converter can handle the combined power demands of the color sensor, LCD, and motor driver without compromising stability. Additionally, this power regulation mechanism contributes to the overall energy efficiency of the system, allowing for optimal battery utilization. The motor driver module, an L298N dual H-bridge, interfaces the Arduino with two DC motors that control the robot's movement. The driver receives PWM signals from the Arduino to adjust motor speed and direction, enabling precise navigation along the colored paths. By varying the motor speeds, the Arduino can steer the robot through curves and intersections on the line, ensuring that it remains aligned with the designated path. The driver's design allows for bidirectional control of each motor, facilitating smooth turns and adjustments based on sensor feedback. The efficient integration of the motor driver and color sensor enables the robot to navigate complex paths without additional mechanical components, relying instead on software-based steering algorithms. A 16x2 LCD, connected via an I2C module, provides real-time feedback on the robot's operational status, including battery level, sensor readings, and current path. This display offers insights for maintenance personnel and can assist in troubleshooting during the robot's deployment. Additionally, a battery voltmeter is incorporated into the design to continuously monitor the voltage levels of the onboard battery. This data is processed by the Arduino to make intelligent decisions about when to initiate the search for a charging station, thus ensuring that the robot maintains sufficient power for uninterrupted operation.

The system is designed with scalability and flexibility in mind, allowing for integration with additional sensors or modules based on specific industrial needs. The use of standard components such as the Arduino Uno and

TCS3200 sensor simplifies both initial setup and future upgrades. For instance, if more complex path patterns are required, additional color sensors can be added to increase the robot's accuracy in line detection. Furthermore, the wireless charging system's modular nature enables compatibility with a wide range of receiver-transmitter coil configurations, facilitating deployment across multiple workstations within an industrial facility. The charging strategy, combining solar and wireless power, significantly extends the operational autonomy of the robot. The solar panel harnesses ambient light energy, ensuring that the robot's power source is not solely reliant on periodic station-based charging. This feature is particularly advantageous in environments with intermittent access to charging stations, as the solar panel can maintain the battery at an adequate level during daylight hours. Meanwhile, the wireless charging mechanism provides a fast and efficient means of recharging when the robot returns to the designated charging station, reducing downtime and increasing the overall productivity of the automation system.

TABLE I. TECHNICAL SPECIFICATIONS OF THE PROPOSED SYSTEM

Parameter	Specification
Microcontroller	Arduino Uno R3
Color sensor	TCS3200
Solar panel	70 mm × 70 mm, 6 V, 80 mA
Battery	3.7 V Li-ion rechargeable battery
Wireless charging	5 V, 1 A output
Charging range	2–10 mm
DC–DC converter	MT3608
Motor driver	L298N
Battery threshold	25%
Full charge threshold	95%

Table I summarizes the technical specifications of the proposed solar-assisted wireless rechargeable line-following robot. The table lists the major hardware components and their corresponding specifications used for autonomous navigation, power management, and wireless charging.

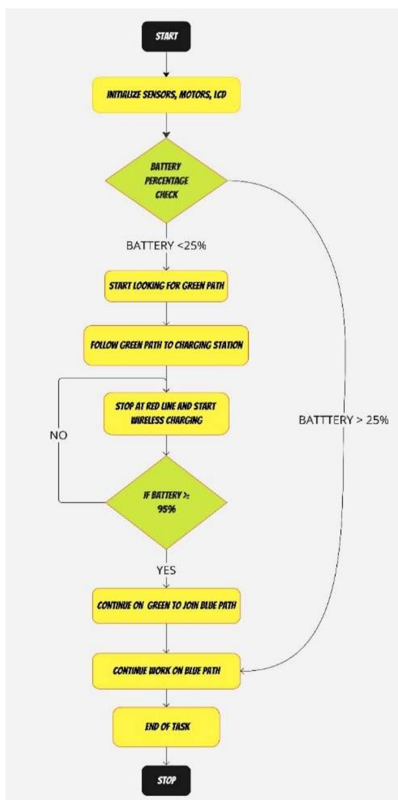

Fig. 2. Flow chart of the implemented system

The flowchart shown in Fig 2 outlines the operational process of a solar-powered wireless chargeable line-following robot designed for industrial automation. The workflow begins with the initialization of essential components, including sensors, motors, and an LCD display. This step ensures that the robot is fully functional and ready to perform its tasks efficiently. Once initialized, the robot checks its estimated battery state of charge (SoC) as the first decision-making step. If the battery level is above 25%, the robot continues its primary operation, following the blue line that represents the designated work path. This allows the robot to focus on its assigned tasks without interruptions. However, if the estimated battery state of charge (SoC) falls below the critical threshold of 25%, the robot diverts from its main task to prioritize energy management. It begins searching for a green path, which is predefined as the route to the charging station. This intelligent diversion ensures that the robot autonomously transitions to energy replenishment mode without requiring human intervention. Upon detecting the green path, the robot navigates toward the charging station, showcasing its ability to adapt to its environment and make dynamic decisions. At the charging station, the robot identifies a red line, which serves as a stopping marker. Upon detecting this line, the robot halts and initiates wireless charging. The integration of a red line for precise localization ensures that the robot docks at the correct position for efficient wireless power transfer. During charging, the robot continuously monitors its estimated battery state of charge (SoC) and displays the current charge level on the LCD screen. This real-time feedback provides transparency regarding the charging process. The robot remains in this state until the battery level reaches or exceeds 95%, ensuring that it has sufficient energy to resume its tasks without frequent interruptions. Once fully charged, the robot seamlessly transitions back to its work mode. It follows the green path to rejoin the main blue path, thereby reintegrating into its regular workflow. This autonomous resumption of work tasks demonstrates the robot's operational efficiency and adaptability. After returning to the blue line, the robot continues performing its assigned tasks until they are completed. At the end of its workflow, the robot marks the conclusion of its operations, signifying the end of the task cycle. This systematic approach ensures continuous functionality and operational efficiency. By integrating sensors for path detection, real-time battery monitoring, and wireless charging technology, the robot is capable of working autonomously in an industrial environment. The flowchart demonstrates a robust energy management strategy and decision-making framework, making the robot highly suitable for sustainable and efficient industrial automation. The system incorporates a robust power management structure designed for efficient energy harvesting, regulation, and utilization, ensuring sustained operation in an industrial setting. The primary power source is a 70mm x 70mm polycrystalline solar panel with a single cell, generating a stable (at maximum light intensity) 6V output at 80mA. Although this power is limited, it provides a continuous supplementary charge to the battery when ambient light is available, extending the robot's operational time without needing frequent manual charging. The output from the solar panel is fed into a charging module that accepts input voltages from 4.5V to 5.5V. This module leverages a constant-current/constant-voltage (CC/CV) charging method to optimize battery life and protect it from overcharge, over-discharge, and overcurrent scenarios. The charging module, with its regulated output of 4.2V at up to 1A, is designed for charging single-cell lithium-ion batteries. It features a micro-USB input, allowing flexible charging options, including from standard 5V mobile chargers, further enhancing the robot's adaptability for various power sources. To maintain stable operation even when the battery voltage drops, a DC-DC step-up converter (MT3608) is used. This converter ensures a steady 5V output essential for the robot's control electronics. With an efficiency rating of up to 93%, the MT3608 reduces power losses, thereby extending battery usage. The output current is capped at 2A, providing ample power for the Arduino and other components, ensuring consistent functionality even under low-battery conditions.

For automated recharging, the robot employs a wireless charging module based on resonant magnetic coupling, allowing it to recharge upon reaching a designated charging station. The transmitter (TX) side of this module, located at the station, requires an input of 5V with a current draw between 1.2A and 2A. The receiver (RX) coil, positioned on the robot, captures this power within a range of 2mm to 10mm and outputs a stable 5V at up to 1A. This wireless charging capability allows the robot to recharge autonomously without physical connectors, reducing mechanical wear and enabling seamless charging cycles. The RX coil's compact design (approximately 3mm in diameter) allows easy integration within the robot's body while still achieving efficient energy transfer. As the RX coil receives the transmitted power, the charging module directs it to the battery, which provides the necessary energy to power the entire system, including the motor driver and DC motors. Finally, the charged battery powers the robot's motors via the L298N motor driver, which receives the battery's stabilized voltage (typically 5V regulated by the DC-DC step-up converter) and directs power to the motors. Each motor draws around 500mA to 700mA, providing sufficient torque for the robot to navigate its path accurately. This power management configuration enables the robot to perform continuous operations, transition to the charging station as needed, and resume tasks autonomously. To monitor the battery level of the 3.7V rechargeable battery in our line-following robot, we utilize the Arduino Uno's analog input capability. Although the Arduino cannot directly measure estimated battery state of charge (SoC), it can estimate the battery’s voltage, which serves as a proxy for battery life. The reduced voltage is then fed into one of the analog input pins, where the Arduino’s analog-to-digital converter (ADC) provides a reading that represents the scaled-down battery voltage. By applying a formula to convert this reading back to the actual battery voltage, we can approximate the estimated battery state of charge (SoC).

IV. RESULTS AND DISCUSSION

The developed solar-powered wireless chargeable line-following robot represents a significant advancement toward sustainable and energy-efficient automation for industrial applications. By integrating advanced technologies such as wireless power transfer, solar energy harvesting, and autonomous navigation, the proposed system provides an innovative solution to meet the increasing demand for intelligent and energy-efficient industrial systems. The robot successfully combines multiple functionalities, including line-following capability, energy monitoring, and dynamic decision-making, within a compact, reliable, and autonomous platform. This integration enhances operational efficiency while reducing dependence on conventional energy sources, thereby contributing to the development of environmentally sustainable and cost-effective industrial automation solutions.

TABLE II. OPERATIONAL PERFORMANCE OF THE PROPOSED SYSTEM

Parameter	Performance
Path detection	Successful (blue, green, red)
Charging mode	Stationary wireless charging
Charging initiation	Battery < 25%
Charging completion	Battery ≥ 95%
Human intervention	Not required
Navigation	Autonomous
Downtime	Reduced
Energy source	Battery + solar assistance

Table II presents the operational performance of the proposed system. The results demonstrate the robot's ability to autonomously detect paths, monitor battery status, navigate to the charging station, and resume operation with reduced human intervention and downtime.

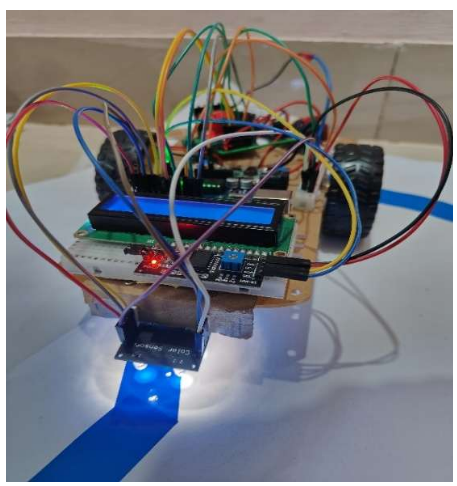

Fig. 3. Front view of the Line follower

Fig. 3. Shows the front view of the line follower. One of the primary objectives of this work was to enhance the robot's autonomy and sustainability. The incorporation of a polycrystalline solar panel allows the robot to harness renewable energy, reducing dependency on conventional charging methods and contributing to energy conservation. The wireless charging feature further improves efficiency by eliminating the need for physical charging connections, thereby reducing maintenance requirements and increasing the system's durability. Together, these features make the robot highly suitable for long-term deployment in industrial environments.

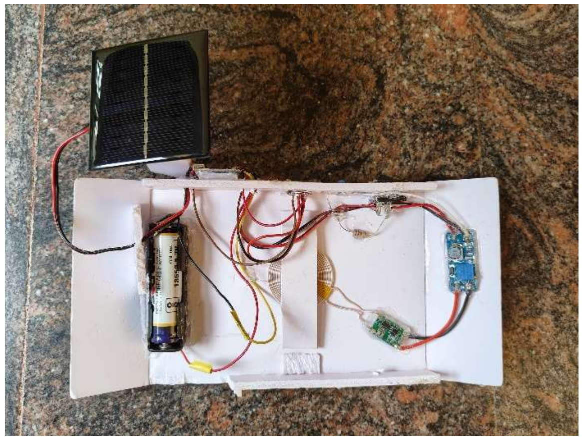

Fig. 4. Charging station of the implemented system

Fig.4. shows the charging station of the implemented system. The robot's ability to monitor its battery status in real-time and make decisions based on predefined thresholds adds a layer of intelligence to its operation. When the battery level drops below 25%, the robot autonomously navigates to the charging station by detecting a green path. The integration of a red line at the charging station ensures precise docking for wireless power transfer, and the robot resumes its tasks only after the battery level reaches 95%. This energy management strategy not only minimizes downtime but also ensures uninterrupted task execution, making the system highly efficient and reliable.

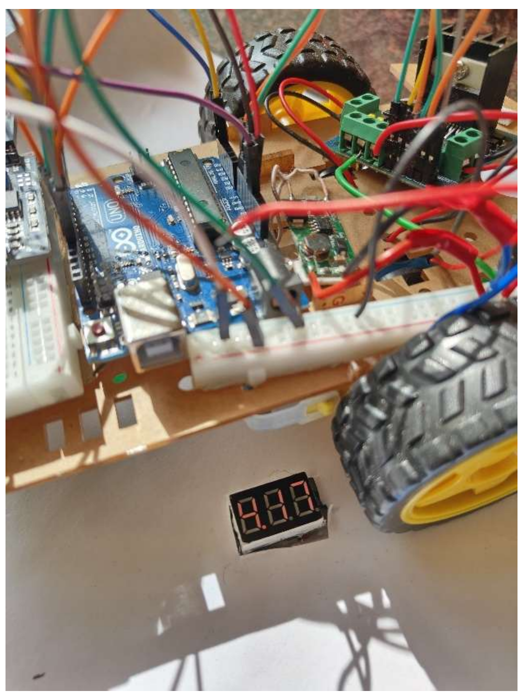

Fig. 5. Voltage display

Fig.5. shows the voltage being displayed and the use of sensors, including the TCS3200 color sensor, has enabled precise line detection and differentiation between blue, green, and red paths. This capability ensures that the robot can adapt to dynamic environments and follow its designated workflow accurately. Additionally, the Arduino Uno R3 microcontroller serves as the robot's brain, managing all sensors, motor drivers, and decision-making processes effectively. The LCD display, connected via the I2C module as shown in fig.6., provides real-time feedback, improving transparency and user interaction.

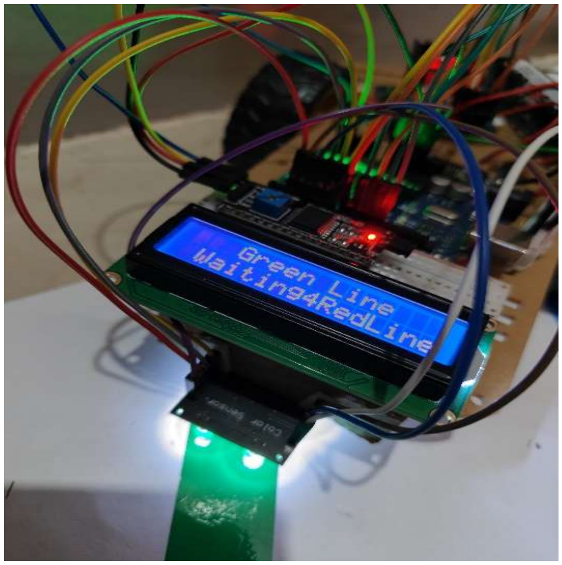

Figure 6: Line follower in green path

This work demonstrates the feasibility and effectiveness of integrating renewable energy sources with advanced technologies in autonomous systems for industrial automation. The proposed robot addresses key challenges related to energy efficiency while offering a scalable, reliable, and adaptable solution for a wide range of industrial applications, including warehouse management, manufacturing, and logistics operations. By combining sustainable energy utilization with intelligent automation, the system contributes to improving operational efficiency, reducing energy consumption, and promoting environmentally responsible industrial practices.

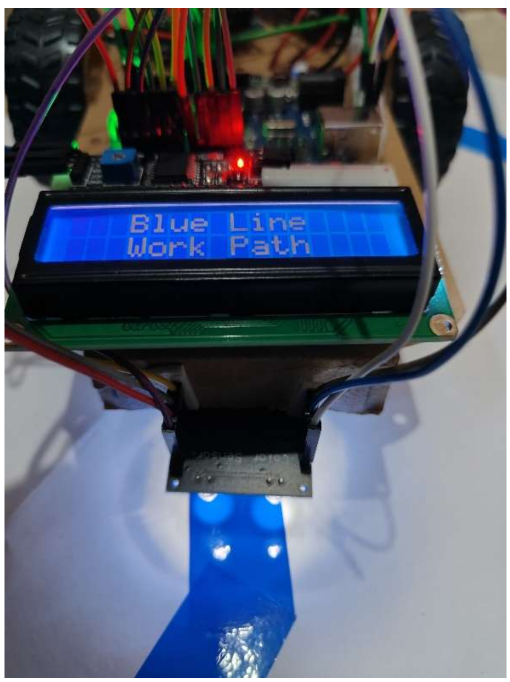

Fig. 7. Line follower in blue path

As shown in Fig. 7., the line follower robot accurately follows the blue path by detecting the line using its sensors. It continuously adjusts its direction to remain on the path and ensure smooth movement.

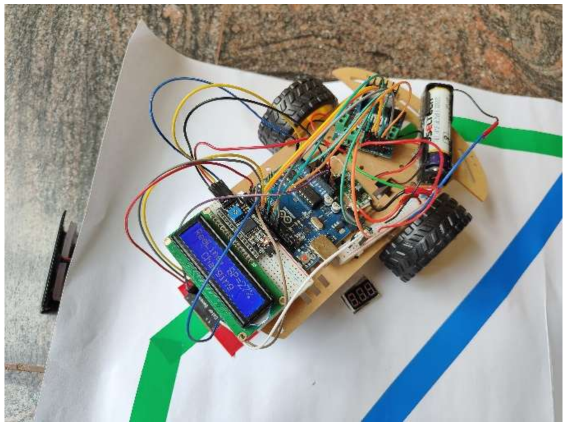

Fig. 8. Line follower at the charging station

As shown in Fig. 8., the line follower robot has reached the charging station by following the designated path. It stops at the station to enable battery charging before resuming its operation. This work highlights the practical benefits of combining renewable energy sources with autonomous robotic systems. The solar-powered wireless chargeable line-following robot serves as a proof-of-concept for sustainable industrial automation, paving the way for further innovations in the field. Future developments could include enhancements such as higher-capacity solar panels, extended wireless charging ranges, and integration with IoT platforms for remote monitoring and control. These advancements would make the robot even more versatile and capable of meeting the evolving demands of industrial operations.

V. Conclusion and Future Scope

This work demonstrates the development of a solar-powered wireless chargeable line-following robot designed to overcome the limitations of traditional wired systems in industrial applications. By integrating solar energy and wireless charging, the proposed system enhances sustainability, reduces downtime, and minimizes maintenance efforts. The robot's intelligent diversion mechanism, based on real-time battery monitoring and color-based navigation, ensures seamless charging and uninterrupted operation. The incorporation of a strategically placed solar-powered charging platform provides a renewable energy source while reducing dependency on manual interventions. This innovative solution highlights the potential of combining autonomous technologies with renewable energy systems to improve operational efficiency and reliability in industrial automation. The proposed approach lays a strong foundation for future advancements in smart robotic systems, paving the way for sustainable and efficient industrial processes.

Future enhancements for this work include integrating advanced sensors for improved path detection, implementing machine learning for adaptive navigation, and expanding the system to support multi-robot coordination. Additionally, optimizing solar panel efficiency, exploring long-range wireless charging technologies, and incorporating IoT connectivity for real-time monitoring can further enhance its industrial applicability.

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