

Resonant Wireless Power Transfer to Ground Sensors from a UAV

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Abstract—Wireless magnetic resonant power transfer is an emerging technology that has many advantages over other wireless power transfer methods due to its safety, lack of interference, and efficiency at medium ranges. In this paper, we develop a wireless magnetic resonant power transfer system that enables unmanned aerial vehicles (UAVs) to provide power to, and recharge batteries of wireless sensors and other electronics far removed from the electric grid. We address the difficulties of implementing and outfitting this system on a UAV with limited payload capabilities and develop a controller that maximizes the received power as the UAV moves into and out of range. We experimentally demonstrate our prototype wireless power transfer system by using a UAV to transfer nearly 5W of power to a ground sensor.

I. INTRODUCTION

The idea of wireless power transfer is more than a century old [1], but resonant medium ranged wireless power transfer has been receiving much more attention in recent years due to the increase in popularity and availability of battery-powered, handheld electronics [2], [3]. The prospect of this technology being used to recharge electronic devices while in range of the electric grid and appropriate power providing stations is exciting, but also captivating is the prospect using unmanned aerial vehicles (UAVs) to provide wireless power to remote locations.

As early as 1964 wireless power was used to supply energy to a flying helicopter [4] and recently has been used to enable a 12 hour, record-length flight [5]. In this paper, we investigate the reverse problem of supplying energy to ground sensors from a UAV, as shown in Fig. 1. While other researchers are correct in aiming to expand the practicality of wireless power technology by increasing transfer power and efficiency [6], this paper offers new means of delivery to broaden applications. By creating a UAV that can act as a mobile power station, sensors and other electronic devices that are located away from the electric grid and other conventional energy sources but in range of a UAV can be powered and recharged. This includes highway messaging systems, ecological sensors located in forests, or sensors shallowly embedded underground or in concrete.

In this paper, we present hardware, control algorithms, and experiments which verify a wireless power transfer system that enables a UAV to power and recharge ground sensors. Our contributions are 1) developing a resonant power transfer system which can be carried and operated

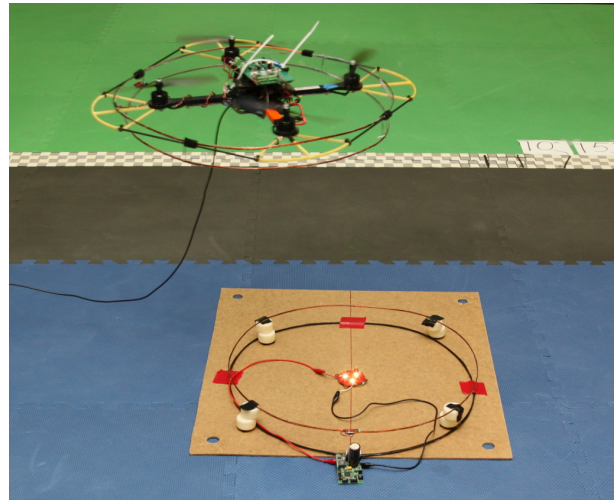


Fig. 1. UAV wirelessly transferring power to light a LED.

from a UAV, 2) designing a power receiving board that uses sensors for autonomous optimization of power transfer, and 3) experimentally demonstrating the ability to transfer power to ground based sensors. Observations from these tests also suggest the possibility of being able to use feedback to generate an autonomous controller for finding and optimizing proximity to the sensor node for power transfer.

The choice to use wireless magnetic resonant power transfer has many advantages with respect to adaptability to dynamic environments and relatively efficient transfer of power over medium ranged distances, as is explained in detail in Section II. Section III describes the system design used for demonstration and experiments. Information pertaining to the control algorithms used for localization and power transfer is covered in Section IV. Next, Section V depicts the experiments that were performed and their results. Finally, conclusions and future works are discussed in Section VI, followed by acknowledgments and references.

II. WIRELESS MAGNETIC RESONANT POWER TRANSFER

Wireless power transfer through the use of strongly coupled magnetic resonances works very well for efficient mid-ranged power transfer in dynamic environments compared with other wireless power technologies. For example, long range wireless transmission of energy through the use of microwaves, while impressive for its efficiency and capacity to transfer power over great distances [7], can be cumbersome for its requirement to have a direct line of site connection between source and receiver with no interferences. Worse yet, this method of power transfer can be damaging to any object that comes into contact with its beam of energy.

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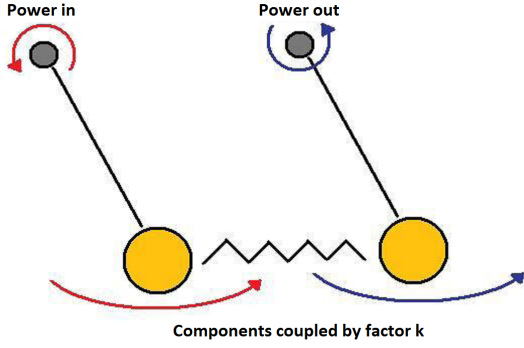


Fig. 2. Mechanical analogy for resonant coils.

Magnetic resonant power transfer on the other hand can be nearly omnidirectional and has little interference with any surrounding objects in its environment [3]. Resonant power transfer can work around and through objects, which lends itself well to operating in many different environments without exact positioning. Radio Frequency Identification (RFID) is another technology that has been demonstrated to wirelessly transmit power over great distances [8], but with magnitudes less power than resonant magnetic coupling, even when operating in close proximity.

Traditional inductive coupling on the other hand has good efficiency and power transfer over short distances (e.g. an electric toothbrush), but generally the transmission of energy diminishes at a rate of $1/x^3$ as distance increases. This is because for a given current traveling through an inductor the magnetic flux density drops off sharply with increasing distance from the source. Resonant coupling reinforces standard induction where it falls short. By including two coupled resonant coils between the driven and loaded inductive coils, power transfer is much more efficient over medium ranged distances. If the resonant coils are driven at their resonant frequency, they will oscillate with greater and greater amounts of energy, yielding farther reaching magnetic fields that create better coupling between the two coils when separated.

A great mechanical analogy for how this resonant energy transfer works is a system where two pendulums are connected by a spring [9]. In this example, Fig. 2, the two pendulums are assumed to oscillate at the same frequency and maintain sufficient coupling through the spring such that one pendulum can transfer and share momentum and energy with the other. By exciting one of these elements at the correct frequency, it will not only oscillate with greater alternating kinetic and potential energy, its counterpart will as well. In this manner power can be taken from the second element as long as this energy is replaced and maintained by the power source driving the first.

Just as the pendulums' resonant frequency can be determined by their mass and pivoting distance, coils can be designed to have the same resonant frequency by their capacitance and inductance. Energy oscillates in the resonant coil's case from voltage across the capacitor (potential energy

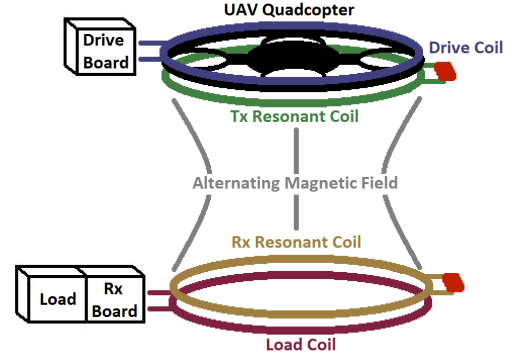


Fig. 3. UAV power transfer illustration.

in pendulum analogy) to current in the inductor (kinetic energy for pendulum), which generates the alternating, power transferring magnetic field that couples the two resonant coils together. One coil can even simultaneously supply power to multiple receiving coils [10], [11]. The caveat in any system like this is that high currents can generate heat in resonant coils with an appreciable resistance, which can cause a loss in overall power transfer efficiency.

Section III details how we use resonate wireless power transfer to supply power from a UAV to ground sensors or other electronic devices.

III. UAV ENERGY DELIVERY SYSTEM DESIGN

Designing and building a wireless power transfer system takes some determination, and doing the same such that it can be carried and powered by a UAV is at least slightly more arduous. Some challenges are managing added weight to stay within a UAV's payload, using the on board battery to drive the resonant circuit, designing a receiver board that can optimize power transfer from a dynamically changing system, and stabilizing the UAV to augment effective power transfer. Note that it is possible to land and transfer power in some environments, however, recharging sensors located on hazardous terrain or underneath bridges can make landing unfeasible. For this reason, this system is designed to operate during flight. To begin this section, we give a general description of the overall system, followed by in depth information on the power transfer coils, helicopter, and receiver node.

A. Overview

The overall design begins with the components that are carried by the UAV. First, power is taken from the UAV's battery and converted to an alternating voltage by the Drive Board. This alternating voltage is then applied to the power providing coil, also called the Drive Coil (Fig. 3). The Drive Coil then generates an alternating magnetic field that drives the neighboring resonant coil, abbreviated as the Tx Coil, by standard inductive coupling. From the Tx Coil a greater magnetic field resonates and couples over a distance with the first component of the grounded sensor system, the resonant receiving coil abbreviated as the Rx Coil.

Similar to the Drive and Tx coils, the Rx Coil is located in close proximity to, and inductively couples with the Load

Coil. The Load Coil is connected to the receiving board, abbreviated as the Rx Board, which ultimately uses the supplied power and applies it to the load receiving power.

B. Power Transfer Coils

The two primary factors for resonant coil performance are that they resonant close to the same frequency and that they have a sufficiently high enough quality factor. The quality factor represents how well a resonant coil can hold energy without losses to heat. The first calculation for determining the resonant frequency of a coil is to find its inductance [12]:

$$L = \mu_0 r N^2 \left(\ln \frac{8r}{c} - 1.75 \right) \quad (1)$$

where L is the inductance of the coil (H),
 μ_0 , mu nought, is a constant ($4\pi \times 10^{-7}$ Tm/A),
 r , is the radius of the coil (m),
 N , is the number of turns of coil,
and c is the wire bundle thickness (m).

It is then possible to calculate the resonant frequency given capacitance and inductance with the following equation:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

where f_r is the resonant frequency (Hz),
and C is capacitance (F).

The other component is the quality factor of the resonant coils, which can be found with the following equation:

$$Q = \frac{1}{R} \sqrt{\frac{L}{C}} \quad (3)$$

where Q is the quality factor of the coil,
and R is the resistance of the coil (Ω).

Two ways to increase the quality factor is to lower capacitance or resistance as seen in (3). Capacitance is easily decreased as this can be done by either pairing capacitors in series or by using new capacitors with a lower value. The real effect of a lower capacitance is a higher resonant frequency as shown in (2), which limits significant currents due to voltages having less time to overcome magnetic momentum. The other method of raising the quality factor, lowering resistance, can be achieved by using a lower gauge of wire for the resonant coils. However, lower gauges of wire are also heavier and the amount of weight that the UAV can carry is limited.

In our implementation of raising the quality factor it was found that operating at a higher frequency can actually decrease efficiency due to MOSFETs on the Drive Board operating faster and generating more heat. Also, for weight reduction the inductors on resonant coils were limited to two wraps of 16 gauge coil. This is just one example of many iterative design decisions that had to be made with the whole system in mind.

The inductors for the resonant coils were made to a specific radius of 0.265m to mount directly to the UAV's frame. These coils were used with 0.1uF capacitors to form

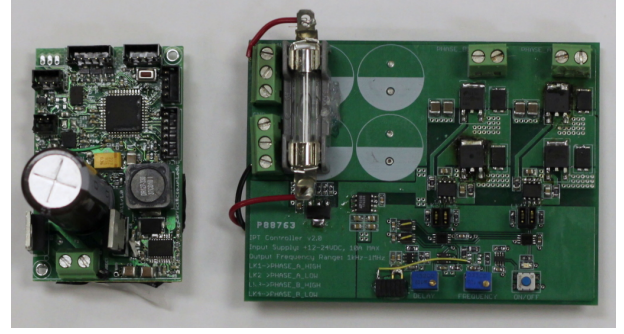


Fig. 4. The Rx Board (left) and the Drive Board (right).

the resonant coils. Using these parameters along with (1), (2), and (3) we find that the resonate frequency is approximately 189KHz and that the quality factor is about 192 (dimensionless). These equations work well as a starting point for designing coil and capacitor combinations, but final values are highly sensitive to physical parameters such as bends in the inductor coil and variability between manufactured capacitors.

C. Helicopter

We use an Ascending Technologies Hummingbird quadrotor helicopter [13] to carry the transmitting coils and power system as seen in Fig. 1. This quadrotor has a 200g payload. The power transmitting coils are each 38g and the Drive Board is 51g for a total of 127g of added mass. With this payload the flight time is between 15 to 20 minutes when using a 2.1Ah, 11.1V LiPo battery. This battery also powers the Drive Board mounted on the UAV, which uses 50A, 40V MOSFETs switched by a function generator operating at the resonant frequency of the system. For this prototype the Drive Board is tethered to a function generator which operates between 190-210KHz dependent upon the exact configuration. In future work signal generation will be placed onboard, eliminating the need for this cable.

The Hummingbird uses approximately 80W of power and the Drive Board peaks at about 45W. The battery can supply more than 550W continuously, so this 125W total is not an issue, but the UAV does lose as much as 1/3 of its flight time when providing power transfer. Despite carrying all of these components the helicopter is extremely stable and still has significant power for dynamic motions (see video attachment).

D. Rx Sensor Node

The receiving board collects power from the Load Coil for powering or charging the sensor node. The Rx Board (shown in Fig. 4) consists of a power conversion circuit, a battery charging circuit, a processor to monitor and control operation, inputs for a variety of other sensors, and power outputs for driving or controlling other circuitry.

The Load Coil is directly connected to the Rx Board. The Rx Board starts by rectifying high voltage AC power coming from the Load Coil (typically 50V peak-to-peak, although

some configurations reach 150V). Diodes in a standard high-speed, full-wave rectifier configuration rectify the AC voltage into a DC voltage. A large 1mF, 100V capacitor stabilizes the rectified voltage. A LM5005 switching power supply then converts this high, variable voltage into a stable 5V supply and is capable of driving a load at up to 2.5A. The LM5005 has a minimum input voltage of around 7V, so the rectified voltage must stay above this level to maintain power transfer.

The stable 5V supply then goes to a 2A single cell LiPo battery charger (LTC4001), which enables the Rx Board to recharge its battery. In addition, the 5V supply is externally available via MOSFETs (controlled by the processor) to power components or circuitry when energy is being received. From the battery a 3.3V LDO linear regulator supplies power to onboard sensors and the processor.

The processor is an 8MHz, low-power Atmel AT-Mega1284p processor. The processor monitors the rectified voltage, as well as the output of the 5V switching regulator. In addition, the processor reads the output of an INA198 high-side current shunt monitor to determine the power that is being used out of the 5V regulator. This enables the calculation of the overall power being drawn from the wireless power system. Since the switching power supply can supply a maximum of 2.5A, the maximum power the Rx Board can draw from the Load Coil is 12.5W, more than enough for our applications.

IV. POWER CONTROL ALGORITHM

Due to the dynamics of a proximity dependent power transfer system from a mobile aerial vehicle, a properly designed and optimized control system can increase performance substantially. To implement this, the sensors on the Rx Board were used to create a PD control algorithm to manage how much power transfers from the Load Coil to the Rx Board. The idea is to draw the maximum amount of power that is available in the Load coil without drawing so much that the voltage drops below the minimum 7V input required for the switching power supply.

In addition, the amount of power drawn from the Load Coil can have a substantial effect on the overall stability of the power transfer system. If the coupling between the Tx and Rx coils is relatively weak and a large load is applied, too much power will be drawn from Rx which will then couple less with Tx and energy transfer to the node will crash. A major disadvantage of this is not only the lack of power transfer, but unwanted oscillations as components turn on and off as energy builds up and falls in the system repeatedly. To avoid this the rectified voltage sustained across the capacitor is monitored and maintained to a set minimum by controlling the power that is supplied to the load.

For the experiments performed in this paper, a 2 Ω resistor is used across the 5V supply which will draw up to 12.5W. The processor uses a PWM signal to control the amount of power the resistor will draw by quickly switching a MOSFET on the Rx Board. Similarly, the battery charge rate can be controlled to vary the power draw from the Load Coil.

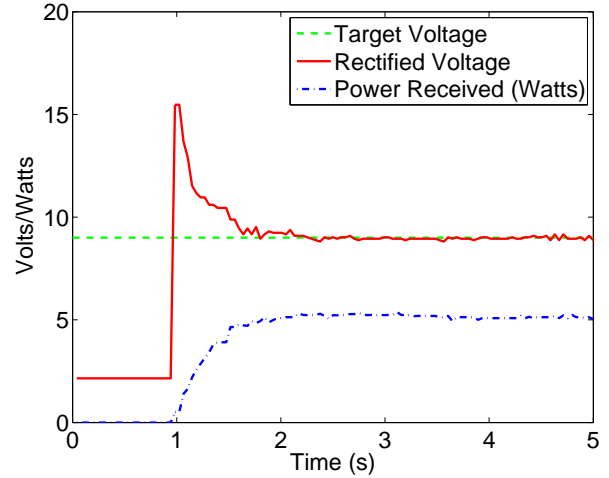


Fig. 5. Step response of the PD control system.

Initially, PWM was controlled additively as the rectified voltage raised and lowered about its set point. This works well for a static system, but as the UAV moves the entire system shifts dynamics and the power being supplied to the load must change quickly and accurately. With motion the additive controller exhibited strong oscillations and the minimum voltage had to be set high to keep the input voltage high enough for the voltage regulator. To optimize power transfer from a UAV, we implemented a Proportional-Derivative (PD) controller to adjust the power usage.

The PD controller tries to maintain a rectified voltage of 9V, which gives a suitable safety margin above the minimum 7V allowed by the switching regulator. We found a purely proportional controller oscillated too much as the UAV moved, and adding the derivative term resulted in a stable controller. Figure 5 shows the step response of the controller when the transmitter is turned on. Initially, the voltage overshoots (the rise time is about 0.1 seconds), but then within a second the controller has stabilized with a rectified voltage of 9V and a power draw of over 5W. This overshoot is acceptable and is, in fact, preferable to a more aggressive controller, which may result in larger oscillations below 9V and could result in the rectified voltage dropping below the 7V minimum.

V. POWER TRANSFER EXPERIMENTS

We performed numerous experiments to characterize the power transfer system. In this section, we start by presenting the results of static experiments we used to analyze the system without the UAV. We then present results of experiments performed with a UAV wirelessly transferring power to a ground sensor.

A. Static Power Transfer

Before beginning any aerial power transfer experiments, static tests were performed on the ground to tune the system and establish what levels of power transfer could be achieved over various distances. To do this a flat shelf system was built which could hold individual coils at set distances while

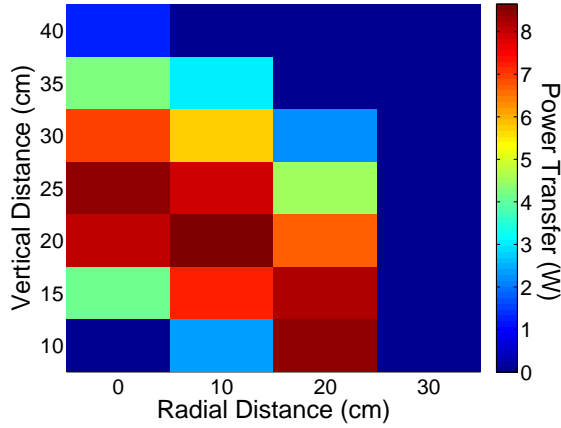


Fig. 6. Power transfer for various distances between Rx and Tx coils.

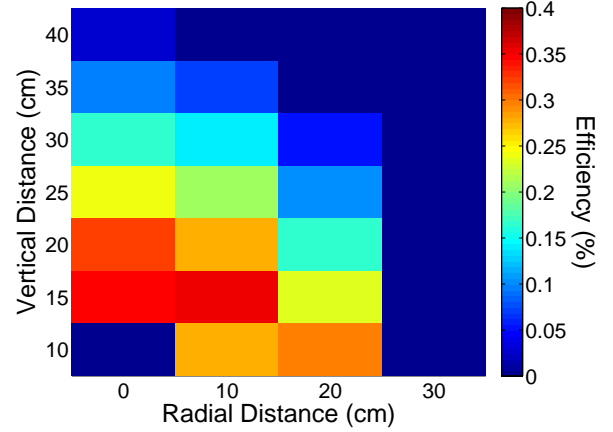


Fig. 7. Efficiency for various distances between Rx and Tx coils.

tests were performed. The distance between the Tx and Rx coils is variable in this application, but the distance between the Drive and Tx coils and the distance between the Rx and Load coils can be optimized for power transfer over a specific distance. Along with coil distances being calibrated, the drive frequency can also be tuned for a given load and coil locations [14].

The optimized conditions used for data collection were with 3.5cm between the Drive and Tx coils, 4cm between the Rx and Load coils, and a drive frequency of 207KHz. This drive frequency is 9.5% greater than our theoretical resonant frequency calculated in Section III-B, but this is due in part to the frequency being effected by the overall system characteristics (e.g. what load is applied) and also because there will be some quality error between designed and actual parts. To the extent of operating within the intended range, this frequency is close enough that the Drive and Rx boards have similar performance to what would be expected at the predicted 189 KHz.

Fig. 6 depicts measured power transfer and Fig. 7 illustrates efficiency for a range of distances between the Tx Coil and the Rx Coil. In these two figures vertical distance is the vertical displacement between the coils and radial distance is the horizontal displacement in any radial direction. One trend that is evident in the data is that if the two coils come too close together they become over coupled and less efficient, just as when they become too far apart they become under coupled; this is consistent with the theory and findings in [9]. More importantly, there was significant power transfer when the Tx and Rx coils were separated vertically 0.2-0.3m with a radial tolerance up to 0.1m. This area of operation provides a window large enough for the UAV to drift as it transfers power without significant losses.

The peak efficiency from these tests was slightly over 35% as calculated from Drive Board supply power to the power the load received. This is similar to other researchers' results which are in the range of 15%-50% depending on distances [9], [2]. With stationary energy transfer tests complete, Section V-B finally takes power transfer to the air.

B. Aerial Power Transfer

After demonstrating that power transfer would work with the designed system on the ground, tests were performed by flying the UAV equipped with the Drive Board, Drive Coil, and Tx Coil over the Rx Coil, Load Coil, and Rx Board as seen in Fig. 1. The Rx Board controlled the power draw using the PD controller described in Section IV and the results were logged. A plot for power transfer during a manual flight is shown in Fig. 8. Autonomous navigation is planned for future work. In this particular flight, the UAV is hovering over the sensor for about 30 seconds and then flies away. Flight was attempted to stay in the 0.2-0.3m target range described in Section V-A, but due to manually flying with ground effect and drift, power transfer often took place between from 0.15-0.4m.

The peak power transferred was 5.41W, with an average of 4.43W in the first 30 seconds. This magnitude of power transfer is sufficient for near complete recharge of most sensor network nodes (e.g. MICA Mote). The cause of the variations in power transfer is candidly explained: the coils mounted on the flying UAV move much more than when on a fixed base and the system dynamics are frequently changing as the pilot tried to maintain a steady position. Every difference in angle and distance between any of the coils causes shifts in the system, so power transfer is not going to be constant unless held artificially low or if the UAV is held absolutely still. The Rx Board and its control algorithm was able to adapt and keep power transfer occurring all the way up until the UAV flew away, and this demonstrates the Rx Board's ability to function in an unpredictable environment as duly intended by design.

Comparing quantitative data between the static and aerial experiments, it is evident that the aerial system is not quite on par with the static system as far as peak power performance. This is expected as when the tests were performed on adjustable shelves, all the distances between coils were fixed at an optimal distance in comparison to when continually moving with the UAV. The Tx Coil is suspended below the UAV in a flexible manner to allow the coil to retract when

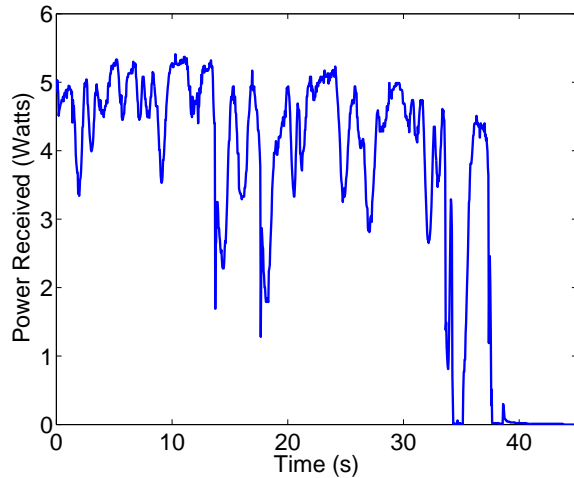


Fig. 8. Power transfer during a manual flight.

the UAV lands and extend when the UAV takes off. This is useful for its purpose, but it also allows the coil to sway and sometimes reposition unevenly on the moving UAV. Despite the obstacles of a system which transfers power from a flying UAV to the ground, the results of this last experiment validate meaningful, sustainable power transfer with this new method.

VI. CONCLUSIONS AND FUTURE WORKS

This paper demonstrates that wireless power transfer from a UAV to a ground sensor is possible and practical through experimental results. This has numerous and exciting applications for powering sensors in remote locations without access to grid or solar energy, such as: underwater sensors that surface intermittently to send data and recharge, underground sensors, sensors placed under bridges for structural monitoring, sensors that are only activated when the UAV is present, and sensors in locations where security or aesthetic concerns prevent mounting solar panels.

Wireless power transfer from a UAV was achieved by building and improving on established methods to account for the challenges that come with transferring power from a moving UAV. We developed a control algorithm that is able to optimize the received power even while the dynamics of the helicopter prevent it from maintaining the optimal position for power transmission. The transmitter is light and efficient enough for the UAV to carry and operate. Our experimental results show that the aerial transmission does not achieve as much power transfer as the static case, in large part due to the relative motion of the Drive and Tx coils on the helicopter and the deformations of these coils. Another challenge that reduced overall power transfer was maintaining an exact position over the Rx Coil. Despite these problems we were able to transfer nearly 5W continuously from the UAV to the ground sensor.

In future work, we plan to address these issues. First, we are constructing a new light-weight fixture for maintaining the proper circular shape and distance between the coils on the UAV. Second, we are exploring different methods for

autonomously and precisely localizing the UAV above the receiver. Outdoors, GPS does not provide sufficient accuracy and resolution to enable power transfer; however, we are exploring using feedback from the Rx Board (rectified voltage level or received power) or the Drive board (transmitted power, although large discrepancies in efficiencies make using this challenging) to aid in optimizing the location of the UAV. Another alternative we are exploring is to use a camera or another system to provide more accurate relative localization between the UAV and receiver. Finally, we are exploring other parameters that will improve both the efficiency and amount of power transferred. These include: raising the Q value of the coils, exploring different operation frequencies, increasing the input voltage, changing the number of loops of coil, further optimizing the receiving board, and storing received energy in super capacitors instead of batteries.

VII. ACKNOWLEDGMENTS

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