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VISTA

Implementation of Wireless Charging in a Mobile Robot

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A B S T R A C T

This paper discusses the design and component-level implementation of a teleoperated mobile robot featuring a custom-built wireless charging system. The System consists of a mobile robotic vehicle and a stationary charging dock. The Mobile Robot is constructed using an ESP32 Microcontroller for Wi-Fi-based manual control, an L298N motor driver for locomotion, and a 3S Lithium-ion battery pack with an Integrated Battery Management System (BMS) for power.The charging station uses an Arduino microcontroller to manage activation of the Power for Station. A key innovation of this research work lies in the development of a wireless power transfer (Wireless Power Transfer) system from separate components. It avoids pre-fabricated modules. The transmitter circuit at the station is based on a NE555 IC-based module fora Frequency Duty Cycle Adjustable, which drives an IRF540N MOSFET to energise a hand-wound transmitter coil. The wireless circuit is completely in-house designed.This paper provides a detailed architecture of the system, its working, and operational workflow.After successful assembly and testing of both the transmitter and receiver circuits, the system exhibited functional wireless charging within a 1–3.5 cm air gap. Wireless charging efficiency was 70.4%. The transmitter produced a variable output voltage ranging from 5V to 14V, depending on coil alignment and distance.

Keywords : *Wireless Power Transfer (WPT), Inductive Coupling, Mobile Robot (MR), Charging Efficiency, MOSFET.*

1. Introduction :

In the 21st century, robots are used for various purposes in hospitals, disaster zone relief, patrol systems, product delivery, hazardous areas, cleaning large buildings, office automation, dangerous environment detection, and ware houses [1, 2]. The development has been taking place in the field of automation. Mobile robots used are air-based mobile robots, land-based robots. A major limitation in the robotic infrastructure is its limited battery life and the need for repetitive charging. In a conventional charging infrastructure, charging is done with wired connections or charging systems that require physical contact [3]. Thus, it raises issues such as physical damage, an increase in operational downtime, and requires human intervention [2, 4]. So, for this problem best solution was wireless power transfer (WPT). In this paper WPT system station and a mobile robot were used for the demonstration of WPT in a mobile robot, via a wheeled mobile robot.

1.1 Wireless Power Transfer System for Mobile Robot :

Wireless Power Transfer (WPT) is done through inductive coupling, magnetic resonant coupling, and electromagnetic radiation. Among these, the best-suited system for a wireless power transfer for a mobile robot is Inductive Coupling. WPT enables a system to transmit electrical energy through an air gap without a physical connection [5]. Inductive Power Transfer (IPT) is based on inductive coupling. It offers an efficient and reliable method for short-range charging [6]. Integrating WPT with a fixed charging dock enables mobile robots to recharge autonomously, reducing downtime and increasing system autonomy without human intervention [2, 6]. A wireless power supply system is used for charging the battery of a Mobile Robot (MR). The Wireless Power Supply System consists of three parts: transmitter, receiver, and voltage converter. The primary and secondary coils are coupled to each other by mutual induction. Power is transferred to the receiving circuit, and the charge is stored in the battery [1]. This review discusses the design, real-life implementation, and study of a remotely operated mobile robot with a wireless charging system.

A basic innovative improvement for the WPT system is to create a circuit with individual components rather than using pre-fabricated modules to provide an in-house designed solution. The system has an ESP-32 Wi-Fi-based manual control and an Arduino to actuate the charging station. The transmitter circuit uses an NE555 timer to generate a pulse-width modulated signal that drives the MOSFET (IRF540N), which in turn energises the transmitter coil. The receiver circuit receives induced electricity and converts it into DC electricity for charging a battery with a Battery Management System (BMS). The system has been tested and worked properly with an air gap of 1 cm -3.5 cm with wireless charging efficiency of 70%. The main objectives are development of real-life testing of a custom-made Inductive Power Transfer system, complete system segmentation, and analysis of workflow for the Mobile Robot and fixed charging station, as well as evaluating charging efficiency by analysing the air gap between two coils.

2. Literature Review :

The servey of literature was conducted for limitetions in mobile robotics, wireless power transfer as follows.

2.1 Operational Limitations in Mobile Robotics :

The primary limitation of Mobile robots is their limited battery life. Normally, charging is done via wired connections or systems requiring physical contact [3]. Key issues with mobile robots are physical damage, the need for human intervention, and increased operational downtime [2, 4].

2.2 Wireless Power Transfer (WPT) :

Wireless Power Transfer (WPT) allows a system to transmit electrical energy via an air gap without a physical connection. Among the available methods, Inductive Power Transfer (IPT), based on inductive coupling, offers an effective and reliable method for short-range charging [5, 6]. WPT reduces downtime and helps automate the system [6]. The Resonant Inductive Power Transfer (RIPT) is particularly effective for semi-autonomous robots for maintaining stability even under varying environmental conditions [7].

2.3 Theoretical Framework and Principles :

This system works on the principle of inductive coupling. The system converts DC power into a high-frequency oscillating magnetic field via a transmitter, which induces an electromotive force (EMF) in the receiver coil [8]. This induced energy is then rectified into a stable DC voltage to charge the onboard battery [9].

2.4 Technical Barriers (misalignment and alignment) :

Manual winding is dificult with the same consistency and specification. There is effect of turning ratio of the coil, and the effect of winding space on the inductance value and system performance [10]. Vertical misalignment (air gap) or lateral distance between the coils weakens the magnetic field [8]. Researchers have emphasised that lateral misalignment is the main reason for the efficiency drop in wireless charging [11]. Accurate positioning is the technical problem resulting in reduction of the efficiency of WPT [7].

3. Methodology :

The mobile robot system architecture and charging station are discribed as follows.

3.1 System Architecture :

The project is architecturally divided into two main subsystems: Mobile Robot and stationary charging station.

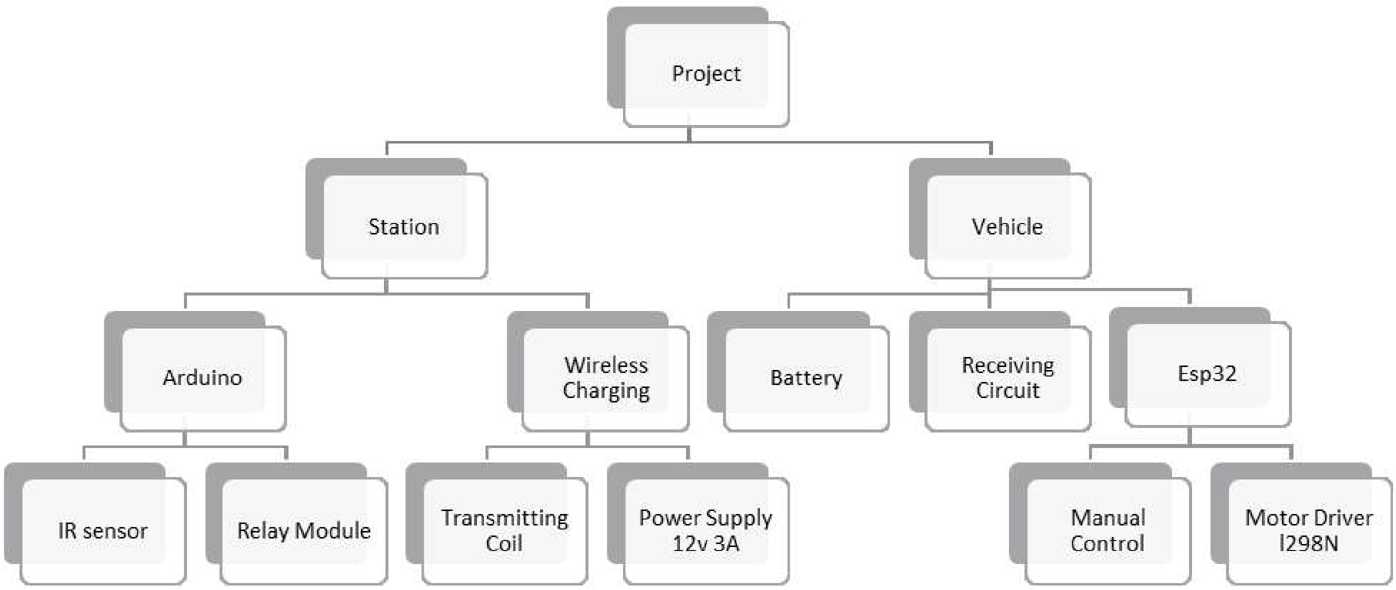

Fig.1. Project Structure Diagram

3.1.1 Mobile Robot Subsystem :

The mobile component of the project integrates control, locomotion, power, and the wireless charging receiver. The wheeled robot is used in this project, as it is a type of mobile robot. Manual Control for ESP32 hosts a web server that can be accessed through IP (Internet Protocol), and provides a control interface with buttons for forward, backwards, left, and right movements [12]. This allows the operator to teleoperate the robot from any device with abrowser on the same network. Locomotion is provided by a 4-wheel-drive chassis with four DC "Battery Operated" motors the power distribution and controlled by an L298N Dual H-Bridge. The Microcontroller ESP32 sends digital signals to the L298N's input pins to control the direction and speed of the motors.

The Mobile Robot is powered by a 3S (10.8 V nominal) Lithium-ion battery that is 3C rated. 18650 mAh, and the power supply received by the receiving circuit was handled by the LM2596S DC-DC Buck Converter, which is set to regulate the voltage to 12V.

3.1.2 Wireless charging Power Receiver:

Bottom side of the MR, receiving coil (L2) coil is the place of the mobile robot, receiver circuit captures energy induced by the TX coil, wireless energy is in AC and converts it into DC power for battery charging [13]. It is constructed from the following components.

a. **Receiving Coil (L2):** It was placed in an oscillating magnetic field then this coil receives an alternating current (AC).
b. **Bridge Rectifier:** Four diodes or a W04M full bridge rectifier convert the induced Power AC from the coil into direct current (DC).
c. **Capacitor :** Electrolytic capacitor (1000µF, 50V) smooths out the pulsating DC.
d. **Buck Converter :** The buck converter is set to output a voltage of 12V, 2.2A (max)

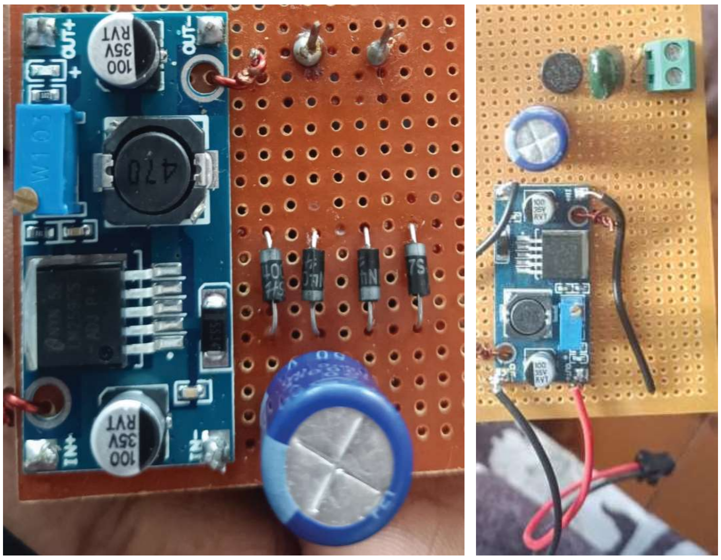

Fig. 2. Receiver Circuit

3.1.3 Charging Station Subsystem :

The station is automated by an Arduino microcontroller. It is used to control when the power transmitter circuit is active. An infrared (IR) sensor is used to detect the presence of the robot. When the robot is positioned in front of the station, the IR sensor sends an input signal to Arduino Uno about state changes. Relay module is connected to Arduino Uno based on the IR signal input. Arduino controls the relay module. IR detects motion input signal, sends to Arduino, Arduino sends output signal to the first-channel relay module. In this case, the relay switches the 12V main power supply for the transmitter circuit.

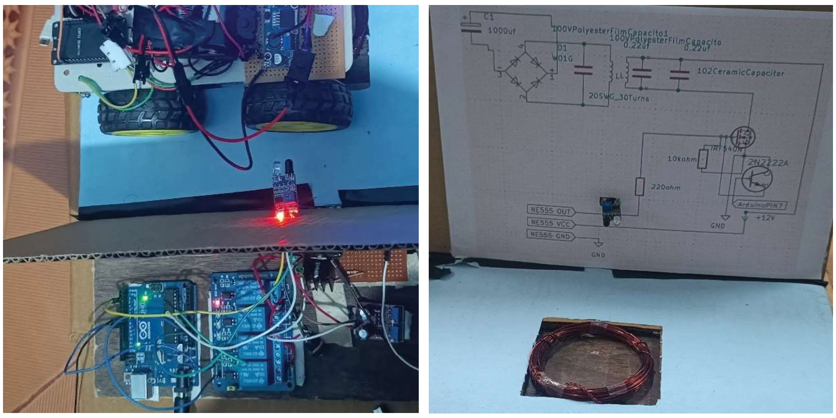

Fig. 3. Charging Station via Arduino, Relay Module and TX circuit

3.1.4 Wireless Power Transmitter Circuit (TX) :

This circuit is responsible for generating the high-frequency alternating electromagnetic field, this field induces an electric current in the RX coil.

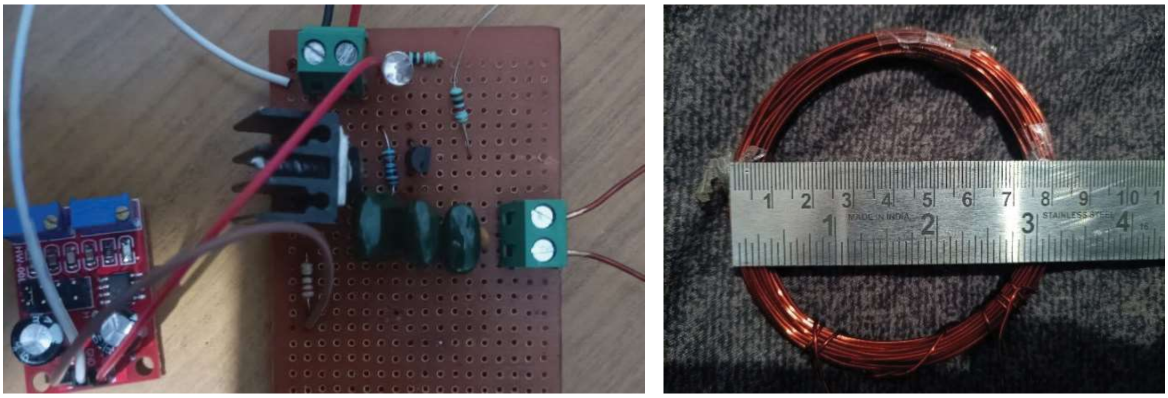

Fig. 3. Transmitting Circuit

Hand-built circuit was developed using the following components:

a. **Power Supply:** A 12V, 3A DC power adapter used for the power supply for the TX circuit.

b. **NE555 Module:** The NE555 Pulse Frequency Duty Cycle Adjustable Module transmitter is an NE555 timer IC configured as an astable multivibrator. This module is used to generate a continuous square wave (a high-frequency oscillating signal) which can be set from 10KHz to 200KHz.

c. **2N2222A Transistor:** Used to drive the MOSFET's gate, it switched on and off rapidly. The MOSFET is used as a high-speed, high-power switch. The output from the NE555 is not high enough to drive the MOSFET Gate Pin, so a 2N2222A transistor is used to switch a power MOSFET (IRF540N).

d. **Polyester capacitor:** The 100V, 0.22µF polyester capacitor creates a resonant LC circuit with the transmitter coil.

e. **Transmitter Coil (L1):** IRF540N MOSFET drain pin is connected to one end of the transmitter coil, while the other end is connected to the 12V supply [6]. The frequency is set on the NE555 by use of a jumper and a potentiometer, which creates a square wave. The fast-switching current creates an oscillating magnetic field around the coil, which is induced.

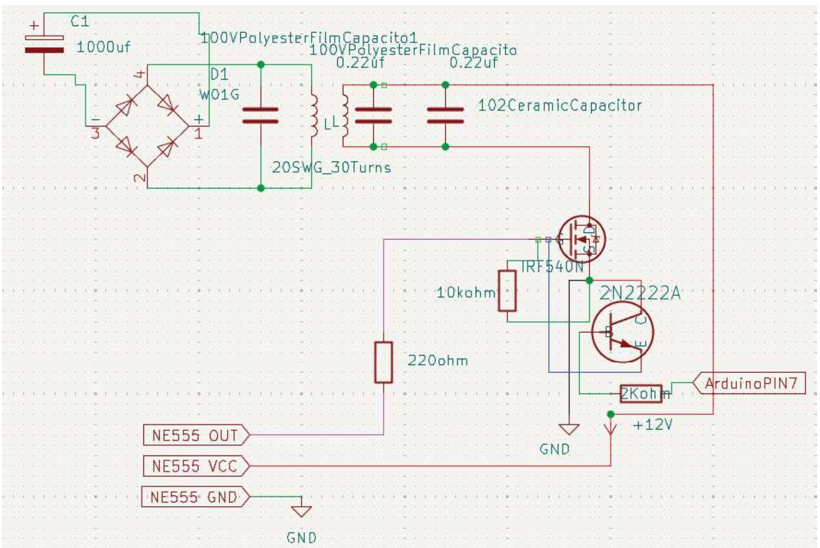

Fig. 4. Inductive Coupling circuit Diagram of TX and RX

3.2 Wireless Power Transfer (WPT) Circuit Design :

Wireless charging works on the principle of inductive coupling. Two main circuit transmitters convert 12V DC power into a high-frequency oscillating magnetic field, and a receiver on the robot captures the induced magnetic field, converting it into stable DC to charge the battery without any physical connection [8].

3.2.1 Transmitting Circuit :

The transmitter circuit is generating a high-frequency oscillating magnetic field [13]. It is generated by an NE555 timer module, which acts as the signal generator, and an IRF540N MOSFET for power switching.

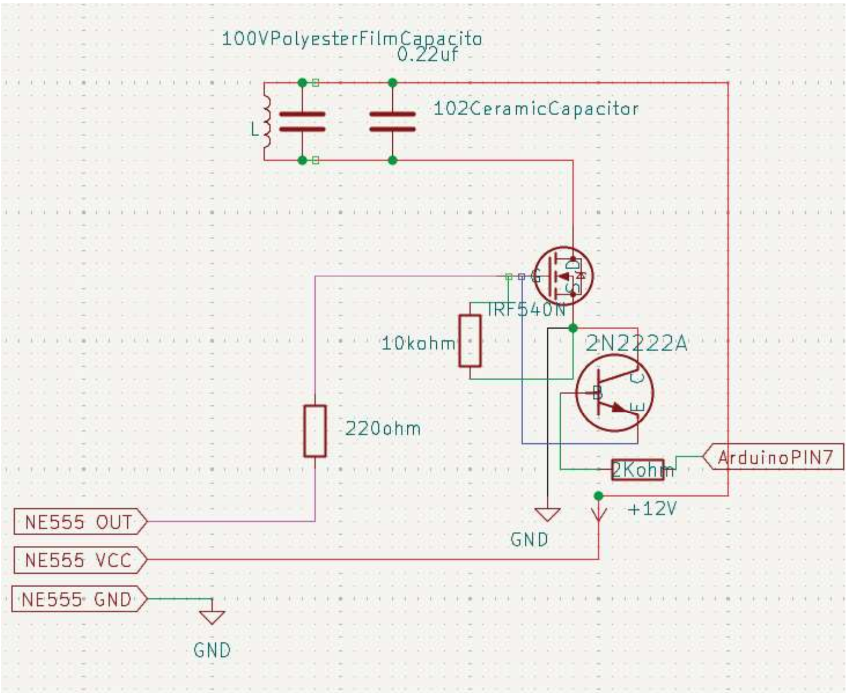

Fig. 5. TX Circuit of Wireless Charging Diagram

The Transmitter Coil (L1) consists of 30 turns of 20 SWG with 8.4cm diameter insulated copper wire. When activated, the NE555 Module generates a square wave signal to control the frequency of the circuit. A transistor (2N2222) used as a switch for IRF540N MOSFET. This MOSFET rapidly switches the DC power to the transmitter coil (L1), converting the DC into a high-frequency AC by on/off switching. It generates an oscillating magnetic field that induces an EMF in a receiving coil [8].

3.2.2 Receiving Circuit :

The L2 coil, below the chassis ground distance of 0.8 mm from the mobile robot, captures induced energy from the transmitter's oscillating magnetic field. A bridge rectifier for AC-to-DC conversion, and a C1 capacitor for smoothing the output. After converting it into a stable DC voltage for charging the onboard battery[9]. The stabilised DC voltage across the 1000 µF capacitor is connected to the LM2596S DC-DC buck converter. This is set to regulate the voltage to 12V for charging the mobile robot.

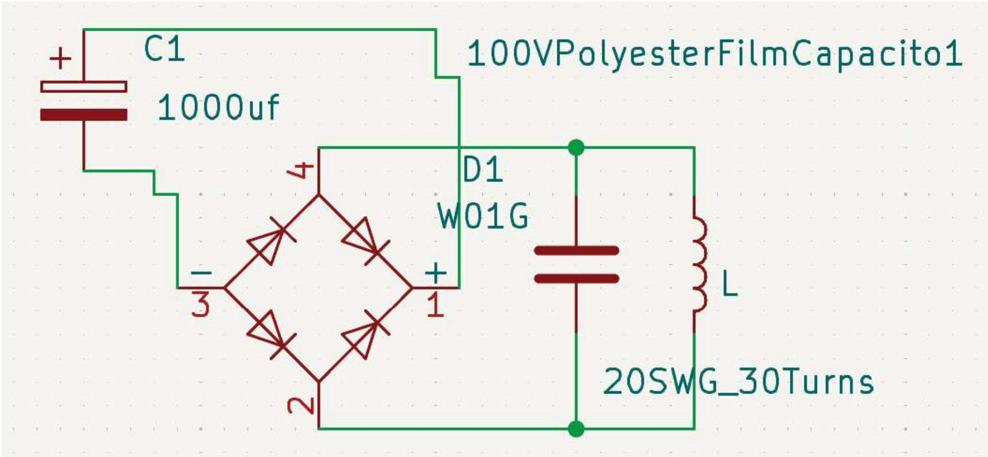

Fig. 6. RX Circuit of Wireless Charging Diagram

3.3 Software Flow of Operation :

The complete software operation can be divided into two main phases:

A. Locomotion (Robot in Operation)

- The ESP32 initialises Wi-Fi
- The robot ESP32 connects to the Wi-Fi network
- The user accesses the robot control bytyping the ESP32 IP address in a browser
- Commands (Forward, Backwards, Left, Right, Stop) are sent via the web interface
- The ESP32 processes the commands and drives the motors through the L298N motor driver
- This locomotion is controlled by a tele-operator to operate the Mobile Robot

B. Charging (Automatic Wireless Charging)

- The Mobile Robot teleoperated toward the charging pad.
- The IR sensor for detecting motion. Based on motion detection, send an input signal to Arduino Uno.
- Arduino activates the relay, turning on the wireless transmitter.
- The L2 coil on MR converts the induced EMF into a DC voltage.
- Regulate the output voltage of the 3S Li-ion battery through the BMS.
- The IR sensor sensesif no object is detected sends Arduino switches off the transmitter.

Due to automation, this method of wireless charging is safe, efficient, and contactless charging without manual involvement.

3.4 Challenges :

a. **Winding:** Manually winding two coils with exactly 30 turns and equal diameters is challenging. Any inconsistencies in winding tension, turn spacing, or overall shape will result in different inductance values (L) for each coil [10].

b. **Lateral Misalignment:** The translational offset along the X or Y axis, where the centres of the coils are no longer aligned.

c. **Angular (or Rotational) Misalignment:** orientation of coil is perpendicular to the z axis of MR based on orientation efficiency effects (the axis perpendicular to the coil planes).

d. **Vertical Misalignment (Air Gap):** The distance between the two coil planes. An air gap is necessary; increasing it beyond the design optimum weakens the magnetic field and reduces coupling [8,10].

A 2N2222A NPN transistor is used as an intermediate driver between the NE555 output and the MOSFET gate, which is parallel connected to the MOSFET. The NE555 alone cannot supply enough current to rapidly charge and discharge the MOSFET's gate. Slow gate switching causes heating and losses. It was challenging, and the solution was to use Switch, which needs to open and close rapidly to the MOSFET gate and Source pin, and the solution was a 2A2222A transistor.

3.5 Measure Charging Efficiency :

Efficiency is based on energy, not current or voltage alone.

1. Measure Input Power (to the charger or BMS)

If Input Voltage (V_{in}), Input Current (I_{in}), then one can evaluate Input Power as

Input Power, $P_{in}=V_{in}\times I_{in}$

2. Measuring Battery Output Power

At the battery terminals, one can determine output power of battery by measuring Battery Voltage (V_{batt}) and Charging Current (I_{batt}) as follows:

Output Power: $P_{out}=V_{batt}\times I_{batt}$

Charging Efficiency [14]: $\eta=\frac{P_{ou}}{P_{in}}\times 100$

e.g. Using the 12V and 3A Charger for the Wireless Charging Unit:

Input Power from the Charger: V_{in} = 12.0 V, I_{in}= 3.00 A

$P_{in}=12\times 3=36$ W

Initial Observation at the terminal of Battery Management System of Mobile Robot:

V_{batt}= 10.8 V (charging a 3-cell Li-ion pack), and

I_{batt}= 2.2A (current reduces because of the conversion losses of the buck converter)

$P_{out}=10.8\times 2.2=23.76$ W

Charging Efficiency:

$$\eta=\frac{23.76}{36}\times 100=66.7\%$$

4. Results and Discussion :

The results of wireless charging as compared to wired charging are discussed as follows.

4.1 Results :

After testing transmitter and receiver circuits, the wireless charging is within a 1–3.5 cm air gap. The transmitter produced a variable output voltage ranging from 5V to 14V, depending on coil alignment and distance. All results in Table 1 were tested in a 0.5 cm air gap and a 12V 3A DC charger for power.

Transmitter Frequency: Approximately 25 kHz–200 kHz

Receiver Output Voltage: ~13.8 V

Regulated to 12V 2A by use of LM2596S DC-DC Buck Converter

Table 1. Result of wireless charging compared to wired charging

Sr.No.	Voltage Range (V)	Wireless Time (min)	Wired Time (min)	Time Difference (min)	Wireless Efficiency (%)
1	9.0 – 9.5	12	8	4	66.7%
2	9.5 – 10.0	14	10	4	71.4%
3	10.0 – 10.5	16	11	5	68.7%
4	10.5 – 11.0	18	13	5	72.2%
5	11.0 – 11.3	15	11	4	73.3%
6	11.3 – 11.7	17	12	5	70.5%
7	11.7 – 12.01	20	14	6	70.0%
Average	**10.42 – 10.85**	**16.0**	**11.3**	**4.7**	**70.4%**

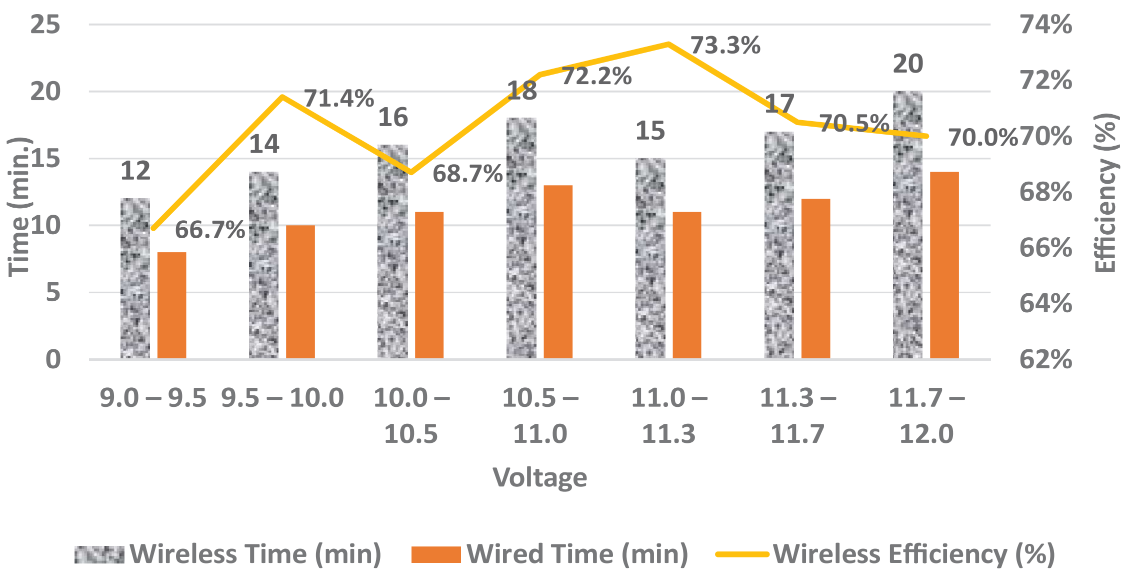

Fig. 7. Comparison of Wireless and Wired charging for time and range of voltage

4.2 Discussion :

The results obtained have following key observations.

1. Charging efficiency dropped significantly with coil misalignment greater than 1 cm.
2. The temperature of the MOSFET and coil increased after extended operation (>10 min) due to heating.
3. Stable charging was achieved when the robot's receiver coil was centred directly above the transmitter coil.
4. The performance of the robot's motors and Microcontroller ESP32 was consistent.
5. Interference of EMF was not observed on the performance of electronic components with wireless charging.

5. Conclusion :

This paper presents the design, implementation, and evaluation of a wireless charging for battery of Mobile Robot. The unit contains a customised wireless charging system. The paper gives narrations on the Wireless Power Transfer (WPT) system using individual components such as the NE555 module, the IRF540N MOSFET, and hand-wound coils. The unit developed to demonstrate an in-house designed solution for wireless charging.

In Inductive Power Transfer (IPT), the transmitter coil generates a magnetic field, which induces an EMF in the receiver coil. Few tests were conducted to demonstrate that the system achieved operational wireless charging across an air gap of 1 cm to 3.5 cm. The evaluated performance indicates an average Wireless charging efficiency of 70.4% upto 0.7 cm air gap between wireless charging primary and secondary coils.

The charging stability and efficiency are dependent on coil alignment. The charging voltage drops drastically when there is misalignment greater than 1 cm. Technical challenges like low voltage to the gate pin for switching the MOSFET are addressed by using a 2N2222A transistor. Overall, this project demonstrates the practical use of wireless charging in the Wheel Mobile Robot and different types of Mobile Robots / Drones.

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