Highly Efficient Smart 3-Coil Wireless Power Transfer System with Automatic Tracking

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Abstract—**This paper presents the design of a highly efficient smart wireless powering platform based on object detection algorithm. Power transfer efficiency (PTE) and power-delivered-to-the-load (PDL) are two key parameters used to evaluate the performance of the proposed design. A 3-coil inductive link is used to achieve higher PTE than a 2-coil link when coupled at a considerable distance. The simple design methodology employed enables an optimised geometry for the 3-coil link. The optimised 3-coil link achieves a PTE of 62.1% in measurements. A wireless power transfer system is constructed with a Class-E primary coil driver with 60.6% efficiency. A camera-based tracking system is implemented to maintain the transfer link robustness under changing coupling conditions. The You Only Look Once version.4 (YOLO4) algorithm is used to detect the moving receiver with 71% accuracy and 0.2s response time, and stepper motors controlled by an Arduino process drive the transmitter coil to track the moving receiver coil.**

Keywords—3-coil inductive link; receiver coil tracking; wireless power transfer; YOLO4.

I. Introduction

Inductive powering is a rapidly evolving wireless power transmission technology. There are several advanced methods to achieve wireless power transfer (WPT), including inductively coupled power transfer (ICPT) [1], ultrasonic power transfer (UPT), and capacitively coupled power transfer (CCPT). Compared with the other two methods, ICPT provides the feasibility of combining loads with different power consumption and high system efficiency [1]. In a typical inductive coupling link, the transmitter side (Tx) is usually supplied by a highly efficient power amplifier (PA). The Tx coil is mutually coupled with the receiver coil to transmit the wireless power to establish the transfer link. Thus, the load connected to the receiver side (Rx) is driven by the power going through the link. In this paper, the analysis and verification of the system are under of the specifications of powering implanted devices, where the size of the Rx coil is relatively small (a few centimetres size).

There are two key parameters to evaluate the performance of the inductive link: power transfer efficiency (PTE) and power-delivered-to-the-load (PDL). ICPT systems can have different configurations in the number of coils used in the link (2-coil, 3-coil, and 4-coil). The 2-coil configuration has been proven to be unable to provide both optimized PTE and PDL for fixed load and separation distance [2], which brings limitations to inductive link designers. In [2], the 4-coil system is confirmed to have weak PDL performance when PTE is high. At a fixed separation distance, the 3-coil configuration is the most suitable for providing high PDL while maintaining high PTE [2]. In this paper, the 3-coil configuration is adapted to construct an optimized transfer link design. A simpler link design procedure is proposed by gathering all the possible combinations of coil geometry instead of using countless iterative verifications for geometry recommendation.

The selection of the PA design makes significant difference in the efficiency of an inductive link. In [3], the principles of four different PA configurations (Class-C, Saturating Class-C, Class-D, and Class-E) are analysed. Although all of them are suitable for modern IPCT systems, Schuylenbergh et al. have found that the Class-E PA design method combines the advantages of Class-D and saturating Class-C, which is more attractive to ICPT system driven at MHz frequency of [3]. In ideal situations, the efficiency of the Class-E PA can reach 100% with no power dissipated at the switch. In this design, Class-E PA is chosen to minimise the power loss of the system.

It is difficult for the inductive link to maintain a stable transfer condition, where the load variation is not only caused by the resistance change on the Rx side, but also by the position change of the coils. Schormans et al. [1] has provided a concise conclusion on the numerical methods for calculating the mutual inductance in misalignment cases based on Soma's results [4]. Misalignments reduce the mutual coupling strength between coils. A tracking method of designing a coupled Tx coil array is proposed in [5] to eliminate lateral misalignment. Based on impedance reflected theory, this method actives different Tx coils in the array according to the detection of the reflected load from the Rx side. However, the Tx coil array is limited due to its sensitivity to load. An unexpected resistive change or inductive connection on the load causes low accuracy in detecting the receiver. Another method, namely EnerCage, proposed in [6] succeeds in removing the influence of resistive changes by using multiple Tx coils to ensure a balanced distribution over the entire range of receiver activity. Kilinc [7] also suggests a Tx coil tracking method to avoid using multiple Tx coils, which reduces the cost of building complex arrays. However, an extra magnetic sensor array is required to detect the position of the Rx coil. These existing methods share a common problem, which is the scalability of the system. If the range of the receiver is required to be extended, the Tx coil array/magnetic sensor array must be increased accordingly. Increasing these arrays brings relatively huge cost and complexity to the construction of the ICPT system, which in turn reduce the scalability of the system. In this paper, a method of implementing a detection algorithm in the system is introduced to maintain low cost and high scalability.

The development of object detection algorithms provides alternative ways for other disciplines to solve tricky locating problems. One stage model, YOLO turns out to be more advantageous than other algorithms in real-time object detection tasks. The coverage of the camera determines the

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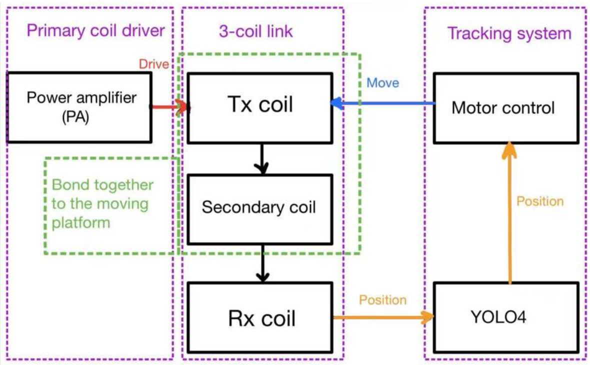

Fig. 1. Block diagram of the overall system design .

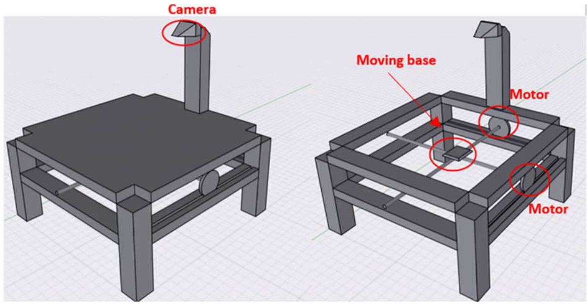

Fig. 2. Tracking platform prototype.

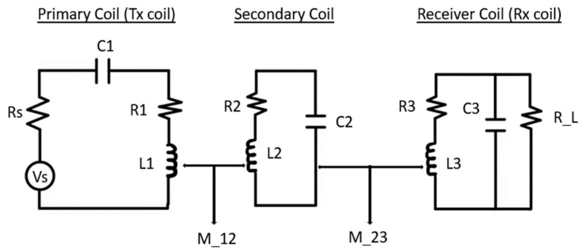

Fig. 3. Circuit configuration of 3-coil link.

available range of the detection system. Hence, the ICPT system can eliminate most range limitations when conducting experiments on freely moving animals with wirelessly powered implants.

The paper introduces a highly efficient smart 3-coil wireless power transfer system based on YOLO. Section II presents the overview of the system. Section III describes the optimised 3-coil model and PA design. Section VI presents the design of the tracking module. Section V analyses and discusses the performance of the whole smart wireless power transfer system. Section VI concludes the paper.

II. Overall System Design

The relationships between the three parts are illustrated in Fig. 1. The 3-coil inductive link is driven by a Class-E power amplifier connected on the Tx side. The Tx coil and the Secondary coil are bonded together at a fixed distance, and the Rx coil is a moving target in a plane that is detected by the camera over the plane. The YOLO4 detection algorithm immediately processes the real-time video stream from the camera, and the detected position of the Rx coil is transmitted to an Arduino-based stepper motor control system. Lateral misalignment between the Rx coil and the powering platform comprising the Tx and secondary coils are processed in the Arduino, triggering the motor to reduce the difference to achieve tracking. Fig. 2 shows the proposed prototype setup of the highly efficient wireless powering platform.

The prototype contains two planes, the lower one, a moving base, for the Tx and secondary coil, and the upper one for the Rx coil. The secondary coil is attached to the Tx coil at a short distance on the moving base. Above the upper plane, there is an upright part that represents the location of the camera. Motors on the x-axis and y-axis control the movements of the moving base that functions as a charging platform.

A. Optimised 3-Coil Transfer Link and PA Design

Fig. 3 shows the schematic diagram of the 3-coil inductive link. According to the reflected load theory, any arbitrary load resistance at the receiver side can be tuned to the optimised load resistance in the 3-coil link by adjusting the link conditions between these two coils. Detailed analysis for evaluating PDL and PTE of the link are presented in [2]. Under the same coupling distance, a 3-coil inductive link presents a PTE that is around twice that of a 2-coil link when suppling the same PDL. The aim of this design is to achieve high PTE with at least 100 mW PDL by a centimetre-sized Rx coil. Table I summarises the determined parameters for the 3-coil link design.

The design flow for calculating the optimum combination of coil sets for a 3-coil link is shown in Fig. 4. The electrical parameters of the coils are derived based on “CuCCo” [1], [8]. The process starts by considering all possible coil geometries for the secondary coil with the initialised input features. To avoid the link breaking down when the operating frequency of the system is close to the self-resonant frequency (SRF), a sorting method is employed. This method emphasizes on checking the quality factor and the SRF of the secondary coil. If a negative quality factor or a small SRF occurs, the geometry for the secondary coil is deemed unsuitable for a system working under the specified frequency. All feasible geometries of secondary coils are stored in one matrix called “Accepted_2nd”, while for those unsuitable ones, zeros would be stored in that matrix. The same sorting step is implemented when choosing appropriate Tx coil geometries. After combining all possible sets of Tx and secondary coil sets into the matrix “Accepted_2nd_Tx”, another MATLAB function

TABLE I. Design Parameters for 3-coil Link Modelling

Parameter	*Value*
Operating frequency	6 MHz
Load resistance	100 Ω
Wire radius of Rx coil	0.56 mm
Coil radius of Rx coil	5 mm
Wire radius of Tx & Secondary coils	0.56 mm-1.5 mm
Coil radius of Tx & Secondary coils	1.12 mm-150 mm
Distance between Tx & Secondary coils (D12)	20 mm
Distance between Secondary & Rx coils (D23)	10 mm

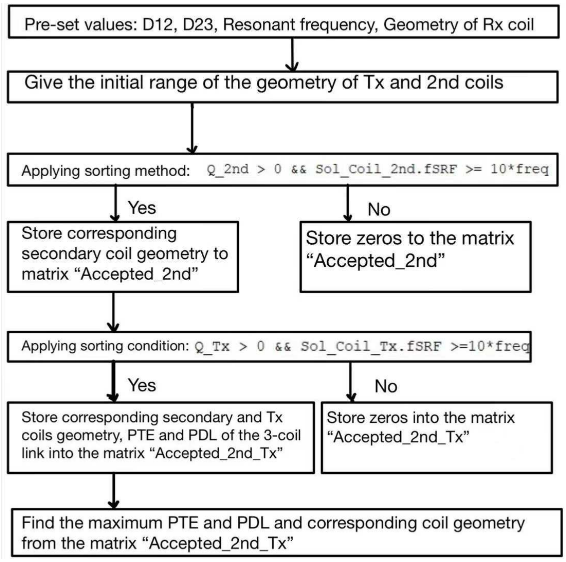

Fig. 4. 3-coil MATLAB model design structure.

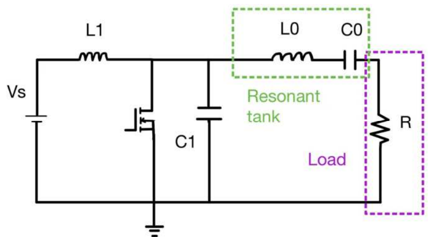

Fig. 5. Circuit configuration of Class-E power amplifier.

(Named Inductive3CoilLink) is used to process the PTE and PDL of different coil sets under a fixed Rx coil. The model automatically provides the coil set with the highest PTE in the final stage under a pre-set minimum PDL condition.

The design of Class-E PA is mainly based on Sokal's paper [9]. Simultaneous high voltage and high current are avoided in the switch for less power consumption. Fig. 5 illustrates the circuit configuration of a low-order Class-E power amplifier.

B. Tracking Module Design

The design structure of the tracking system is illustrated in Fig. 6, and the experimental setup of the tracking system is shown in Fig. 7. In the first implemented prototype, only one-dimension tracking is established to test the feasibility of the design.

The training section of the YOLO4 algorithm used here is developed based on open-source code from [10]. Creating image data sets for training is essential for accomplishing detection accuracy. The coil is not considered an object in existing large open data sets such as COCO or VOC. LabelImg is the method that gives the designer a way to label the target on their own. In this design, a training set of 900 images (856 with coil in sight) and a test set of 100 images (91 with coil in sight) were created for the algorithm to recognize the receiver. After the training section, the weights for detecting Rx coils are fed into the predicting section of the YOLO4 algorithm. In the predicting section, the algorithm processed the image stream input from the camera (Logitech C270 with 720p resolution and 30fps). The output of the

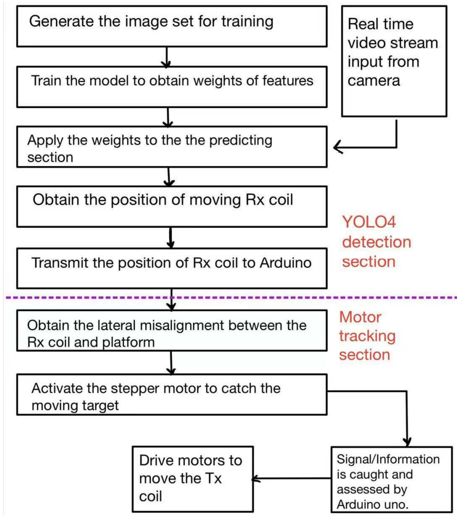

Fig. 6. Structure of the tracking system.

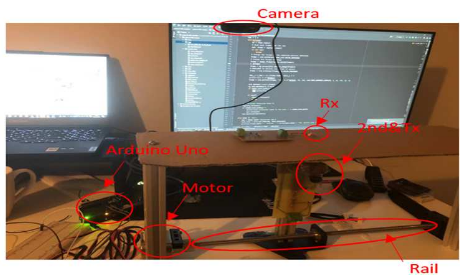

Fig. 7. Experimental setup of the tracking system.

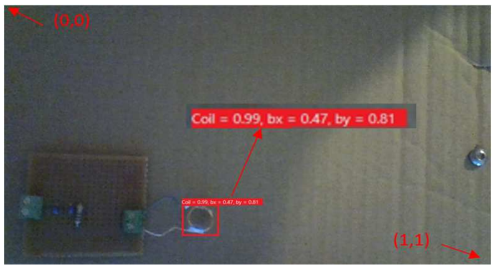

Fig. 8. Output of the YOLO4 predicting section.

predicting section contains the probability of being a coil, and the x-y position of the central point of the coil in the image. Fig. 8 shows the output from the YOLO4 predicting section, where the Rx coil is recognized, and its location is given.

C. Results and Analysis

1) 3-coil ICPT System

Fig. 9 shows the measured coupling coefficient of the link L1-L2 and L2-L3 against the simulated value. The better performance in the experimental data than in the simulation may be due to slight deviations of the coil geometry from the set values. The measured PTE is 62.1% under the load and coil distance specified in Table I.

The measured efficiency of the Class-E PA is 60.6%. Table II compares the experimental and simulated results of 3-coil and 2-coil ICPT systems. The experimental results show better performance in coupling coefficient because the

TABLE II. EXPERIMENTAL AND SIMULATED RESULTS OF 3-COIL AND 2-COIL ICPT SYSTEMS

	Effi. Of PA	*PTE*	*PDL*
Experimental 2-coil	60.6%	10.13%	12.2 mW
Simulated 2-coil	60.6%	1.59%	9.11 mW
Experimental 3-coil	60.6%	37.76%	196 mW
Simulated 3-coil	60.6%	24.5%	140 mW

simulation model views the solenoid coil as a plane coil while in fact the solenoid coils create stronger magnetic field with some length or depth.

2) Automatic tracking system

Combing the F1 score results, the final threshold is chosen as 0.5 to balance the influence made by recall and precision. The small vibrations in the last two graphs of Fig.10 are due to computational noise in algorithm which can be negligible when valuing the performance of the system. 'Respond Time' shows how long the platform takes to start moving while the 'Time Taken to Move' describes the time spent on moving a distance of 9.4 cm. According to the results shown in the first row of Fig. 10, the precision of the YOLO4 detection method in this project is around 71%.

In this design, the stepper motor is chosen for high precision since the targeted application is for tracking freely moving rodents with implanted microelectronic devices over a large area, where the Rx coil is small. However, the drawback of the stepper motor is its slow speed, which is only 22 mm/s as shown in the last graph in Fig. 10. It is suitable for the specified application but is too slow for other applications, such as continuously charging a wireless power-driven robot at high speed.

III. CONCLUSION AND FUTURE WORK

This paper has presented a high-efficiency wireless power transfer platform with automatic tracking of a free-moving charging target. A simple, MATLAB-based coil geometry design procedure has been proposed for a 3-coil link configuration. Also, a dynamic tracking method combining image-based target recognition using YOLO4 and automatic Tx tracking using an Arduino-controlled motor has been proven feasible to establish an easily scalable ICPT system. For further development, the tracking platform could remove the restrictions of the rails by designing robust free-moving intelligent robotic carriers for the Tx.

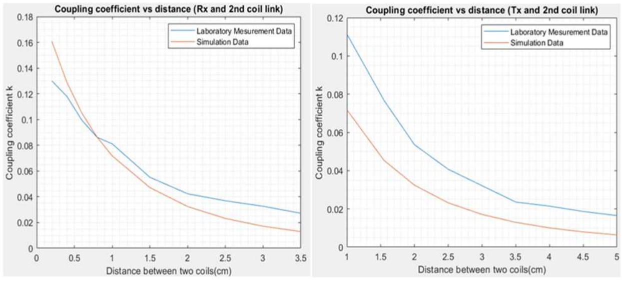

Fig. 9. Experimental and simulated data comparision.

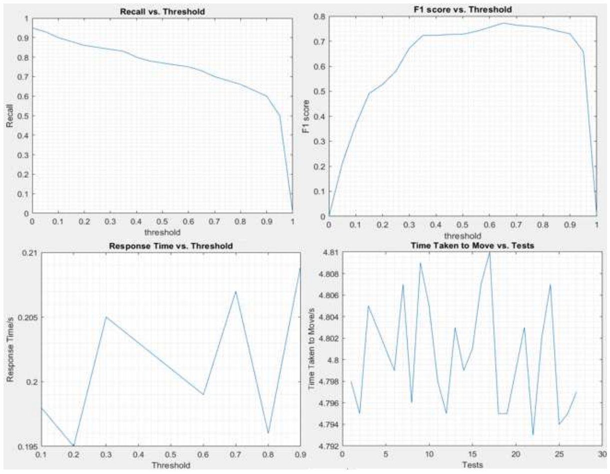

Fig. 10. Performance of algorithm and tracking platform with a distance of 9.4 cm.

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