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Wireless Power Transfer System for Mobile Robots via Magnetic Resonant Coupling with Impedance Matching

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Abstract

Wireless power transfer via magnetic resonant coupling can be used to supply power to a mobile robot within a few meters of a transmitter coil. However, when the robot moves or its power consumption fluctuates, its input impedance varies and causes power reflection. Therefore, we propose the use of a driver coil on the transmitter side to match the input impedance. The input impedance is matched and power reflection is eliminated by regulating the coupling coefficient between the driver and the transmitter. During experiments, the transmitting efficiency showed good agreement with the calculated value, and the input impedance was matched under varying distances and load resistances. Therefore, the proposed system was demonstrated to solve the power reflection problem in mobile robots.

Key Words: Wireless power transfer, Mobile robot, Impedance matching, Coupling coefficient, Driver coil

Introduction

In recent years, various unmanned mobile robots, such as automated guided vehicles and autonomous mobile robots (AMRs), have been widely studied and developed [1–5]. In particular, AMRs that fly near the ceiling, including drones, could be used for automatic surveillance in warehouses to eliminate the blind spots of surveillance cameras [6] or for serving customers indoors to make effective use of space [7, 8]. However, in both these applications, the power supply method remains an unsolved problem because the robot must fly continuously over a wide area. A wired power supply is limited by the cable length and the risk of tangling the cable. Further, a battery-only power supply is limited by the battery capacity, and the larger the capacity gets, the heavier the battery gets. Therefore, these power supply methods are undesirable for AMRs. As an alternative, wireless power transfer (WPT) is considered an effective power supply method, and is being actively researched [9, 10].

WPT is of two main types: radiative and nonradiative [11]. This study uses magnetic resonance coupling, a type of nonradiative transfer. In this method, inductor and capacitor (LC) circuit resonance is used to transmit power over longer distances than in the case of inductive coupling alone [12]. This approach is being investigated for applications such as power supply for electric vehicles (EVs) and implantable medical devices like artificial hearts [13–17].

As shown in Fig.1, this study proposes a system in which several transmitter coils are installed in the ceiling at constant intervals to supply power, and the receiver coil is mounted on the flying robot. The robot then receives power from the nearest transmitter coil.

Most existing and proposed technologies for applications such as power supply for EVs during the stoppage period [18–20] assume conditions in which the distance between the transmitter and receiver coils is almost constant. The distance between coils changes with vertical and horizontal movements in WPT for mobile robots. Further, fluctuations in power consumption are predicted; these will change the input impedance of the circuit and make it unequal to the output impedance, resulting in power reflection as shown in Fig.2. Increased power reflection reduces the power delivered to the later part of the circuit [21]. In a previous study, impedance matching was performed by controlling the output voltage (i.e., duty cycle) of the DC-DC

converter [22]. Although this method reduces the reflected power when the load resistance is lower than the optimal point, it is not applicable when the load requires a constant voltage drive and the matching range is narrow. An impedance matching circuit with switching has also been proposed [23]. Although it realizes almost completely automatic impedance matching with changes in the distance between the coils, it requires numerous capacitors and multiple coils to change the capacitance and inductance, and the matching accuracy is not high in some cases.

To solve these problems, this study proposes a novel system that can perform more effective impedance matching with both changes in the distance between coils and in the load resistance. Installing an additional mechanism that could increase the weight of the flying robot is undesirable. Therefore, we add another coil to the transmitter side and control its position to match the impedance. Based on this principle, we have designed and fabricated coils to achieve high output power over a wide area and experimentally evaluated the effect of impedance matching in our proposed system.

Fig.1 Expected usage environment

Fig.2 Condition under which power reflection occurs

Principle of proposed impedance matching

Fig.3 shows the circuit diagram of a conventional WPT system. In this figure, V is the input voltage to the circuit; Z_s , the output impedance of the power source; R_L , the load resistance; k_{12} , the coupling coefficient between the coils; L_i , the self-inductance of the coil; C_i , the capacitance of the capacitor; R_i , the parasitic resistance of each circuit; and I_i , the current flowing through each circuit. In all these notations, $i = 1$ or 2 , respectively, indicating the transmitter side or receiver side. This two-coil system affords the advantage of thinner and lighter coils; however, the impedance fluctuates greatly, resulting in power reflection. In the high-frequency band, the output impedance of the equipment and the characteristic impedance of the transmission line are designed to be 50Ω . To maximally use the capability of the power source, the input impedance of the whole circuit should be matched to 50Ω .

In this study, we propose an impedance matching method with a driver coil that can be applied for addressing both coil misalignment and load fluctuation. As shown in Fig.4, the driver coil is installed over the transmitter coil, and its position is controlled by an actuator in the horizontal direction to change the coupling coefficient k_{01} between itself and the transmitter coil to match the impedance. Fig.5 shows the circuit diagram of the proposed system, and Fig.6 shows its T-type equivalent circuit. Note that the subscript 0 indicates the driver coil circuit. For simplicity, the cross-coupling between the driver coil and the receiver coil is ignored. Under the condition that the resonant frequencies ω of all circuits are the same, the impedances Z_0 , Z_1 and Z_2 can be expressed as follows:

$$\omega = \frac{1}{\sqrt{L_0 C_0}} = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \quad (1)$$

$$Z_2 = R_2 + R_L \quad (2)$$

$$Z_1 = R_1 + \frac{(\omega k_{12} \sqrt{L_1 L_2})^2}{R_2 + R_L} \quad (3)$$

$$Z_0 = R_0 + \frac{(\omega k_{01} \sqrt{L_0 L_1})^2}{Z_1} \quad (4)$$

Z_1 is the input impedance of the two-coil system, and it varies with the position and power consumption of the robot. In other words, because k_{12} varies with the distance between the transmitter and the receiver coils and R_L varies with the state of the load, Z_1 inevitably varies in mobile robots. However, the input impedance Z_0 in the proposed three-coil system can be kept constant by varying the coupling coefficient k_{01} . When Z_1 becomes larger, the driver coil is moved to overlap the transmitter coil more to increase k_{01} , and vice versa. For example, when the coupling coefficient changes depending on the distance between the transmitter and the receiver coils, the driver coil is moved as shown in Fig.7(a), and when the load resistance changes, the driver coil is moved as shown in Fig.7(b). Notably, the driver coil must be designed to achieve the required range of k_{01} to match the impedance of the system.

Considering the impedance of each part and the fact that only the parasitic resistance reduces the transmitting efficiency, the three-coil system is expressed as follows:

$$\eta = \eta_0 \eta_1 \eta_2 = \frac{Z_0 - R_0}{Z_0} \times \frac{Z_1 - R_1}{Z_1} \times \frac{Z_2 - R_2}{Z_2} \quad (5)$$

Compared to the two-coil system, the three-coil system is smaller by η_0 ; however, the effect can be almost ignored if the parasitic resistance R_0 is small enough for $Z_0 = 50 \Omega$. In this study, the transmitting efficiency is defined as the ratio of the received power at the load resistance to the active power input to the circuit.

Fig.3 Circuit of two-coil system with magnetic resonant coupling

Fig.4 Arrangement of proposed coils

Fig.5 Equivalent circuit of three-coil system with driver coil

Fig.6 T-type equivalent circuit of three-coil system

Fig.7 Movement of driver coil

System design

System overview

Fig.8 shows an overview of the entire system. On the transmitter side, the signal from the function generator was amplified by the power amplifier and fed into the circuit using magnetic resonant coupling. The energy transferred to the receiver side was converted to a predetermined DC voltage through a rectifying/smoothing circuit and a DC-DC converter. Moreover, it was used to float the robot, charge the battery, etc. In addition, the reflected power was measured from the information of the driver coil circuit, and the optimal position of the driver coil was estimated and controlled so that the reflection becomes smaller. However, to verify the principle, the driver coil was set to the optimal position by moving it manually.

Further, we designed the coils assuming a power supply frequency of 150 kHz. All coils were assumed to be parallel, and the power losses in the robot material and after the rectifier were not considered. The rated output of the power amplifier was 100 W at this time, and we aimed to supply 20 W over a wide area and a maximum instantaneous power of 50 W.

Fig.8 Proposed configuration for WPT

Coil design

For coil design, we ignored the power losses in the AC-DC conversion and the metal surface of the robot; therefore, all efficiencies were derived using Equation (5).

The dimensions and shapes of the transmitter and receiver coils were determined as follows. The coil diameters were set to the largest possible value, $D_t = D_r = 0.7$ m, based on the space behind the ceiling and the robot size. In addition, we decided to use solenoid coils to keep the coil diameter large, because a coil with a larger diameter can generally transmit power over a longer distance. The receiver coil had strict weight and thickness limits because it was mounted on the flying robot. Therefore, we first determined the parameters of the receiver coil and then determined those of the transmitter coil to achieve the appropriate transmission efficiency. The coil pitch was determined to be two times the wire diameter; this was optimal considering the quality factor of the coil [24]. We also used the calculation model for the inductance and coupling coefficient of the coil by the filament method [25] and the calculation model for the parasitic resistance of the coil [26]. We used multilayer ceramic capacitors (MLCCs) as they have low parasitic resistance. Preliminary experiments suggested that their parasitic resistances were 0.5Ω on average; therefore, we used this value in the simulation.

For the receiver coil, the weight and thickness limits were respectively 60 g and 50 mm. We then set the number of turns $N_r = 15$ and the wire diameter $d_r = 0.4$ mm to achieve the maximum quality factor in a range in which the wire diameter was not too small to avoid making it difficult to wind the coil. Under these conditions, the distance between the centers of the coils was defined as $[x, 0, z]$, as shown in Fig.9, and the transmitter coil was designed to have a transmitting efficiency of more than 40% at a distance of $[0 \text{ m}, 0 \text{ m}, 1.0 \text{ m}]$ when the load resistance was 10Ω . Equation (5) with $\eta_0 = 1$ was used for calculating the efficiency. The transmitter coil had no weight or thickness limits; nonetheless, extreme values are not necessary. Therefore, we selected the combination in which the number of turns was $N_t = 30$ and wire diameter was $d_t = 1.5$ mm from Fig.10.

For the driver coil, we set the coil diameter $D_d = 0.7$ m and the wire diameter $d_d = 1.5$ mm to maintain consistency with the transmitter coil. In this case, the coupling coefficient k_{01} between the driver coil and the transmitter coil was the maximum when they were completely overlapped, and it became smaller when the driver

coil was moved sideways. For a 5-mm gap between the driver and transmitter coils, the magnitude of the coupling coefficient k_{01} was calculated to be approximately in the range of 0–0.5 regardless of the number of turns of the driver coil. Solving Equation (4) for the magnitude of k_{01} gives

$$|k_{01}| = \frac{1}{\omega} \sqrt{\frac{(Z_0 - R_0)Z_1}{L_0 L_1}} \quad (6)$$

The L_0 and R_0 values were calculated based on the number of turns of the driver coil; therefore, the number of turns should be decided to satisfy $|k_{01}| \leq 0.5$ at $0.3 \leq z \leq 1$ m, which is the flight range of the robot, when Z_0 is matched at 50Ω . It is sufficient to assume the maximum value of Z_1 ; therefore, we assumed that $R_{\square}$ is the minimum from Equation (3). $R_{\square}$ is the resistance value when looking at the later part of the circuit from the front of the AC-DC converter, as shown in Fig.8. Assuming that $R_{\square\square\square}$ is the load resistance of the battery, motor, etc., $R_{\square}$ is calculated as

$$R_{\square} = \frac{R_{out}}{D^2} \times \frac{1}{1.347} = V_{in}^2 \times \frac{R_{out}}{V_{out}^2} \times \frac{1}{1.347} \quad (7)$$

where D is the conduction ratio of the DC-DC converter, and the coefficient is the theoretical impedance transformation ratio when a diode bridge rectifier circuit is used [27]. The DC-DC converter used in the system (UWE-12/10-Q48N-C, Murata) has an output voltage of $V_{out} = 12$ V and input voltage of $V_{in} = 18$ –75 V; the robot's maximum power usage P_r is 50 W. Therefore, the minimum value of $R_{\square}$ was obtained as 4.8Ω . Under this situation, when the number of turns of the driver coil $N_{\square} = 10$, the coupling coefficient k_{01} required for impedance matching satisfies the condition as shown in Fig.11.

Fig.9 Definition of distance between coils

Fig.10 Transmitting efficiency against parameters of transmitter coil

Fig.11 Simulation results of required coupling coefficient k_{01} for $R_{\square} = 4.8 \Omega$

Simulation of transmitting efficiency

Fig.12 shows simulation results of the transmitting efficiency versus the position of the receiver coil when the load resistance is 10Ω . The efficiency exhibited a valley in the graph because the direction of the magnetic flux to the receiver coil changed depending on the position of the coils, as shown in Fig.13. When the direction was switched, the sum of the magnetic flux through the receiver coil as well as the efficiency were zero. Nonetheless, the simulation revealed high efficiency over a sufficiently wide area.

Fig.12 Simulation results of transmitting efficiency for $R_{\square} = 10 \Omega$

Fig.13 Direction of magnetic flux

Prototyping

Fig.14(a) shows the prototype coils. When the center of the receiver coil was hollowed out, it weighed only 50 g and had a thickness of approximately 2 mm. A vinyl-insulated stranded wire was used for the driver and the transmitter coil, and a solid wire was used for the receiver coil. In addition, leaded MLCCs (RDE series,

Murata) were used for the capacitors. Considering the withstand voltage, the capacitor for the transmitter circuit was made as shown in Fig. 14(b), and the others were produced similarly.

(a) Coils

(b) Capacitor for transmitter circuit

Fig.14 Prototype developed in this study

Experiments, results, and discussions

In the following experiments, a function generator (AFG-2125, GW Instek), a voltage follower (when power was low), and a power amplifier (T145-5027A, Thamway; when power was high) were used in the power supply system. In addition, a DC-DC converter was not used for simplicity. Because iron and other metals near the coils would adversely affect the power transmission, the coils were placed to avoid them.

Measurements of efficiency and impedance

By using the prototype coils, we measured the efficiency and impedance to evaluate the validity of the proposed system. First, the coil positions were adjusted manually. Further, the experiment was performed at low power (<1 mW) for safety reasons. When the resonant frequency was shifted, the power supply frequency was adjusted to achieve a perfect resonant state and power factor of 1. In this experiment, the transmitting efficiency and input impedance were measured for the lateral displacement of the receiver coil (load resistance: $10\ \Omega$) and the load variation ($x = 0$ m) at $z = 0.5$ m. The input impedance was also measured in the two-coil system without the impedance matching mechanism. Fig.15 shows a demonstration of the matching operation when a light bulb was connected as a load.

Figs.16 and 17 respectively show the measurement results for the lateral displacement and load variation. Good agreement was seen between the simulated and measured transmitting efficiency. As in Fig.12, the efficiency exhibited a valley in Fig.16(a). The results in Figs.16(b) and 17(b) confirmed the effectiveness of the proposed impedance matching system and indicated that the input impedance of the three-coil system can be matched to approximately $50\ \Omega$.

(a) Without matching

(b) With matching by driver coil

Fig.15 Demonstration of impedance matching system

Fig.16 Measured results for $R_L = 10\ \Omega$ at $[x, 0, 0.5\text{ m}]$

Fig.17 Measured results for variable R_L at $[0, 0, 0.5\text{ m}]$

Comparison of received power

We experimentally compared the received power between the two- and three-coil systems when the output power of the power source was kept constant at 10 W . The received power of the three-coil system was estimated to be higher because the input power to the circuit was reduced by the reflected power in the two-coil system. A noninductive resistor of $10\ \Omega$ was used as the load. Under these conditions, we measured the received power at 24 points with 0.2-m intervals in the range of $x = 0\text{--}1.0$ m and $z = 0.4\text{--}1.0$ m.

Fig.18 shows the measurement results. All data were normalized

by the received power of the two-coil system at $[x, 0, z] = [0 \text{ m}, 0 \text{ m}, 1.0 \text{ m}]$. The data with the same amount of lateral displacement were plotted by lines. This graph shows that the received power of the three-coil system was higher than that of the two-coil system over a wide range. At the point where the received power of both systems was almost the same, such as $[x, 0, z] = [0 \text{ m}, 0 \text{ m}, 0.6 \text{ m}]$, the input impedance can be assumed to be 50Ω even for the two-coil system.

Fig.18 Comparison of normalized received power between two-coil and three-coil system

High-power transmission

The above-described experiments revealed that the impedance matching mechanism of the proposed system was effective over a wide range. The effect was particularly noticeable for a large distance between the coils. Accordingly, we experimentally tested whether 20 W can be transmitted when the coil was displaced laterally at $z = 1 \text{ m}$. For safety reasons, we took the data when the received power exceeded 20 W or when the output power of the power source reached 100 W. We used a load resistance of 10Ω and performed measurements at 0.1 m intervals in the range of $x = 0\text{--}0.5 \text{ m}$ as this was considered to have a transmitting efficiency above 20% from Fig.12.

Fig.19 shows the experimental results. The system could supply 20 W at distances of up to $x = 0.3 \text{ m}$, thus confirming that it can supply power over a sufficiently wide area. At the same time, the system could not supply power at distances of $x = 0.4$ and 0.5 m . This might be partly because most of the power was consumed as heat in the parasitic resistance of the coils and capacitors. This heat can increase the resistance of the conductor, resulting in additional heat loss, and change the capacitance of the capacitor, resulting in a deviation from the resonant state. If heat is the cause of the efficiency loss, an environment that facilitates heat dissipation must be created.

Fig.19 Received power for $R_{\square} = 10 \Omega$ at $[x, 0, 1.0 \text{ m}]$

The efficiency can be improved in other ways. In the frequency range of 100–200 kHz, the use of a Litz wire has been reported to reduce the skin effect and decreases the parasitic resistance of the coil [28], thereby improving the efficiency. In addition, the incorporation of ferrite would not only increase the coupling coefficient between the coils but also provide a shielding effect to reduce external influences [29, 30].

Conclusions

We proposed a system that can match the impedance by the driver coil with changes in both the distance between coils and the load resistance to solve the impedance mismatch problem in WPT due to the state of mobile robots. Simulation and experimental results confirmed that impedance matching could be achieved by moving the driver coil for mitigating the load fluctuation and relative displacement between the transmitter and the receiver coils in the axial and horizontal directions.

In this study, the driver coil was set to the optimal position by moving it manually to verify the principle. In a future study, we will design a system that can automatically control the position of the driver coil based on the measured reflected power.

Abbreviations

AMR: Autonomous mobile robot; WPT: Wireless power transfer; MLCC: Multilayer ceramic capacitor.

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Author's contributions

TO proposed the method described in this paper, conducted all simulations and experiments, and drafted the manuscript. XL, HN and SO provided advice, conducted some of the experiments, and checked and revised the manuscript. WH proposed the method described in this paper, provided advice, conducted some of the experiments, and checked and revised the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Declarations

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Competing interests

The authors declare that they have no competing interests.

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