MISALIGNMENT PARAMETERIZATION OF A 13.56 MHZ INDUCTIVE POWER TRANSFER SYSTEM FOR IN-SITU SOIL SENSING

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ABSTRACT

This paper discusses the measurement and characterization of the coil-to-coil misalignment in a 13.56 MHz inductive power transfer (IPT) system using variables that are either measurable on the wireless power transmitter alone (inverter current) or in conjunction with the receiver's Bluetooth module (rectifier voltage). A two-axis gantry transported the receiver on a plane 22 cm below the transmitter to perform these tests. The results from these tests demonstrate that the lateral coil-to-coil misalignment of this IPT system can be parameterized over the range of 0 to 30 cm with an average error of less than 2 cm. At peak alignment, this error decreases power transmission efficiency by less than 0.2%.

KEYWORDS

Wireless Power Transfer, Inductive Power Transfer, Coil Misalignment, Underground Power Transfer.

INTRODUCTION

Record-setting droughts and water scarcity have driven members of the agricultural sector to further incorporate technology into their water management strategies [1]. Advancements in soil sensing technology can help farmers optimize irrigation application, improve yields, and conserve water. However, these novel soil sensing technologies often use obtrusive and inconvenient aboveground hardware. In prior works, agricultural sensor networks have used wireless inductive power transfer (IPT) to power underground electronics without needing stationary aboveground hardware [2]. Unfortunately, these prior works have also shown that aligning the IPT system's coils without an automated procedure is extremely difficult (Fig. 1.a). This paper discusses how the lateral misalignment of a 13.56 MHz IPT system can be parameterized using variables measurable on the IPT transmitter alone or with a Bluetooth module attached to the IPT receiver. The parametric model generated in this paper represents the first step in creating an automated coil alignment system for the IPT system and soil sensor network discussed in prior works [3]. This alignment procedure will work cooperatively with GPS/Radio search algorithms and only use inductive localization for the final alignment stage (less than 30 cm misalignment).

The work presented in this paper is part of a collaborative effort between the University of Utah, Imperial College London, the University of Aberdeen, and Utah State University. This work aims to create an effective *in-situ* soil monitoring system powered by IPT through the soil.

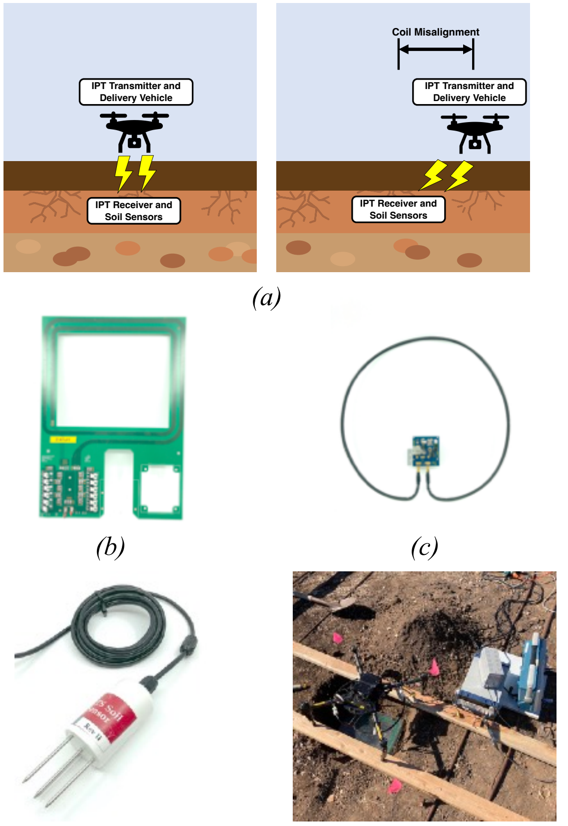
IPT SYSTEM FOR SOIL SENSING

The IPT system discussed in this paper consists of a single transmitter/receiver pair coupled at a frequency of 13.56 MHz. Consisting of a Load-Independent Class EF inverter [4] and copper-pipe coil (single-turn, 20 cm radius), this system's transmitter is capable of delivering over 35 Watts [3] to an underground load (Fig. 1.c). Although initially made to mount onto a DJI Matrice 100 drone, fixing this transmitter on a land vehicle such as an irrigation pivot or trailer is possible with some hardware modifications. Whereas a mobile structure carries the IPT transmitter, the receiver is designed to be stationary. This receiver uses a PCB coil to power a Class D voltage multiplier rectifier (Fig. 1.b). When stationed underground, a sizeable IP67 plastic case houses the receiver and any accompanying electronics (battery chargers, radio modules, soil sensors, etc.).

Wireless Power Transfer in Soil Monitoring

For the end-to-end *in-situ* soil monitoring system, custom soil sensors (see Fig. 1.d) attach to and receive power from a supercapacitor module in the buried receiver. In turn, vehicle-mounted transmitters periodically locate the receiver stations and power them wirelessly with IPT. The two subsystems communicate wirelessly over Bluetooth [3] or ultra-wideband radio [5].

Several field tests (Fig. 1.e) have demonstrated that the overall IPT/soil sensing system performs as expected [3]. Though a seemingly trivial problem, locating the underground receiver proved more difficult than initially predicted. Despite using survey flags, physically aligning the coils of the aboveground transmitter and underground receiver (not visible) was a persistent issue. This issue was difficult to circumvent because the metallic flag posts negatively impact inductive coupling and could not be placed too close to the receiver or transmitter. Since maximum power transfer only occurred in a relatively small section over the large (80 by 70 cm) disturbed patch of soil above the receiver, the drone needed to move several times before adequately aligning with the receiver and transferring the expected amount of power (around 30 Watts). Because coil-to-coil lateral misalignment tolerance is so low (less than 30 cm), GPS and radio ranging are generally inadequate for localization [6, 7]. Therefore, a method for characterizing misalignments of several centimeters using quantifiable variables is necessary for effective recharge missions between the vehicle-mounted transmitter and underground receiver of this soil monitoring system.



(a)

(b) *(c)*

(d) *(e)*

Figure 1: Inductive power transfer for soil condition monitoring and automated crop irrigation: (a) system diagram of IPT in an underground sensor network, (b) receiver, (c) transmitter, (d) Utah soil sensor, and (e) March 2022 field test in Kaysville, Utah.

TWO AXIS GANTRY FOR COIL-TO-COIL MISALIGNMENT CHARACTERIZATION

Many past works have examined how IPT receiver/ transmitter pairs can be localized. Of these works, those involving vehicles often use multiple transmitters to triangulate the receiver's position [8]. Works involving drones almost exclusively involve attaching the receiver to the drone and attempting to charge them above a transmitter (opposite of the case presented in this paper) [9]. Regardless of application, almost all techniques use reflected impedance to measure and quantify misalignment from the transmitter's perspective [8, 9]. However, on this 13.56 MHz system, accurately measuring reflected impedance without lab-level equipment would prove quite challenging. Other parameters must therefore be measured and used to quantify the misalignment of the IPT system.

Parameter Selection

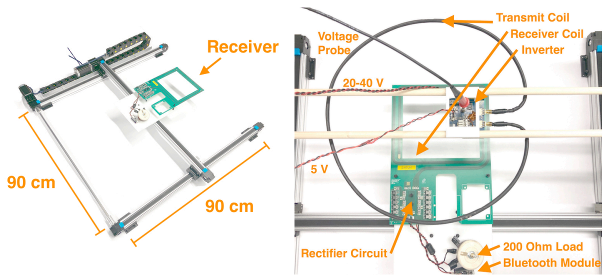
In [10], the authors present several methods that can be used to estimate the induced voltage of an IPT system containing a GaN transistor-driven class EF inverter. They demonstrated that the transistor's drain current, drain voltage, and input current correlate directly to the induced voltage in the receiver. Since induced voltage is related to the amount of power transferred to the receiver, these parameters provide a means of quantifying the coil-to-coil alignment of an IPT system. However, there are some drawbacks with some of these quantities. Measuring the transistor's drain current introduces inductance that can detune the IPT system. Likewise, reading drain voltage requires a significant amount of additional hardware. Of these options, the input current to the inverter is the easiest quantity to measure. This parameter can be measured using relatively small and inexpensive integrated circuits (ICs), and measuring it has no significant effect on the tuning of an IPT system [10]. For these reasons, the input current to the inverter was selected as a parameter to characterize coil-to-coil misalignment. Since the IPT system in this paper also uses wireless data telemetry, the induced voltage can actually be measured directly in the receiver and broadcast to a separate Bluetooth module.

Gantry and Testing Setup

Throughout these misalignment characterization tests, the receiver of the IPT system was connected to a large (90 by 90 cm work area) XY gantry (Fig.2.a). This custom-built gantry can move precisely (0.0144 mm per step) and features a custom driver for automated parameterization sweeps. The receiver also connects with a Bluetooth module, multimeter, and 200 Ohm rheostat. This Bluetooth module uses a 134 kOhm voltage divider and 15 Hz lowpass filter to send rectified voltage data directly to a cell phone application. The multimeter simply verified the results of the Bluetooth module. During testing, the transmitter was mounted 22 cm above the plane of the receiver and gantry (Fig. 2.b). The transmitter likewise required additional hardware in the form of a 5 V supply (for the timing circuitry), a variable voltage supply with a current readout (0-60 V for powering the inverter), and an oscilloscope (to confirm that the inverter was working correctly).

MISALIGNMENT CHARACTERIZATION ON A SINGLE AXIS

For the first set of parameterization tests, the gantry and receiver were positioned such that one axis of the receiver's coil aligned perfectly with the transmitter's coil. Initially, the receiver sat 40 cm away from the transmitter's center along the other axis. The gantry then transported the receiver 80 cm in the direction of the fixed transmitter in 1 cm steps. The additional hardware connected to the transmitter and receiver recorded the input current and rectifier voltage at each of the gantry's steps. This test was conducted under three conditions: 20 V transmitter input without the rheostat (134 kOhm as the only load, nearly open circuit), 20 V transmitter input with



(a) *(b)*

Figure 2: Parameterization testing setup: (a) receiver coil attached to xy gantry and (b) labeled test setup.

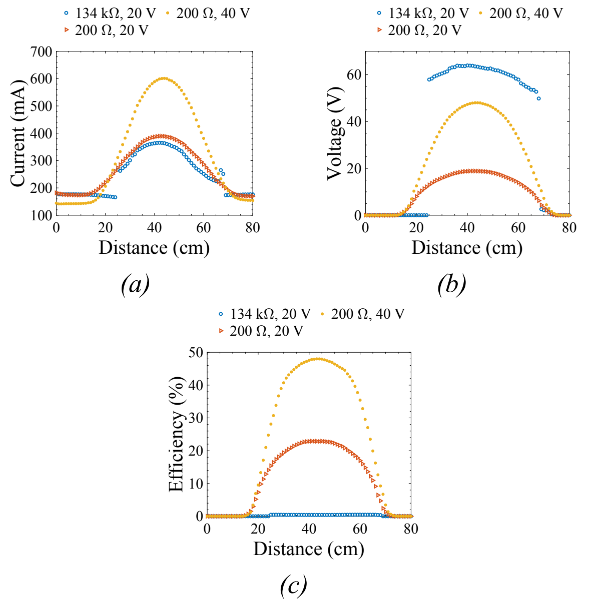


Figure 3: Results of the single axis characterization: (a) inverter current consumption, (b) rectified voltage, and (c) power transmission efficiency.

the rheostat, and 40 V transmitter input with the rheostat. Fig. 3 shows input current, rectifier voltage, and power transfer efficiency as functions of distance traveled. Note that the coils perfectly align at roughly 43.5 cm from the starting position. Table 1 shows benchmark figures from these tests.

Overall, the data from these tests demonstrate that inverter input current and rectifier voltage change significantly as the receiver moves under the transmitter. When the rheostat was attached, the system remained coupled until the coil-coil misalignment exceeded 30 cm, regardless of direction and input voltage. While efficiency increased significantly with the 40 VDC input (maximized tuning at this input voltage), increasing input voltage had no noticeable effect on misalignment tolerance.

For the test at 20 V with no rheostat, the system decoupled after the coil misalignment exceeded 17 cm and 26 cm when moving towards and past the transmitter, respectively. Although this behavior is unexpected, this effect can be explained by the fact the 134 kOhm load in this test acts as an open circuit. Without a load, the receiver's tuning capacitors saturate. Since their capacitance is a function of voltage, unanticipated saturation voltages can detune the coupled system. No similar effect was observed in the two tests with the 200 Ohm rheostat.

Table 1: Single axis characterization test results.

Parameter	134 kΩ	200 Ω	200 Ω
Inverter DC Input (V)	20.0	20.0	40.0
Peak Inverter Current (mA)	365	390	601
Peak Rectifier Voltage (V)	64.0	18.9	48.0
Peak Transmitter Power (W)	7.30	7.79	24.0
Peak Receiver Power (W)	0.0305	1.78	11.5
Peak Power Efficiency (%)	0.498	22.9	48.0

MISALIGNMENT CHARACTERIZATION ON TWO AXES

During the next test, the gantry and receiver were swept about a 75 by 80 cm grid in 5 cm steps. Initially, the receiver sat in the lower-left corner of the grid. The transmitter was positioned roughly in the center of the gantry's workspace. This test only examined the case with the 40 V transmitter input and rheostat. Fig. 4 and Table 2 show the results of this grid sweep test.

As demonstrated with the last set of tests, inverter input current and rectifier voltage change as the receiver moves towards and away from the transmitter. Again, the system remained coupled so long as the lateral coil misalignment stayed within 30 cm.

Table 2: Two axis characterization test results.

Parameter	200 Ω
Inverter DC Input (V)	40.0
Peak Inverter Current (mA)	600
Peak Rectifier Voltage (V)	47.9
Peak Transmitter Power (W)	24.0
Peak Receiver Power (W)	11.5
Peak Power Efficiency (%)	47.7

PARAMETERIZATION USING POLYNOMIAL REGRESSION

Data from the two axes swept were taken and used to create parametric relationships between misalignment distance and the measured values of inverter current consumption and rectifier voltage. Since there was no measurable coupling between the transmitter and receiver beyond 30 cm misalignment, data points at further distances were eliminated. First, second, third, and fourth-degree polynomial regression was applied to the test data. Fig. 5 shows the fitting curves and their residuals.

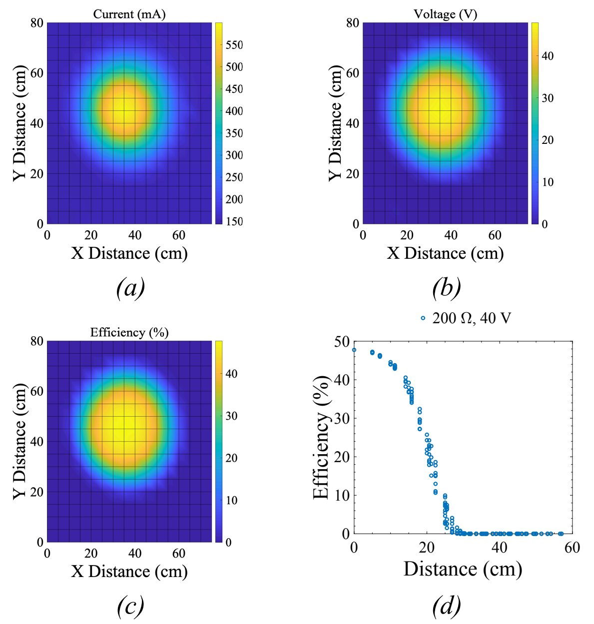


Figure 4: Results of the two axis characterization: (a) current consumed by the inverter, (b) rectified voltage, and (c,d) power transmission efficiency as a function of radial distance from maximum coil coupling.

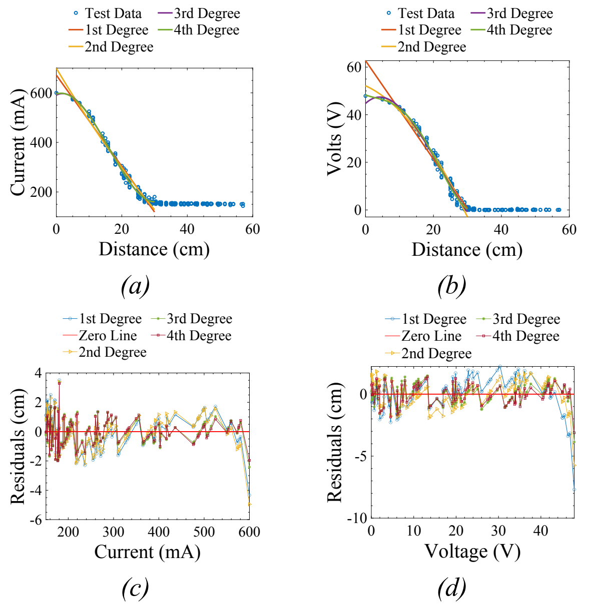


Figure 5: Parameterization estimate with polynomials: (a) inverter current consumption, (b) rectified voltage, (c) voltage fit residuals, and (d) current fit residuals.

All the parametric relationships had average residuals of less than 2 cm for both the input current (Fig. 5.c) and rectifier voltage (Fig. 5.d) best-fit curves. This error reduces efficiency by less than 0.2% at peak alignment (Fig. 3c). Most polynomial fits had larger residuals at low misalignment distances (i.e., high voltage and current values). This effect is not unexpected, given the 5 cm resolution of the grid sweep. Because there is a sparse amount of data in the low misalignment regions, comparing average residuals may not be the best method for selecting a good polynomial fit. A 3rd-degree polynomial fit kept the residual value below 2 cm for all input current values. However, a 4th-degree was needed to achieve this benchmark for the rectifier voltage characterization. A more refined grid sweep would likely show that lower degree polynomials can meet or surpass the 2 cm residual figure.

CONCLUSIONS AND FUTURE WORK

These experiments demonstrate that easily measurable parameters can quantify the coil-to-coil misalignment distance of an inductive power transfer system. For the IPT system used in these tests, receiver rectifier voltage and transmitter current consumption vary significantly over lateral coil misalignments of 30 cm and below. These quantities can be accurately modeled using polynomial best-fit models.

Ultimately, the goal of these parametric models will be to create an automated alignment algorithm for the coils of the IPT system. This alignment algorithm will be applied to aerial (drone) and land vehicles (gantry mounted on irrigation pivot). Localization will involve multiple stages. GPS and radio ranging algorithms will move the charging vehicle within the detection radius of the induction-based localization scheme developed in this paper and future works.

These parametric data are only useful for the case of constrained optimization, i.e., when the relationship between parameters and coil misalignment is known beforehand. Future work will examine alignment for the unconstrained case where there is no known relationship between inverter current consumption, rectifier voltage, and coil misalignment.

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REFERENCES

[1] M. Kummu, J. Guillaume, H. deMoel, S. Eisner, M. Flörke, M. Porkka, S. Siebert, T. Veldkamp, and P. Ward, "The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability," *Scientific Reports*, vol. 6, 2016.

[2] J. M. Arteaga, P. D. Mitcheson, and E. Yeatman, "Development of a fast-charging platform for buried sensors using high frequency ipt for agricultural applications," in *2022 IEEE Applied Power Electronics Conference and Exposition (APEC)*. IEEE, 2022.

[3] J. Sanchez, J. Arteaga, C. Zesiger, D. Young, R. Goel, P. Mitcheson, E. Yeatman, and S. Roundy, "Integration of a high frequency inductive power transfer system to energize agricultural sensors through soil," in *IEEE Wireless Power Week (WPW) Proceedings*, 2022.

[4] S. Aldhaher, D. C. Yates, and P. D. Mitcheson, "Load-independent class E/EF inverters and rectifiers for MHz-switching applications," *IEEE Trans. on Power Electron.*, 2018.

[5] Q. Qian, J. OKeeffe, Y. Wang, and D. Boyle, "Practical mission planning for optimized uav-sensor wireless recharging," *arXiv preprint arXiv:2203.04595*, 2022.

[6] Y. You and C. Wu, "Indoor positioning system with cellular network assistance based on received signal strength indication of beacon," *IEEE Access*, pp. 6691–6703, 2020.

[7] S. Lee, "Ultrawideband (uwb)-based precise short-range localization for wireless power transfer to electric vehicles in parking environments," *PeerJ Computer Science*, 2021.

[8] M. Rozman, A. Ikpehai, B. Adebisi, K. M. Rabie, H. Gacanin, H. Ji, and M. Fernando, "Smart wireless power transmission system for autonomous ev charging," *IEEE Access*, vol. 7, pp. 112240–112248, 2019.

[9] L. Lan, T. Polonelli, Y. Qin, N. Pucci, C. H. Kwan, J. M. Arteaga, D. Boyle, D. C. Yates, E. M. Yeatman, and P. D. Mitcheson, "An induction-based localisation technique for wirelessly charged drones," in *2020 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*, 2020.

[10] N. Pucci, J. Arteaga, C. Kwan, D. Yates, and P. Mitcheson, "Induced voltage estimation from class ef switching harmonics in hf-ipt systems," *IEEE Trans. on Power Electron.*, vol. 37, no. 4, 2022.