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Foreign Object Detection for Wireless Power Transfer Based on Machine Learning

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***Abstract*—A simple foreign object detection (FOD) method utilizing a neural network is discussed. For a receiver and transmitter structure, open helical types of coil resonating at 13.56 MHz were used with different distances and with and without the presence of foreign objects (a copper plate or plastic bottle filled with water). An FOD system was constructed based on a neural network that detects foreign objects based only on reflection coefficient (S11) parameters. This approach for FOD achieved an accuracy of approximately 98% in the range 12–18 cm.**

Keywords—Wireless power transfer, WPT, magnetic resonance, foreign object detection, FOD, machine learning, neural network

I. Introduction

In a wireless power transfer (WPT) system, foreign object detection (FOD) is an important issue for safety. The previous FOD method is difficult to apply to a system in which the distance between the transmitting coil and the receiving coil is not constant, and the system tends to become complicated.

WPT is already widely used, particularly in small devices, such as portable terminals, and it is beginning to be applied to electric vehicle (EV) charging. There are several types of WPTs. One of the most common methods for such applications is WPT using magnetic coupling between the transmitting coil and the receiving coil with magnetic resonance. This system can transmit power even when the coupling coefficient between the coils is low; therefore, it is robust to a large gap and a misalignment between coils [1]. However, for these WPT systems, there is a problem to be solved, which is to ensure safety against foreign objects [2]. Strong electromagnetic fields are generated around the transmitting coil and receiving coil, and, if a metal is present in the vicinity, the metal gets heated because of the induction heating effect. This can cause fires and can be very dangerous, because humans can touch the hot metals. There is also the safety problem that the human body is exposed to the electromagnetic field [3].

For these reasons, a safety device for detecting foreign objects and stopping the power supply or lowering the power may be installed in the WPT system. If a foreign object approaches the system, an influence is exerted on the transmitting coil and receiving coil, thereby changing the electrical characteristics of the coils. In some FOD methods, the change in the electrical characteristics caused by the approach of foreign objects is detected by measuring the electrical parameters of the coils, such as the current value, impedance, Q factor, and transmission efficiency [4], [5]. The typical algorithm for detecting change of these parameters consists of comparing the measured parameters with a predetermined threshold value. For example, if the efficiency falls below a predetermined threshold value, it is determined that there is a foreign object. An advantage of this FOD method is that the algorithm is simple; however, a disadvantage is that it is difficult to apply to applications in which the position of the coils is not constant, because the parameters are affected not only by presence of the foreign object, but also by the change of distance between the coils. There is also a method that determines the presence of foreign objects based on electrical parameters and the distance between coils measured by an additional distance censor; however, this complicates the system. There are also FOD methods that detect parameters other than that of transmitting and receiving coils measured by sensing coils [6], image sensors [7], and thermal sensors [8]. However, these approaches require the installation of sensing devices, which can complicate the system and constrain the physical structure of the system.

In this work, an FOD method utilizing machine learning (ML) is proposed in which foreign objects are detected with high accuracy by measuring the electrical parameter only of the transmitting coil in a condition in which the distance between the coils is not constant.

II. Overview of Experiment

A. Configuration of the Wireless Power Transfer System

To demonstrate the FOD method utilizing a neural network, a WPT system was designed in which the receiver and transmitter coils are open-helical, resonating at 13.56 MHz, and they were designed as described in TABLE I. A vector network analyzer was used for powering and measuring reflection coefficient (S11) parameters at 48 points from 11.5 to 15.9 MHz, and the results are shown in Fig. 1. These 48 points of S11 parameters were extracted into real and imaginary parts and became 96 data. The data indicating the presence (represented as “0”) or absence (represented as “1”) of a foreign object and the S11 measurement data were combined to create training data.

TABLE I. Parameters of the Open-Helical Coil for the Experiment

Parameters	Values
Radius of coil	50 mm
Diameter of wire	1 mm
Gap between loops	0.2 mm
Number of turns	26 turns
Height of coil	60 mm
Self-resonance frequency	13.56 MHz

For the foreign objects, a 230- × 150- × 1.2- mm copper plate was used to imitate a metal object, and plastic bottles containing 15 or 30 mL of water were used to imitate a human body. The copper plate was placed at the midpoint between the transmitting coil and the receiving coil to block 1/4 or all of the coil diameter, as shown in Fig. 2. To simulate the condition without a foreign object, a condition was created in which copper plates were not placed. For each arrangement, the measurement was performed under three conditions of the distance between the coils being 12, 15, and 18 cm. In total, 135 measurements were recorded, and 135 training data were created.

In a similar manner, measurements were made in the condition in which a bottle containing water was placed as a foreign object, and training data were created. A 15- or 30-mL bottle was placed between the transmitting and receiving coils randomly, as shown in Fig. 3. A condition was created without a foreign object by removing the bottle. For each arrangement, the measurement was recorded under three conditions of the distance between the coils being 12, 15, and 18 cm. In total, 135 measurements were recorded, and 135 training data were created.

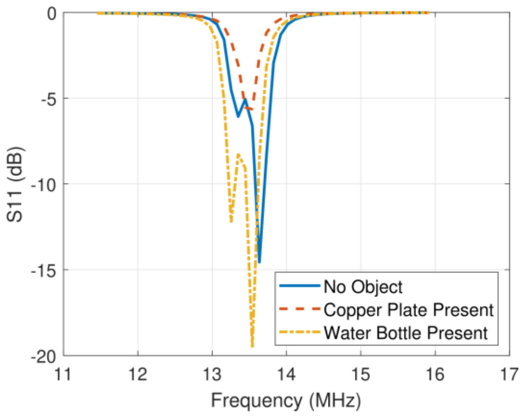

Fig. 1. S11 Parameter in which distance between coils was 12 cm

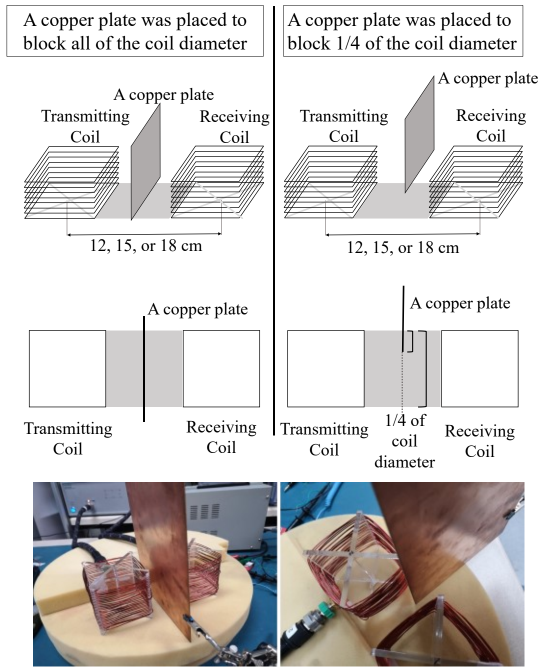

Fig. 2. Layout of copper plate for the experiment

III. Machine-Learning Approach

ML is a computer system that performs a specific task without using explicit instructions, relying on patterns and inference. ML is used in many systems, such as thermal camera analysis for FOD systems [8].

A. *Neural Networks*

Neural networks are one method of ML. They mimic the human brain and are a powerful tool for solving nonlinear problems. They consist of layers of neurons connected in series by parallel logical units that mimic human neurons. When a signal is input to the input layer, the signal is weighted in each neuron and input to the next layer to obtain a final output (answer). In the training, a large dataset combining inputs and correct answers is prepared, and an optimization problem for minimizing errors is solved typically by a backpropagation method. There have been several reports of the use of a neural-network strategy for several WPT-related applications [9], [10]. The method proposed here constitutes (to the authors' knowledge) the first demonstration of such concepts for FOD of WPT systems [11].

B. *Performance Evaluation*

To test the performance of the proposed FOD system, the MATLAB neural-network toolbox was utilized. The toolbox enables to design the structure of neural networks and train the designed neural networks easily. In this experiment, 4

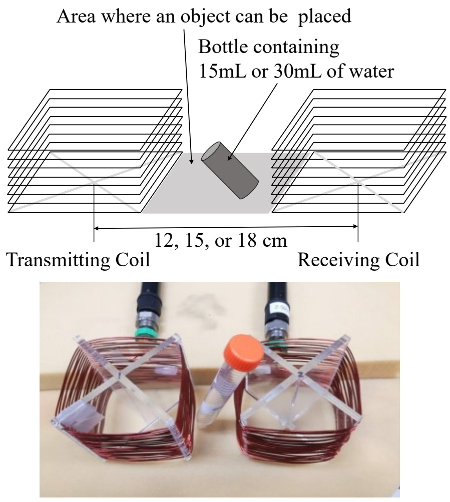

Fig. 3. Layout of bottle containing water for the experiment

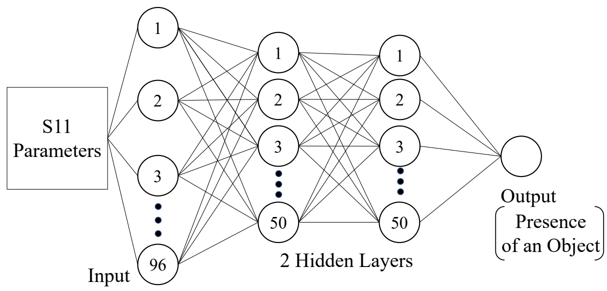

Fig. 4. Configuration of neural network for the experiment

layers (2 hidden layers) neural network was used, as shown in Fig.4. The measurement data (270 data) were randomly divided into training data (70%), validation data (15%), and test data (15%) and input to the neural network for each purpose. The neural network output the estimation of whether or not the object is present.

Fig. 5 shows the confusion matrix of the results of the training and test. According to the test confusion matrix, 41 test data were input to the trained neural network, and then 13 data were determined to be "an object is not present" and 28 data were determined to be "an object is present." These determinations were all correct — that is, the accuracy was 100%.

In addition, an experiment was conducted to test whether the trained neural network could detect foreign objects in a condition not included in training. Three conditions that are different from the training condition were created for the test.

- [Condition A] The distance between the coils is 13.5 cm, and the copper plate blocks half of the coils.
- [Condition B] The distance between the coils is random from 12 to 18 cm, and a bottle containing 15- or 30-mL of water is placed.
- [Condition C] The distance between the coils is 12, 15, or 18 cm and the misalignment between them is 3 or 6 cm. Additionally, a bottle containing 15- or 30-mL of water is placed, as shown in Fig. 6.

The measurement data of these three conditions were inputs to the trained neural network. Fig. 7 shows the confusion matrix of the results of the test in Conditions A and B. According to the test confusion matrix, the trained neural network could detect the foreign object with 100% and 98.7% accuracy in Conditions A and B, respectively. In Condition C, the accuracy was 79.3% and 65.9% when there was a misalignment of 3 and 6 cm, respectively.

Considering the experiments in Conditions A and B, the neural network that was trained based on S11 parameters could detect a foreign object with high accuracy, even when the distance between the coils was not constant. In Condition C, the neural network could detect the foreign object to some extent, even though the accuracy reduces with increased misalignment.

However, it is presumed to be difficult to detect foreign objects in a condition completely different from the training condition—for example, the condition in which the material and size of the foreign objects are completely different from those of the training condition, as indicated by the result of the experiment in Condition C. Moreover, as a future work, it is necessary to verify the FOD performance of a more practical system that automatically corrects the characteristic of transmitting power (e.g. impedance) according to the coil alignment and also performs FOD. On the other hand, these promising preliminary results open the door to a broad area of research that could enhance the state of the art of FOD in WPT systems.

IV. Conclusion

An FOD method utilizing a neural network that does not need additional structure of the WPT system and is robust to change of the alignment of coils was proposed. The FOD system constructed could detect foreign objects (a copper plate or a plastic bottle containing water) in a condition in which the distance between the coils was not constant with an accuracy of approximately 98% even if the condition was not exactly the same as the training condition. Additional verification tests conducted for misalignment conditions featured promising detection results that indicate the wide potential applicability of the neural network to an FOD

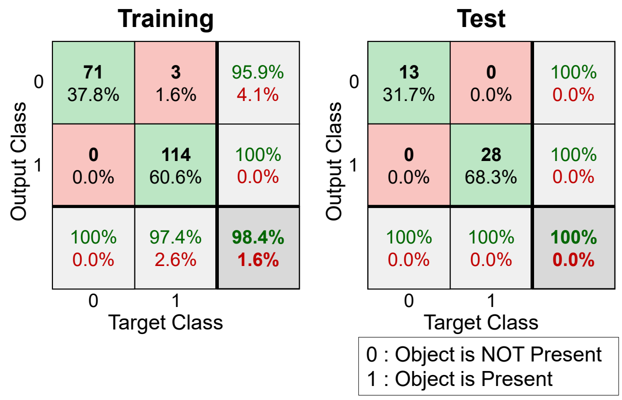

Fig. 5. Confusion matrix of training and test

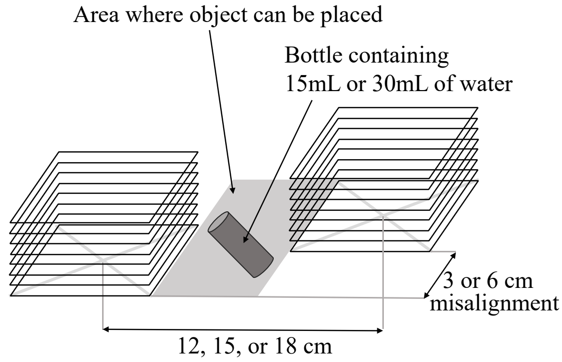

Fig. 6. Layout for the experiment in Condition C

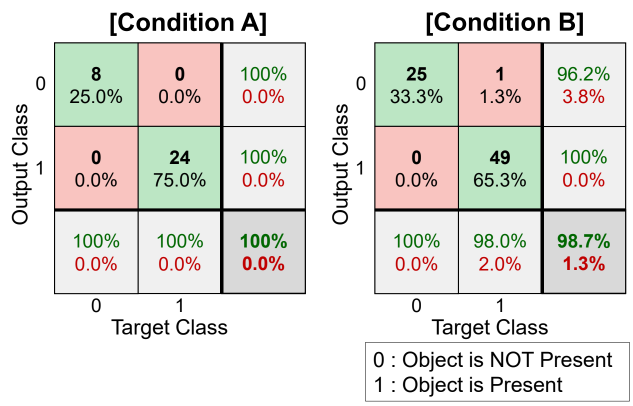

Fig. 7. Confusion matrix of test in Condition A and Condition B

method in the WPT system. Note that the affiliation is as of the time of writing (May 2020).

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