Extending the range of wireless power transmission for bio-implants and wearables

N Garraud, D Alabi, S Chyczewski, J. D. Varela, D P Arnold, A Garraud
Interdisciplinary Microsystems Group, Department of Electrical and Computer Engineering, University of Florida, Gainesville, FL, 32611, USA

E-mail: agarraud@ufl.edu

Abstract. This paper reports the latest achievements on an electrodynamic wireless power transmission (EWPT) system employing low-frequency (~17 Hz), low-amplitude (< 1 mT) magnetic fields. Compared to inductively or resonantly coupled coils, the EWPT approach facilitates power transmission to multiple receivers in a cluttered environment with little restriction on their orientation. Using a 5.5 cm³ receiver, a maximum of 22 mW power transfer (4 mW/cm³ power density), and a maximum transmission distance of 60 cm are independently demonstrated. These capabilities are achieved using one of two transmitter technologies: a coil-based transmitter, and a rotating-magnet transmitter. Through-body transmission and multi-receiver transmission are also demonstrated, opening the way for applications targeting bio-implants and wearables.

1. Introduction
While wireless power transmission (WPT) has been heavily researched in the last few years, there remain numerous challenges for efficiently transferring useful power levels to small power receivers over extended distances. Four interdependent and competing parameters are important for assessing various WPT technologies: the output power, the end-to-end power efficiency, the transmission distance and the receiver size.

In terms of near-field (non-radiative) WPT technologies, inductive coupling is well suited for efficient (>80 %) power transmission at close ranges, where the gap between the two coils is much less than the coil diameter [1]. However, the transmitted power and the system efficiency decrease dramatically while increasing the distance between the transmitter and the receiver (theoretically, the power decreases with the distance to the sixth power, i.e. \( P \propto 1/d^6 \)). Resonant inductive coupling overcame the low mutual coupling problem by using high-Q resonators, demonstrating high power transmission over meters [2]. However, the receiver antenna needs to be finely tuned with the transmitter antenna, and the system efficiency is highly sensitive to their orientation and axial mismatch.

Other WPT constraints to consider include human exposure to electromagnetic fields, receiver orientation independence, transmitter and receiver volume and weight, transmission to multiple receivers, and the ability to transmit power through a “cluttered” environment where conductive and/or ferromagnetic objects may be in between the transmitter and receiver.

The work presented in this paper focuses on mid-range transmission (i.e. 10 to 60 cm) with electrodynamic WPT (EWPT) using a permanent magnet embedded in the receiver that acts as a resonant torsional oscillator. Relying on a high mechanical Q-factor, the EWPT approach is shown to...
transmit power using safe, low-frequency, low-amplitude magnetic fields at mid-range distances (i.e. several diameters of the transmitter antenna).

2. System Design

2.1. EWPT Working Principle
In the EWPT working principle, a time-varying magnetic field emitted by the transmitter imparts a magnetic force or torque on the receiver magnet, inducing its motion (Figure 1a) [3,4]. In the system demonstrated here, a torsion oscillator is used in the receiver. The mass-spring system exhibits a maximum rotation amplitude at the resonance frequency, which is chosen as the system operating frequency. The magnet rotation within the receiver windings generates electrical power by induction and power is delivered to an external load. Resonant-type EWPT relies on a high mechanical Q-factor of the oscillator to maximize responsivity to low-amplitude magnetic fields.

EWPT generally operates at much lower frequencies (10 – 1000 Hz) than inductively or resonantly coupled systems (100 kHz – 10 MHz) [1]. The lower frequencies facilitate higher safety margins for magnetic field amplitudes [5,6] and better penetration through electrically conductive media (e.g. metal, human body, seawater). This enables wireless power delivery to multi-receivers in a crowded, cluttered environment, such as a home/office environment, an automobile, or within the human body for deep-biomedical-implants.

2.2. Receiver Design (Torsion Oscillator)
A macroscale torsion oscillator receiver is built to demonstrate and optimize the EWPT system at mid-range (Figure 1b). It is worth noting that the primary focus of this paper is on the transmitter and not the receiver. The receiver is composed of two cylindrical Nd-Fe-B magnets (8.5 mm diameter, 6 mm long) supported on a rubber band spring, which facilitates torsional resonance around 17 Hz with a Q-factor of 36. The receiver coil is made of 400 turns of AWG-36 wire wrapped around a rigid plastic housing. The receiver is 5.5 cm and 15 g.

2.3. Transmitter Design and Optimization
The alternating magnetic field (17 Hz in this case) can be generated either by a coil transmitter supplied with an AC current [4,7], or by a rotating permanent magnet actuated by a DC motor [8], as illustrated in Figure 2a. While a coil generates a time-varying uniaxial field (meaning at any given point around the transmitter, the field only increases and decreases in time, but does not change direction), the rotating magnet creates a more complex time-varying rotating magnetic field, resulting in increased flexibility in the receiver orientation. The rotating magnet also provides a large magnetic moment for “free,” and is especially efficient at long distances. However, it is limited in rotation rate, relies on moving parts, and the static field cannot be turned off, which may be undesirable for certain applications.

Figure 1: (a) General schematic of EWPT (electrodynamical wireless power transmission). (b) Prototype of resonant receiver built for demonstration.
In order to compare the transmission technologies and their range of transmission, three coils (denoted coil #1, coil #2 and coil #3) and a rotating magnet are built (Figure 2a). A transmitter performance can be analyzed through a figure of merit \( fm = m^2 f^2 / P_{in} \) combining important characteristics of the magnetic source: \( m \) the magnetic moment of the transmitter (units of A-m\(^2\)), \( f \) its operating frequency, and \( P_{in} \) its input power. This figure of merit quantifies how effective the magnetic source is to create a magnetic moment for a given input power and is independent of the operating current (for current-carrying coils). For annular, pancake-type coils, it can be shown that \( fm \) is maximum when the coil inner diameter is about 0.36 times its outer diameter (the inner loops burn proportionally more power than the magnetic moment they generate). The maximum outer diameter is generally limited by the application, but also by the maximum reactive power deliverable by the power amplifier at the operating frequency, since the coil inductance increases with the diameter. Compared to un-optimized coil #1 with a calculated value of \( fm \) of 5.2\( \times \)10\(^6\) W/T\(^2\), coil #2 and coil #3 are optimized with \( fm \) reaching 13.4\( \times \)10\(^6\) W/T\(^2\) and 84\( \times \)10\(^6\) W/T\(^2\), respectively. The more compact rotating-magnet transmitter exhibits a \( fm \) of 72\( \times \)10\(^6\) W/T\(^2\).

![Figure 2: (a) Comparison between the coil transmitter and the rotating-magnet transmitter technologies. (b) Built transmitter coil #1, #2 and #3 and built rotating-magnet transmitter. (c) Main characteristics of each fabricated transmitter.](image)

### 3. Experimental Setup and Results

Measurements are conducted to compare the different transmitters. First, each transmitter is characterized by measuring the magnetic field surrounding it for a given input power. Then, the wireless power delivery to the resonant receivers is measured as a function of the distance from the source.

#### 3.1. Magnetic Field Mapping

An AC input signal generated by a waveform generator (Agilent 33120A) is sent to a linear power amplifier (Crown XLS2500), supplying current to the transmitter coil. The coil current is measured using a current probe connected to an amplifier (Tektronix TCP305A/ TCPA300, respectively), while the output voltage is measured using two 10x oscilloscope probes, all of which are connected to a 4-channel oscilloscope (Agilent DSO-X-2004A) to estimate the coil input power. In the following experiments, the input power to the coils is fixed at 10 W. The rotating-magnet transmitter is supplied by a 19 V wall transformer. The 5 W motor input voltage, regulating the rotation frequency, is modulated by a potentiometer and a TO-220AB MOSFET.

The magnitude of the magnetic field is measured using a 3-axis probe (F.W. Bell, model ZOA99-3208) connected to a 3-axis gaussmeter (F.W. Bell, series 9950). From the measurements, Figure 3a shows various iso-envelopes of magnetic field from 0.05 mT to 5 mT for the four transmitters (the results from each transmitter plotted in just one quadrant). The transmitter coil input powers are kept constant at 10 W for fair comparison (input current of 3.3 A\(_{\text{rms}}\) for coil #1, 5.8 A\(_{\text{rms}}\) for coil #2, 2.8 A\(_{\text{rms}}\) for coil #3, and 4.5 A\(_{\text{rms}}\) for coil #3).
For low magnetic fields, a sharp improvement in range is noticed moving from coil #1 to #2 and again from #2 to #3. The performance of coil #3 is quite similar to the rotating-magnet transmitter: both 0.05 mT envelopes have a radius around 40 cm. Compared to coil #1, the volume of the 0.05 mT envelope increases by 1.6 fold for coil #2, by 4.2 fold for coil #3, and by 4 fold for the rotating-magnet transmitter. It is shown later that 0.05 mT is plenty large enough to deliver power via EWPT.

3.2. Wireless Power Performance

For wireless power measurements, the receiver is connected to a variable resistive load box. The ac power delivered to the load is determined by measuring the time-varying load voltage and load current (via current probe). Figure 4a shows the evolution of the output power with the load resistance for different magnetic field amplitudes. The optimal load resistance corresponds to the maximum load power. Simulations ran with a lumped-element model under Simulink (dashed lines) fit the experimental data (solid lines) for low magnetic fields up to 0.2 mT. For higher magnetic fields, the mismatch corresponds to very large magnet rotation reaching the maximum range (±90º), and correspondingly less well-controlled torsional motion.

The matched-load output power versus the transmitter-receiver distance is reported on Figure 4b, the receiver being along the central axis of the transmitter coils (or perpendicular to the rotating magnet). For mid-range distances beyond 10 cm, coil #3 and the rotating-magnet transmitter outperform the two other coils. 1.5 mW power transmission is achieved up to 60 cm, as well as 140 µW up to 100 cm, which is still useful in powering some electronic devices. Note that the transmitter coils have an advantage in close range (<10 cm) compared to the rotating-magnet transmitter. In fact, at close range, the strong force attraction between the rotating magnet transmitter and the receiver magnet inhibits rotational motion of the receiver.

3.3. Wireless Transmission in Cluttered Environments

Four 2-mW LEDs are connected to multiple receivers for demonstration. Figure 5a demonstrates the power transmission through a body (upper torso), lighting LEDs at 30 cm from the rotating-magnet transmitter. Moreover, Figure 5b demonstrates simultaneous power transmission to three arbitrarily-placed/oriented receivers in environment cluttered with metallic objects.
Conclusion

In this paper, two different WPT transmitter technologies are compared: a coil supplied by an AC current or a rotating magnet operated by a motor. The optimized coil #3 and the rotating-magnet transmitter show similar magnetic field and power transmission performances. These two transmitters can transmit non-negligible power (i.e. 1.5 mW) up to 60 cm with optimized coils and power density up to 4 mW/cm$^3$, a 28-fold improvement compared to previous work [3,7]. Future work will focus on miniaturizing the receiver while keeping a high-power density.

Acknowledgments

This work was supported in part by the NSF I/UCRC on Multi-functional Integrated System Technology (MIST) Center (NSF Grant IIP-1439644).

References

[1] Wei X, Wang Z and Dai H 2014 A Critical Review of Wireless Power Transfer via Strongly Coupled Magnetic Resonances Energies 7 4316–41
[2] Barman S Das, Reza A W, Kumar N, Karim M E and Munir A B 2015 Wireless powering by magnetic resonant coupling: Recent trends in wireless power transfer system and its applications Renew. Sustain. Energy Rev. 51 1525–52
[3] MeEachern K M and Arnold D P 2013 Electrodynamic wireless power transmission to a torsional receiver J. Phys. Conf. Ser. 476 12004
[4] Garraud A, Munzer D J, Althar M, Garraud N and Arnold D P 2015 Watt-level wireless power transmission to multiple compact receivers J. Phys. Conf. Ser. 660
[5] C95.6 2002 IEEE Standard for Safety Levels With Respect to Human Exposure to Electromagnetic Fields, 0-3 kHz
[6] C95.1 2010 IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz
[7] Challa V R, Mur-Miranda J O and Arnold D P 2012 Wireless power transmission to an electromechanical receiver using low-frequency magnetic fields Smart Mater. Struct. 21 115017
[8] Li W 2009 High efficiency wireless power transmission at low frequency using permanent magnet coupling (Master’s Thesis, University of British Columbia)