

Design of a Sensor-Based Misalignment Detector for Wireless Electric Vehicle Charging Systems

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Abstract

Wireless electric vehicle (EV) charging has emerged as a transformative approach in sustainable mobility. However, its widespread adoption is limited by one critical challenge, coil misalignment between the transmitter (T_x) and receiver (R_x). This study presents the design, construction, and evaluation of a low-cost, sensor-based prototype for misalignment detection in static wireless power transfer (WPT) systems. The prototype is an autonomous parking and alignment automaton based on a wheeled robot. The study used three combined sensory modalities: ultrasonic, infrared (IR) and Hall-effect. Under controlled experimental conditions, the system reliably detected alignment. The Hall-effect sensors were used to verify that the terminal coil positioning, IR, and ultrasonic systems synchronised robot operations throughout the manoeuvre. The results of this study suggest that sensor-based detection can effectively support alignment accuracy and serve as a basis for future motorised and AI-assisted coil positioning in real-time EV charging systems.

Keywords: Wireless Power Transfer (WPT), Misalignment Detection, Electric Vehicle (EV), Hall Effect Sensor, Infrared Navigation, Autonomous Parking, Coil Alignment.

1. Introduction

Decarbonisation of transport is core to mitigating greenhouse gas emissions and achieving far-reaching sustainability goals [1][2][3]. Wireless power transfer (WPT) for charging electric vehicles (EVs) can increase user convenience and reduce mechanical stress compared to plug-in systems [4]. However, widespread adoption of WPT has been hampered by its high dependence on coil alignment [5], be it horizontal or vertical misalignment. Such misalignment may reduce power induction to 60%, leading to energy loss, longer charging periods, and significantly higher infrastructure charges. In public and commercial parking scenarios where parking is not possible, a system that can detect and even correct misalignment is therefore absolutely mandatory. The current work proposes a sensor-based demonstrator that recreates coil-alignment sensing

during EV charging, thereby alleviating one of the longest-standing challenges of wireless charging.

2. System Architecture and Methodology

A functional prototype was constructed using readily available and affordable components to simulate a real-world parking and alignment scenario. The system's architecture integrates both hardware and software components to model the alignment behaviour of an electric vehicle concerning a stationary wireless charging pad.

To understand the magnetic coupling in WPT systems, the induced voltage is given by Faraday's Law [6] in Equation 1:

$$V = -M \frac{dI}{dt} \quad (1)$$

where M is the mutual inductance and dI/dt is the rate of change of current.

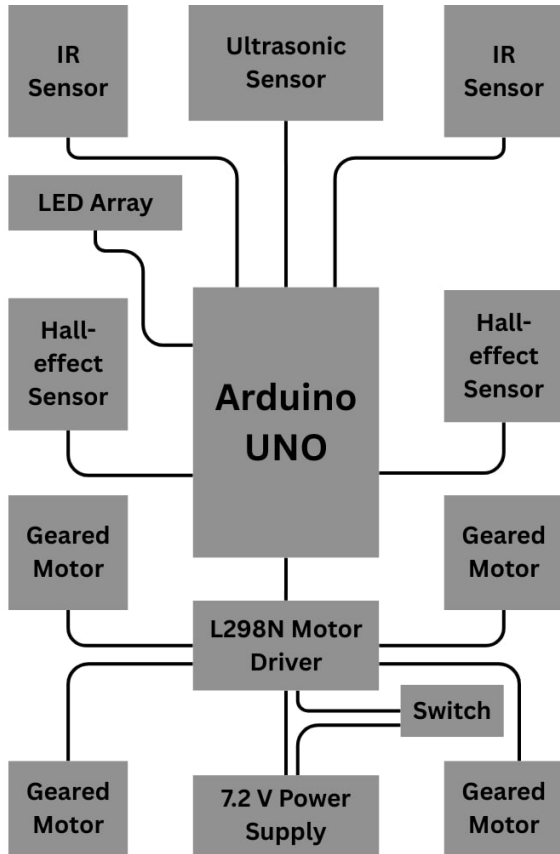


Figure 1: The schematic block diagram of the prototyped system

However, the wireless systems also use LC circuits. The resonant frequency in Equation 2 [7]:

$$f_0 = \frac{1}{(2\pi\sqrt{LC})} \quad (2)$$

where L is inductance, and C is capacitance.

Power transfer efficiency (η) is calculated by Equation 3 [8]:

$$\eta = \left(\frac{P_{out}}{P_{in}} \right) \times 100\% \quad (3)$$

where P_{out} is the power output and P_{in} is the power of the EV system

Heat loss (Q), due to inefficiency, it is modelled by Equation 4 [9]:

$$Q = (1 - \eta) \times P_{in} \times t \quad (4)$$

where t is time.

2.1. Hardware Components

The core of the prototype consists of a wheeled robotic platform powered by two geared DC motors for mobility. Key hardware components are included as shown in Figure 1:

i. **Arduino Uno Microcontroller:** Acts as the control unit, receiving data from the sensors and issuing motor control commands accordingly.

ii. **Infrared (IR) Sensors:** The sensors are mounted under the chassis and detect black lines on the surface, enabling the robot to follow a predetermined course to a charging pad.

iii. **Ultrasonic Sensor (HC-SR04):** Positioned at the front of the robot, this sensor continuously measures the distance to obstacles or to the charging zone. It serves as a proximity detector to trigger stopping behaviour as the vehicle approaches the coil alignment area.

iv. **Hall Effect Sensors (KY-035):** Placed on top of the robot to detect magnetic fields embedded in the test area. These sensors simulate final confirmation of alignment when the robot reaches a magnetic marker representing the transmitter coil location.

2.2. Software and Control Algorithm

A real-time control algorithm was programmed into the Arduino to coordinate the robot's movement and sensory decisions. The algorithm follows this logic:

i. **Line Following:** The robot begins by following a dark guideline using IR sensors.

Proximity Sensing: As it nears the simulated charging pad, the ultrasonic sensor determines when the robot is within $\sim 10 - 15 \text{ cm}$ of the target.

ii. **Final Alignment Check:** Once in close proximity, Hall effect sensors check for a magnetic field. If both sensors activate simultaneously, alignment is considered successful.

iii. **Stopping Mechanism:** As soon as the robot gets the right position, it stops. The modular design proposed here breaks the task execution into three sequential stages: guidance, proximity detection, and alignment detection. Movements between stages are achieved by particular, definite sensory inputs. This architectural isolation allows each sensor to independently perform performance evaluation, free of confounding factors introduced by other sensor modalities.

3. Methods

The prototype's performance was systematically examined through a set of controlled laboratory experiments. These tests were replications of plausible EV parking situations and tested how the system would differentiate between aligned and misaligned

positions. The relationship between the system's physical layout and a general hardware implementation is shown in Figure 2.

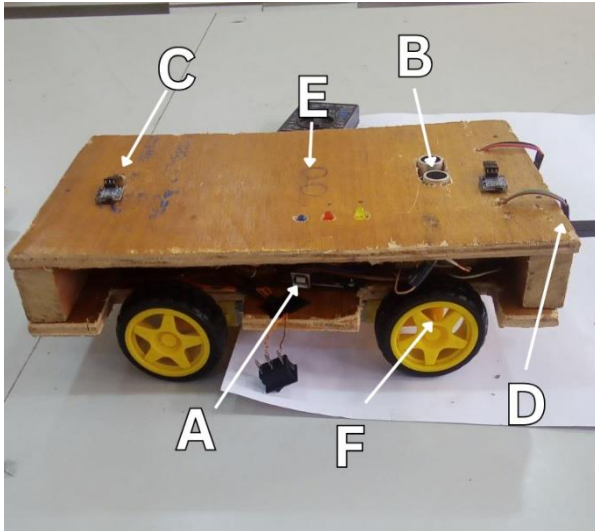


Figure 2: Prototype sensor-based misalignment detection

The Arduino Uno microcontroller (A) serves as the issuing command microcontroller, which interfaces with the ultrasonic sensor (B) that measures distance and detects obstacles. The positions of magnetic markers are used to provide feedback to the robot via a pair of Hall-effect sensors (C). IR sensors (D) are mounted at the front to follow lines, guiding the robot's movement. All these components are assembled on a custom-built wheeled robot chassis (E), driven by geared motors (F) to ensure stable and controlled motion.

3.1. Test Environment

An experimental system was designed on a plain surface using black tape to create visual routes for infrared (IR) navigation. A magnetic marker, which in this case was a neodymium magnet, was placed in the charging zone to simulate the transmitter coil. Intensive controls were implemented to isolate environmental factors in this study and determine their effects on sensor performance. The test setup was made up of three major components:

- i. IR paths to test navigation
- ii. Magnetic strip for Hall effect testing
- iii. Walls and soft barriers to test proximity control.

3.2. Testing Scenarios

Four main test scenarios were executed:

i. Scenario A: Straight Navigation to Charging Zone

The robot followed a straight black path toward the magnetic marker. IR sensors showed high consistency in line detection. Upon nearing the target, the ultrasonic sensor accurately detected proximity, and both Hall sensors activated when the robot was centred over the magnet.

ii. Scenario B: Lateral Misalignment

The robot was deliberately offset from the path. While IR sensors attempted correction, the robot reached the target area with only one Hall sensor activated, indicating partial alignment. The ultrasonic sensor still prompted a stop, but alignment was unsuccessful.

iii. Scenario C: Angular Misalignment

The robot approached at an angle. The IR guidance failed to properly realign it, and only one Hall sensor detected the magnetic field. This emphasised the system's current inability to detect angular deviation.

iv. Scenario D: Obstacle in Path

A barrier was placed in the robot's trajectory. The ultrasonic sensor triggered a stop at ~12 cm, preventing collision and demonstrating effective object detection and reactive behaviour.

Table 1: Outcome of the tested sensor-based alignment EV

Test condition	Outcome
IR-guided navigation	Accurate path following
Proximity detection (Ultrasonic)	Reliable stopping near target (~10 – 15 cm)
Magnetic alignment (Hall)	Only triggered within 1 – 3 cm of the marker
Lateral/Angular misalignment	Detected by a single Hall sensor activation
Obstacle avoidance	Robot halted safely before contact

These tests confirm the reliability of individual sensor systems while revealing the current limitations in angular alignment recognition and early magnetic field detection.

4. Discussion

The results of the prototype tests will be discussed below, providing an interpretation and the consequences of these findings for the applicability of true wireless electric vehicle (EV) charging system

designs. Much focus is on the measured attributes of each sensor, the system's overall capacity to detect a lack of alignment, and how these results are translated into practical, informative use.

4.1. Sensor Performance Analysis

The results revealed distinct strengths and limitations for each sensor type:

i. Hall Effect Sensors

Hall-effect sensors had a detection range of about 1 to 6 cm, which allowed accurate coil validation during the last deployment. However, this limited range of operation under detection precluded tracking the coil position during the vehicle approach. The results show the importance of utilising a sensor with greater magnetic-field sensitivity in a large-scale implementation.

ii. Ultrasonic Sensor

The ultrasonic sensor precisely detected the obstacles, and a reliable distance approximation to the charging zone was achieved (10-15 cm). Despite its ability to prevent the robot from overshooting the charging point, the device subjectively lacked the positional accuracy required for each successive coil alignment adjustment. This being the case, the ultrasonic sensors are best suited as a secondary aid for guidance, rather than as a primary detector of coil positioning.

iii. Infrared (IR) Sensors

The IR sensors reliably guided the robot along predefined paths. This low-cost navigation approach mimicked real-world lane-assist systems and proved robust for guiding vehicles toward a charging pad. However, IR sensors cannot directly detect coil misalignment and must work in combination with other sensors.

4.2. Misalignment Detection Capability

The prototype had adequate discrimination on the aligned and misaligned parking setups. Both Hall sensors were activated when the vehicle was fully aligned, both longitudinally and laterally, confirming that everything was properly aligned. Partially lateral misalignment, as well as angular misalignment, resulted, on the other hand, in activation only of one Hall sensor, indicating that the lateral misalignment was not fully achieved. Due to the nature of detection (binary), the sensor array was utilised to simulate coil-alignment confirmation, and it displayed the ability to

detect errors in the positioning. However, non-motorised correction facilities denied the system the capability to provide anything beyond diagnostic feedback, rendering it unfeasible in practice.

4.3. Prototype Effectiveness and Limitations

Overall, the prototype validated the concept of sensor-based misalignment detection. The robot consistently followed the guided paths, stopped within the designated zone, and accurately identified coil misalignment.

Despite these successes, several limitations were observed:

i. The short detection range of Hall sensors limited early misalignment detection.

ii. Angular misalignment could not be quantified due to sensor placement.

iii. Absence of real wireless power transfer hardware prevented evaluation of energy transfer efficiency under misaligned conditions.

4.4. Implications for Wireless EV Charging

Empirical evidence, however, indicates that integrating inexpensive sensors into wireless charging systems significantly increases alignment precision. During operation, a greater range and increased angular resolution of the sensors are achieved, providing real-time information that can allow relocating vehicles to be detected or transmitter coils to be adjusted on-the-fly. At the same time, we could automate the alignment correction process once the given energy-gathering area is detected by sensors and feedback-controlled actuators, thereby avoiding energy loss and increasing charging efficiency. This approach would make static wireless EV charging systems more practical for public and commercial parking environments where manual precision is difficult to achieve.

4.5. Summary

The prototype demonstrated a proof-of-concept of misalignment during wireless charging of EVs. Despite its limited scope and hardware, the research has shown that basic sensors can consistently determine the status of end-coil alignment. The needs of the future in design and development include implementing high-end sensors, providing robust wireless power hardware, and deploying automatic repositioning devices to achieve comprehensive and effective cordless EV charging technology.

5. Conclusion

This research presents a cost-effective prototype that detects coil misalignment in static wireless EV charging systems using off-the-shelf sensors. The suggested system demonstrates that, even with a relatively simple setup, the linear alignment position can be confirmed using low-cost magnetic and proximity sensors. The practice is further enhanced by integrating IR navigation sensors with ultrasonic distance-measuring sensors.

Further studies should focus on integrating higher-range magnetic sensors or magnetometers to achieve better spatial resolution and more precise detection of the coupled magnetic field. Also, incorporating accelerometers or gyroscopes to detect angular misalignment between the transmitter and receiver, allowing for dynamic behaviour analysis.

These improvements can elevate wireless power transfer (WPT) technology [10], making it more convenient, highly efficient, and feasible for large-scale deployment in electric vehicle (EV) applications.

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