Automated Resonant Wireless Power Transfer to Remote Sensors from an Unmanned Aerial Vehicle

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AUTOMATED RESONANT WIRELESS POWER TRANSFER TO REMOTE SENSORS FROM AN UNMANNED AERIAL VEHICLE

by

Brent Griffin

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AUTOMATED RESONANT WIRELESS POWER TRANSFER TO REMOTE SENSORS FROM AN UNMANNED AERIAL VEHICLE

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Advisers: Carl Nelson and Carrick Detweiler

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 thesis, 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 the prototype wireless power transfer system by using a UAV to transfer nearly 5W of power to a ground sensor. Motivated by limitations of manual piloting, steps are taken toward autonomous navigation to locate receivers and maintain more stable power transfer. Novel sensors are created to measure high frequency alternating magnetic fields, and data from experiments with these sensors illustrate how they can be used for locating nodes receiving power and optimizing power transfer.
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Chapter 1

Introduction

1.1 Motivation

Imagine a heavily trafficked bridge that spans a great distance and contains sensors which monitor its structural integrity. Located underneath the bridge on or embedded in the structure itself, these sensors don’t have access to the electric grid or solar energy. But they still need power to operate. When these sensors run out of energy, it will either be expensive and laborious to gain access to them and repower them one by one, or disastrous if the bridge is failing and going unnoticed by a dead sensor.

Now picture this alternative: when a sensor becomes low on power, an Unmanned Aerial Vehicle (UAV) comes and recharges it (Fig. 1.1). UAVs are able to navigate through many different environments and are able to reach great distances on a single trip. It would even be possible for the sensor to remain inactive, and simply have the UAV go and power it when information is needed. This power upkeep would require much less work, and if the system is made autonomous, practically none. Furthermore, the same system of power transfer used to repower the sensors, can be used to charge the UAV.
To realize a system of this magnitude requires many accomplishments. First, a system of power transfer must be chosen which is robust enough to operate through the dynamics of its carrier. Second, the system must be light enough for mobile operation. Third, since outdoors GPS does not provide sufficient accuracy and resolution to enable autonomous power delivery, some other form of sensing must be integrated with an algorithm for locating nodes to be charged and optimizing position for power transfer. Finally, to be completely free of human interaction, power stations must also be locatable for recharging the mobile platform.

We satisfy these requirements by utilizing wireless power transfer through the use of strongly coupled magnetic resonances, which operates well in changing environ-
ments. The power transmitting coils, drive system, and sensors are designed to be outfitted to an Ascending Technologies Hummingbird quad-rotor helicopter [1] which has a 200 g payload (Fig. 1.2). Quadrotor UAVs are an ideal carrier since they are able to fly to many different locations quickly, and hover in place once they arrive. We improve energy transfer despite drifting power transmitting coils during flight by implementing a power receiving board which increases overall power transfer and efficiency [2]. For the purposes of autonomous navigation and node finding, we develop sensor boards which are able to read high frequency alternating magnetic fields and determine the location of power transmitting coils during operation.

Recharging bridge sensors is just one ambition for this research. Other applications include underwater sensors that surface intermittently to send data and recharge, underground sensors, and sensor in locations where security or aesthetic concerns prevent mounting solar panels. It is also possible to deploy sensors with a UAV, further reducing the level of direct human intervention needed. One IEEE writer envisions even being able to text a service and have a UAV come and recharge your
cell phone in an article about this project [3]. The breadth of applications that lie on
the horizon for wireless power transfer from UAVs is the primary motivation for this
thesis.

1.2 Contributions
This thesis describes the production of a UAV which is able to supply power to
remote locations through the use of wireless power transfer. The thesis contributes
the following: 1) develops a resonant power transfer system which can be carried
and operated from a UAV, 2) implements a power receiving board that uses sensors
for autonomous optimization of power transfer, 3) experimentally demonstrates the
ability to transfer nearly 5 W of power to ground-based sensors, 4) completes a
sensor board design which is able to measure high frequency magnetic fields, and
5) demonstrates the ability of these sensors to collect data with sufficient resolution
and accuracy to, in the future, implement an autonomous flight control algorithm for
node finding and optimizing location for power transfer.

1.3 Overview
This thesis develops a wireless power transfer system that is light enough for a UAV
to carry. Before implementing this system on a UAV, we developed a ground-based
power transfer system, similar to existing systems, to test operation in a controlled
environment. The choice to use wireless magnetic resonant power transfer has many
advantages with respect to adaptability to dynamic environments and relatively effi-
cient transfer of power over medium ranged distances. This lends itself well to a UAV
application where the power transmitting device can fly relatively close to the receiver,
but cannot stay absolutely still as it hovers. Chapter 2 covers related work in the areas of wireless power transfer and how it relates to UAVs, as well as magnetic field sensing and localization. Chapter 3 provides details on the theory behind wireless resonant power transfer and the results of initial experiments with the ground-based power transfer system.

After producing a working model for wireless magnetic resonant power transfer, the objective of developing a UAV which is able to provide power to remote locations through the use of wireless power is undertaken. Chapter 4 presents completion of a working prototype for this application. By implementing a power receiver board which autonomously optimizes power transfer, nearly 5 W of power is transferred to a grounded sensor. This is a significant contribution to UAV and wireless power research as no other system like this is known to exist. Information on modifying the previous system design to work from a UAV, and description of associated experiments, are provided in Chapter 4.

Many parameters are found to effect this method of power transfer, but chief among these is the UAV’s positioning with the node receiving power. For manually guided flights, the power transfer stability is limited by the pilot’s skill and ability to retain visual contact with the UAV. After successful demonstration of wireless power transfer from a UAV to a sensor with manual flights, development of autonomous navigation begins. This goal requires sensing, and magnetic field sensing is chosen as a means for feedback on a UAV positioning system. Without a manufactured magnetic field sensor that is able to sufficiently read high frequency alternating magnetic fields, an original sensor board is designed for this purpose. Using these sensors information about the relative location of the receiving coils to the UAV can be deduced. This information can then be used as feedback to the UAV for locating nodes, and then optimizing its position for power transfer. This will allow UAV power transfer without
human pilot interaction. Magnetic field sensor development and experimental results are described in Chapter 5.
Chapter 2

Literature Review

2.1 Wireless Magnetic Resonant Power Transfer

The idea of wireless power transfer is more than a century old [4], but medium ranged resonant wireless power transfer has been receiving much more attention in recent years due to the increase in popularity and availability of battery-powered, hand held electronics [5, 6]. Further supporting application of this technology, one source can simultaneously supply power to multiple receiving devices of different sizes [7, 8]. The primary benefit for a UAV application is that wireless power transfer through the use of magnetic resonances works very well for efficient mid-ranged power transfer (within a few meters) in dynamic environments compared with other 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 [9], can be cumbersome for its requirement to have a direct line-of-sight connection between source and receiver. Worse yet, this method of power transfer can be damaging to any object that comes into contact with its beam of energy. Magnetic resonant power transfer, on the other hand, can be nearly omni-directional
Table 2.1: Comparison of power and range capabilities of different wireless power technologies with specific examples.

<table>
<thead>
<tr>
<th>Wireless Power Method</th>
<th>Power</th>
<th>Range</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave</td>
<td>10s of kW</td>
<td>&gt; km</td>
<td>Requires direct line-of-sight</td>
</tr>
<tr>
<td>JPL Raytheon</td>
<td>30 kW</td>
<td>1.6 km</td>
<td>W. Brown also led 1964 helicopter flight</td>
</tr>
<tr>
<td>Laser</td>
<td>&gt; kW</td>
<td>&gt; km</td>
<td>Requires direct line-of-sight</td>
</tr>
<tr>
<td>LaserMotive</td>
<td>1 kW</td>
<td>1 km</td>
<td>Laser used for 12 hour flight</td>
</tr>
<tr>
<td>Radio Frequency</td>
<td>10s of µW</td>
<td>&gt; km</td>
<td>Flexible proximity to power source</td>
</tr>
<tr>
<td>Intel Research</td>
<td>60 µW</td>
<td>4 km</td>
<td>Harvested energy from TV towers</td>
</tr>
<tr>
<td>Magnetic Induction</td>
<td>100s of kW</td>
<td>&lt; 1 coil dis.</td>
<td>Little interference with environment</td>
</tr>
<tr>
<td>Energizer Charger</td>
<td>&lt; 5 W</td>
<td>contact</td>
<td>Recharges small devices placed on pad</td>
</tr>
<tr>
<td>Resonant Coupling</td>
<td>10s of W</td>
<td>&gt; 1 coil dis.</td>
<td>Flexible proximity, little interference</td>
</tr>
<tr>
<td>MIT Researchers</td>
<td>60 W</td>
<td>2 m</td>
<td>Safely transferred power through people</td>
</tr>
</tbody>
</table>

and has little interference with any surrounding objects in its environment [6]. Resonant power transfer can work around and through objects, which lends itself well to operating in many different environments without exact positioning, such as when operating from a UAV.

Radio Frequency Power Harvesting is another technology that has been demonstrated to wirelessly transmit power over great distances [10], but with orders of magnitude less power than resonant magnetic coupling, even when operating in close proximity. Traditional coupling based on Faraday’s law of induction, 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. This limitation of induction, however, can be overcome with the use of strongly coupled magnetic resonances. Table 2.1 provides a comparison of these various wireless power technologies with specific examples, and Fig. 2.1 offers a visual comparison.
Figure 2.1: Visual comparison of typical power and range capabilities of different wireless power technologies.

2.2 Wireless Power Transfer and UAVs

The vast majority of current research on interactions between UAVs and wireless power transfer is in an effort to maintain longer flight by receiving power from a ground power station. As early as 1964 wireless power was used to supply energy to a flying helicopter [11] and recently has been used to enable a 12 hour, record-length flight [12]. Even in ground-based mobile systems where additional equipment and weight are more easily accommodated, the effort of using wireless power is often still focused towards a fixed power station charging a mobile platform [13]. The prospect of wireless power 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 of using UAVs to provide wireless power to remote locations.

While other researchers are correct in aiming to expand the practicality of wireless power technology by increasing power transfer and efficiency [14], this thesis offers new means of delivery to broaden applications. We investigate supplying energy to
remote sensors from a UAV, as shown in Fig. 1.2. 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.

2.3 Magnetic Field Sensing and Localization

Researchers have had great success for localization and even control using magnetic field measurements. This includes utilizing generated fields as beacons for localizing moving sensors [15], or more relevant to UAVs, producing magnetic fields along the axes of aircraft and sensing fields to avoid a collision [16]. In both of these examples, however, the magnetic fields are produced solely for the purpose of localization and not for any other form or function.

More relevant work to this thesis is using magnetic field measurements from a power line to determine position and control for perching [17, 18]. In this case researchers are utilizing a magnetic field that is sourced from power lines not originally intended for localization. This is more challenging, but a consistent magnetic field model is derived and the authors use accelerometers to assist with determining trajectory and control.

These same methods cannot be applied directly to this thesis due to operating a faster resonating magnetic field for modeling and measurement. In the generated and power line localization, the conditions of the field source are stable and well understood. This means that directional magnetic field data can be directly compared to a set model for localization. Resonant magnetic fields, however, are not consistent in a dynamic, UAV-carried power transfer system.
The same manufactured three-axis magnetometers used in other work for magnetic field measurement do not benefit this thesis either. Much work has been put into reading literature and testing different magnetic field sensors currently available, but these prove either too insensitive or not able to operate at high frequencies (100s of kHz range) [19]. This included the consideration of optically pumped, search-coil, flux-gate, and magnetoresistive magnetometers and the testing of SS495, SS496A1, HMC1051Z-RC, ZMY20MTA, and ECW-F4104JB hall effect sensors. As opposed to abandoning this pursuit to use another sensing technology (e.g., a camera), this thesis encompasses the development of novel sensors which measure the same high frequency alternating magnetic fields used for transferring power for the purpose of autonomous navigation.
Chapter 3

Wireless Magnetic Resonant Power Transfer

3.1 Introduction

The principal contributions of this thesis are in the design and development of a UAV which is able to transmit power wirelessly, but it is first necessary to build a working ground-based power transfer system to determine the performance and characteristics of the system under controlled conditions. Wireless magnetic resonant power transfer offers many advantages with respect to adaptability to dynamic environments and relatively efficient energy transfer over medium ranged distances, which lends itself well to a UAV application. Chapter 3 provides details on the theory behind wireless resonant power transfer, and the results of initial experiments. Section 3.2 delves into specific theory behind wireless power transfer through the use of strongly coupled magnetic resonances, and Section 3.3 outlines the system design that utilizes this technology. Section 3.4 describes experiments and their results, and Section 3.5 summarizes the accomplishments and findings of Chapter 3.
3.2 Wireless Magnetic Resonant Power Transfer

Theory

The basic principle of inductively coupled power transfer is two overlapping coils in close proximity sharing alternating magnetic fields, or two magnetically coupled inductors. An alternating current (AC) in the transmitting coil produces a magnetic field that generates an alternating voltage in the receiving coil that can be applied to power or charge a device [20]. The main limitation of standard inductive power transfer is that it only operates efficiently over short distances. However, this can be overcome with the use of strongly coupled magnetic resonances.

By including two coupled resonant coils between the driven and loaded inductive coils, power transfer is much more efficient over medium ranged distances. Coupling the transmitter and receiver through the use of correctly sized and aligned inductors and capacitors causes even minute magnetic fields to gain momentum in a coupled circuit. As an introductory example, imagine a small child pushing a much larger adult on a swing. If the force the child exerts on the swing is done with correct timing, although much smaller, the child can use the larger person's building kinetic energy to augment each push and make the adult move over a greater distance than would otherwise be possible. Of course there is some dampening due to air resistance and friction in the hinge, so this oscillation will eventually stop if the driving force is taken away. The resonant coils work in much the same way.

If a pair of resonant coils are driven at their resonant frequency, they will oscillate with greater and greater amounts of energy, yielding farther reaching magnetic fields that maintain 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 [21]. In this example, 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 (Fig. 3.1). 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.

The resonant coils which act similar to the pendulums consist of a closed loop circuit with an inductive coil and a capacitor. An inductive coil carries energy in the form of magnetic momentum when current is running through it, and a capacitor carries energy in the form of charge when it has a voltage across it. For any given LC circuit there is an optimum frequency at which it will resonate. Just as the pendulums’ resonant frequency can be determined by gravity 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 in the pendulum analogy) to current in the inductor (kinetic energy
for the pendulum), which generates the alternating, power transferring magnetic field that couples the two resonant coils together.

In the resonant coil schematic shown in Fig. 3.2, the primary inductive coil, or Drive Coil, receives AC power from the power supply which is then transferred through induction to the first resonant coil, Tx. These first two coils share energy because of their immediate proximity to each other and overlapping magnetic fields. Dependent upon how well the two resonant coils, Tx and Rx, are coupled, Tx will cause Rx to oscillate with a proportional degree of energy. Because the resonant coils are closed loops and lack loads, they are much less limited in the amount of energy with which they can oscillate compared to the two standard inductive coils. In response, the magnetic fields of these two coils can connect and influence one another over a much greater distance than would be possible from standard inductive coils. The last coil, the Load Coil, which inductively receives power from Rx because of its close proximity (similar to the Drive Coil and Tx), applies the voltage it gains across a load, and performs the final step for wireless magnetic resonant power transfer.

Another concept that is important to understand is that of dynamic coupling. In
the mechanical example, the spring constant $k$ determines in large part the amount of power that can be transferred from one pendulum to the other. Resonating inductive coils, however, instead of having a constant $k$, have a coupling coefficient that changes based on the distance between the two coils, the effective load seen from other coils, and a number of other factors such as drive frequency. This makes the modeling of a complete resonant power transfer system very difficult.

However, by using principles of magnetic and electrical theory it is possible to calculate many design parameters. These parameters include the number of coil windings needed in the resonant coil, the initial current in the Drive Coil, and the quality factor which effects the efficiency of power transfer. It is also useful to derive equations which detail standard induction. Doing this provides a theoretical comparison for both resonant and standard induction data.

First, consider equations that depict the effective range of standard induction. This is important in understanding both the limitations of induction and the short ranged coupling that takes place between the standard coils and the resonant coils. The relationship of magnetic field strength and proximity to an inductive coil can be seen in Eq. (3.1) & (3.2):

$$B_x = \frac{\mu_0 NI r^2}{2(x^2 + r^2)^{\frac{3}{2}}} $$

(3.1)

where $B_x$ is the magnetic flux density (T),

$\mu_0$, is the permeability of free space ($4\pi \times 10^{-7}$ Tm/A),

$N$ is the number of turns of coil,

$I$ is the current through the coil (A),

$r$ is the radius of the coil (m),

and $x$ is the perpendicular distance away from the coil center (m).
Figure 3.3: Eq. 3.1 plotted for magnetic flux density vs. distance from source. For any inductive coil, the density of the field it produces becomes weaker by a factor of the distance raised to the third power. When considering this behavior, it is evident why traditional inductive power transfer is extremely limited by distance between the transmitting and receiving coil.

Considering all parameters besides $x$ to be constant for a given coil, as $x$ increases this equation can be approximated as:

$$B_x = \frac{\text{constant}}{x^3}$$ \hspace{1cm} (3.2)

This sharply diminishing field strength explains why it is important to keep the Drive and the Load Coils in close proximity to their respective resonant coils (Fig. 3.3). If the Drive Coil is too far away from Tx, it will not be able to supply enough magnetic field to Tx to drive the system. If the Load coil is too far away from Rx, it will not be able to draw enough power. However, if the inductive coils are located too close
to the resonant coils, the higher coupling will cause the resonant coils to effectively carry the same loads as the inductive coils. A higher effective resistance in the loop of the resonant coils will cause lower resonance and less coupling over greater distances. This means for any given system, there are optimum positions for the coils relative to each other.

This leads to quantifying inductive coupling. The coupling coefficient, $k$, can be defined as the fraction of flux coming from the primary coil which reaches the secondary coil. If the coils are stacked one on top of the other, the coupling coefficient will be high since they are in direct proximity of each other’s magnetic fields. For this same reason, as inductive coils are moved apart, the coupling between the two without resonant coils diminishes. Lower coupling between two coils often means less potential for power transfer. Generally $k$ is calculated for inductive coils with Eq. (3.3):

$$V_P = k \sqrt{\frac{L_P}{L_S}} V_S + j\omega L_P I_P (1 - k^2)$$

(3.3)

where $V_P$ is the voltage across the primary coil (V),

$k$ is the coupling coefficient between coils,

$L_P$ is the inductance of the primary coil (H),

$L_S$ is the inductance of the secondary coil (H),

$V_S$ is the voltage across the secondary coil (V),

$j$ is an imaginary number,

$\omega$ is the angular frequency (rad/s),

and $I_P$ is the current in the primary coil (A).

If the secondary coil has no load across it, and is acting as an ideal receiver, the impedance load that the primary coil sees is only from its own coil. This assumption
allows its current, $I_P$, to be found with Eq. (3.4):

$$I_P = \frac{V_P}{j\omega L_P}$$  \hspace{1cm} (3.4)

From Eq. (3.3) and Eq. (3.4), a simpler equation for $k$ is derived in Eq. (3.5):

$$V_P = k \sqrt{\frac{L_P}{L_S}} V_S + j\omega L_P \frac{V_P}{j\omega L_P} (1 - k^2)$$
$$V_P = k \sqrt{\frac{L_P}{L_S}} V_S + V_P (1 - k^2)$$
$$k = \frac{V_S}{V_P} \sqrt{\frac{L_P}{L_S}}$$  \hspace{1cm} (3.5)

Figure 3.4: Geometry terms of a coil used for calculating inductance.

The inductance of a coil with known geometry (Fig. 3.4) can be calculated by using Eq. (3.6) [22]:

$$\text{Inductive Coil Geometry}$$

$$\text{Coil Bundle}$$

$$\text{Coil Center}$$

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

(3.6)

where \( L \) is the inductance of the coil (H),

and \( c \) is the wire bundle thickness (m).

For resonant power transfer, two primary factors for performance are paired coils resonating at the same frequency and with a sufficiently high quality factor (Q factor). Given a coil's inductance found from Eq. (3.6) and a specific capacitor value, its resonant frequency can be found with Eq. (3.7):

\[ f_r = \frac{1}{2\pi\sqrt{LC}} \]  

(3.7)

where \( f_r \) is the resonant frequency (Hz),

and \( C \) is capacitance (F).

The Q factor of a coil can be found with Eq. (3.8):

\[ Q = \frac{1}{R} \sqrt{\frac{L}{C}} \]  

(3.8)

where \( Q \) is the quality factor of the coil,

and \( R \) is the resistance of the coil (Ω).

There are a few ways to comprehend and then increase Q factor. One definition of Q factor is how much energy a resonant system can hold compared to energy lost during a single cycle. Energy is lost in a resonant coil primarily as heat when high currents conduct through the slightly resistive winds of wire in each coil. Resistance
can be lowered by using less wire in the coil or by using thicker gauge wire, both of which also affect inductance. Because the coils are subjected to a high frequency alternating current, skin effect needs to be taken into account when calculating the resistance of coils. The depth of electricity conduction in a resonant coil can be found in Eq. (3.9):

$$\delta = \frac{1}{\sqrt{\pi f r \mu \sigma}}$$ (3.9)

where $\delta$ is the skin depth (m),
$\mu$ is the permeability of the conductor (Tm/A),
and $\sigma$ is the conductivity of the conductor (S/m).

The resistance of the resonant coils at their resonant frequency can be calculated using skin depth from Eq. (3.9) and coil geometry in Eq. (3.10) [7]:

$$R = \frac{2\pi r N}{2\pi r_w \sigma \delta} = \frac{r N}{r_w \sigma \delta} = \frac{r N \sqrt{\pi f r \mu}}{r_w \sqrt{\sigma}}$$ (3.10)

where $r_w$ is the wire radius (m).

As seen in Eq. (3.8), another way to increase the quality factor is to lower capacitance. 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 Eq. (3.7), which limits higher currents due to voltages having less time to overcome magnetic momentum. This is best understood by following Eq. (3.11) through Eq. (3.13). If a voltage is applied to a coil with a known inductance, it is possible to determine the current flowing
through the coil given the amount of time the voltage is applied with Eq. (3.11):

\[ V = L \frac{di}{dt} \]
\[ di = V \frac{dt}{L} \quad (3.11) \]

where \( di \) is the current through the inductive coil (A),
\( V \) is the voltage supplied across it (V),
\( dt \) is the time voltage is applied to it (s).

For any given frequency, \( T \) (s) is the period of time each cycle takes. When the frequency represents a rate of alternating magnetic fields, there is both a positive and a negative voltage applied to the inductive coil for every period. Therefore the period of time that a single voltage is applied to the inductor, \( dt \), is equal to \( \frac{T}{2} \) as shown in Eq. (3.12):

\[ f = \frac{1}{T} \]
\[ dt = \frac{T}{2} \quad (3.12) \]

Given the resonant frequency from Eq. (3.7), the attributes of inductance from Eq. (3.11), and the relationship between frequency and \( dt \) from Eq. (3.12), it is revealed that current through the coils decreases with capacitance in Eq. (3.13):
\[
\frac{1}{f_r} = T = 2\pi\sqrt{LC} \\
di = V \frac{dt}{L} = V \frac{T}{2L} \\
di = V\pi\sqrt{\frac{C}{L}} 
\] (3.13)

It is important to keep in mind that all Q factor parameters are interrelated with resonant coil design. For example, minimizing resistance with a lower resonant frequency (Eq. (3.10)), can actually have a negative effect since resonant frequency is more heavily related to Q factor through inductance and capacitance than through resistance (Eq. (3.7), Eq. (3.8)). Therefore, either all of these calculations need to be carried out in their entirety or a derivation performed which takes parameter to fundamental properties (e.g., coil geometry) for an accurate theoretical comparison of two systems.

A second important interpretation of Q factor is as a resonator’s bandwidth relative to its center frequency, as seen in Eq. (3.14):

\[
Q = \frac{f_c}{\Delta f} 
\] (3.14)

where \(\Delta f\) is the bandwidth of the resonant coil (Hz).

Since bandwidth is the range of frequencies for which the resonant coil can reach half the energy of peak resonance, there can be advantages to a lower Q factor. It is true that a higher Q factor allows more efficient power transfer through the resonant coils, but if the Q factor is too high, the bandwidth will be very sharp and it will be easy to have two coils that will not resonate together due to even slight manufacturing
differences. Understanding Q factor as a ratio of stored energy to lost energy and as being proportional to bandwidth concomitantly is important for design applications.

3.3 Wireless Power Transfer System Design

Much of what is commercially available for wireless power transfer is near field, standard inductive power transfer. To obtain distances and efficiencies closer to the work in current literature for a UAV application, it is clear from theory that it is necessary to augment inductive coupling with resonating coils.

The first step of implementing a system for resonant wireless power transfer is to have a power source which will be able to drive the first inductive coil with very fast alternating voltage. Jesse Griggs, an electrical engineer with LI-COR Biosciences, wanted and was able to design and build the Drive Board which operates as the AC power source (Fig. 3.5). By having an electrical engineer provide the board design for this system’s current, voltage, and frequency requirements, a lot of expense was saved by not having to purchase an equivalent off the shelf power source. This board
Figure 3.6: Many different geometries and coil types were experimented with. Top left, four loop clover of identical coils. Top right, cylinder used for winding consistent coils. Bottom left, experimental primary and resonant loop. Bottom right, experimental resonant and secondary loop. Best results were found using identical coil geometry.

operates over a variable frequency, but it is important to ensure by calculation that the coils used will resonate within the frequency range available, generate a far reaching field, and operate such that the primary coil will not run at too high a current for the board.

Essentially, the board operates by taking a DC voltage as an input, and alternating the positive voltage and ground across its output. The changing of the current path is done by timing four 50 A, 40 V MOSFETs to operate in a similar way to an H-bridge. Originally this timing was performed on board and was made variable by a potentiometer. However, continual tuning of the potentiometer by hand to a specific frequency proved tedious and sometimes inaccurate for experimentation, so the board is modified to accept an incoming signal from a function generator to trigger the switching MOSFETs.

Many different coil geometries were initially designed and tested (Fig. 3.6). These coils ranged from circular loops with concentric coils spiraling down towards the
center to actual conical lens shaped coils that have a focal point in non-resonant power transfer. Other tests involved coils of varying radii to allow better mobility of the object receiving power. The results of these early experiments were interesting and often mixed, but the difficulty in creating consistent, complex coils by hand and modeling them proved to be outside of the capabilities of the current tool set. When coil inductances did not match, they would not couple well for power transfer, or worse, they would resonate at different frequencies and could not perform at greater distances. For the experimental results in Section 3.4, all of the coils are simple and congruent, facilitating a straightforward analysis of theory.

These resonant coils are easily fabricated to operate within the operating range of the Drive Board by designing circular coils with a set geometry and wire gauge, calculating the inductance, and then choosing an appropriate capacitor. The coils used are wound 5 times around a 0.45 m diameter cylinder with 10 gauge stranded copper wire to have consistent shape and inductance. The inductance for these coils using Eq. (3.6) is $2.82 \times 10^{-5}$ H. Three parallel 0.0056 $\mu$F film capacitors providing 0.0168 $\mu$F of capacitance are used for each of the resonant capacitors. When calculating the resistance of the coils, a value of $4\pi \times 10^{-7}$ Tm/A and $5.8 \times 10^7$ S/m are used for the permeability and conductivity of copper respectively. The Q factor using Eq. (3.8) is 376, and Eq. (3.7) yields a theoretical resonance of 231 kHz, which is well within the practical confines of the Drive Board.

### 3.4 Wireless Power Transfer Experiments

One of the first parameters tested was Q factor. To maximize Q factor, experiments were conducted with coils resonating in the multiple MHz range. However, this had an unexpected consequence. Operating at a higher frequency, although raising
Figure 3.7: Left, adjustable shelf system made to hold coils at variable distances while measurements are taken. Center, shelves lowered to a different level. Right, some of the test equipment used for measurements.

Figure 3.8: Schematic of first three experiments. Left, the Drive Coil changes coupling with and voltage across the Load Coil as it moves closer and farther away. Center, the Load Coil is kept 1 m away while the Tx Coil is moved to tune into the best position to transfer power for that distance. Right, the Tx Coil is kept at optimum distance from the Drive Coil while the Rx and Load Coil move together to find an optimum position for power transfer.

The Q factor, actually decreases efficiency from the Drive Board due to MOSFETs switching more often and generating more heat. Raising Q factor at a reasonable board frequency is still possible using coils with a lower resistance, although thicker gauge wire is heavier and more expensive.
Once the coils are built, the resonant frequency of each is found by finding the maximum voltage produced by the resonant coil when driven by a function generator. The measured resonant frequency of both the Tx and Rx Coils is 237.4 kHz. This is great from a consistency of coil making standpoint, and good from a theoretical standpoint as the completely theoretical resonance calculations are only 2.61% off. This confirms the usefulness of calculation in advance to operate in the intended resonant frequency range.

The first three experiments have the primary coil being driven by a function generator at relatively low power input since no device is being powered from the final coil. Instead voltage alone is read in the final coil and held relative to the input voltage and current from the function generator. These experiments are performed using the setup shown in Fig. 3.7.

The first of these experiments is done completely absent of resonant coils to provide a standard induction system for comparison (Fig. 3.8, left). The Drive Coil is powered by a function generator with 6 V at 237.4 kHz while the Load Coil is moved from 5 cm to 1 m to test voltage and coupling over a variable distance. The voltage across the Load Coil is read along with voltage and current in the Drive Coil using oscilloscopes and current probes, and Eq. (3.5) is used to calculate the coupling coefficient. This experiment verified the predicted trends of non-resonant inductive coupling quickly collapsing as primary and secondary coils move apart, while monitoring the Drive Coil’s power consumption for comparison to other experiments. The results can be seen in Fig. 3.9.

The next experiment introduces the first resonant coil. The Load Coil is placed 1 m from the Drive Coil, and then the Tx Coil is introduced and positioned variable distances from the Drive Coil for testing. In this manner, an optimized position for the Tx Coil relative to the Drive Coil was found to generate the greatest voltage on
Figure 3.9: Both the voltage on the Load Coil and the coupling coefficient between the Drive and Load Coils drop dramatically as distance increases. Notice that the theoretical voltage drop (found using Eq. (3.2)) and actual voltage drop are very similar. This confirms the theoretical limitations of standard inductive coupling with distance.

This experiment establishes the benefits of using even just one resonant coil, and the importance of not under- or over-coupling that resonant coil with the driving source coil. Previously when the Load Coil had been 1 m from the Drive Coil, the voltage across it was 0.0084 V. When the resonant coil is in a tuned position, it increased the voltage across the Load Coil to 0.1015 V (Fig. 3.10). This is a 12× increase in voltage with just one resonant coil. It is also important to note that the greatest voltage does not take place when Tx is closest to the Drive Coil. As predicted in theory, there is in an optimum range where coupling between the two coils is neither too great nor too weak for a given system.

In the third experiment the second resonant coil is brought in and paired with the
Figure 3.10: Voltage across Load Coil when the first resonant coil Tx is moved in and out of its optimum position for power transfer relative to the Drive Coil.

Load Coil to complete the intended four coil power transfer design (Fig. 3.8, right). This experiment also yields the greatest voltages on the Load Coil at 1 m since the Rx resonant coil is nearby to maintain higher coupling with the resonant power source Tx. This experiment also confirms that the optimum position for the Tx Coil changes as the system does. One trial is done with Tx 7.5 cm away from the Drive Coil, and another trial is done with Tx 15 cm away from the Drive Coil (Fig. 3.11). In the previous experiment, 15 cm distance is in the optimal coupling range between the Drive and Tx Coils, but in this experiment it is outperformed by the closer 7.5 cm position in some instances. With the addition of a second resonant coil, more coupling between the Drive and Tx Coils becomes advantageous to supply additional power when the Rx and Load Coils are in closer proximity.

The last set of tests are performed using a 4 W light bulb to act as a load device and receive meaningful wireless power transfer (Fig. 3.12). Load voltage is read using
Figure 3.11: Voltage across Load Coil as it moves farther from Drive Coil. In first run, resonant Tx is 7.5 cm away from the Drive Coil. In second set of data, Tx is 15 cm away. 7.5 cm produced higher voltage overall but had the same voltages at some distance points. The closer proximity between the Drive and Tx Coils has the advantage of better coupling which can provide more power replacement in Tx when the Rx and Load Coils are located closer to the power providing coils.

Table 3.1: Comparison of first three experiments. From these experiments greater voltages at less power consumption with more resonant coils is seen. Perhaps more than two resonant coils could have utility for extending greater power transfer even further in a practical application. Power is calculated by monitoring the voltage and current running into the Drive Coil, but does not account for minor deviations from ideal phase.
Figure 3.12: Left, picture from wirelessly powered light bulb experiment. Center, schematic for powering the light bulb directly off of the Rx resonant coil. Right, schematic for light bulb being powered from the Load Coil.

an oscilloscope as in previous experiments, but now there is a load current flowing through a device which can additionally be measured to quantify transferred power. With a much greater amount of power being driven and used by the system, the Drive Coil is no longer supplied by a function generator but is powered by the Drive Board described earlier. The efficiency calculations in the following experiments are derived from the DC voltage and current going into the board, and not just what actually comes through the Drive Coil. Although this will cause a lower efficiency overall, practically it evaluates the system as a whole.

One of the main advantages of powering a light bulb is that it can run on both DC and AC power. A light bulb can therefore be powered by either the Load Coil (as originally intended) or from the resonant Rx Coil directly. This provides for an insightful experiment which shows the effects of drawing power directly from the Rx Coil (Fig. 3.12, center, Fig. 3.13), as opposed to inductively through the Load Coil (Fig. 3.12, right, Fig. 3.14).
During initial experiments, videos and data were taken for wirelessly powering DC motors which are used in many robotic systems. However, initial results with DC power transfer were not as good due to the inefficiency of the original off the shelf DC rectifier. Once a home made rectifier was implemented, much better results were
obtained for powering DC motors wirelessly. Furthermore, even better results for DC power transfer are realized once a board designed to handle DC specific operation is implemented. These results are presented in Chapter 4.

The most significant difference found between the two light bulb experiments is
from an efficiency standpoint (Fig. 3.15). When both systems are transferring around 2 W, the Rx Coil light bulb power transfer runs at an efficiency of 37% while the Load Coil transfer runs at 61% efficiency. This is quite significant and reinforces the benefit of using resonant coils for support of load coils in power transfer, rather than letting resonate coils act as the source of power to the load themselves. There is a significant conceptual difference between these two methods as well. After all, if power is taken directly from the mass in the pendulum example, it will surely slow down, disrupt resonance, and need more work put in to drive it.

There is one benefit found for using the second resonant coil as the direct power source for the bulb; it provides the greatest amount of power transfer (Fig. 3.16). At 2.44 W, the Rx Coil directly powers the light bulb with 6.6% more power than the 2.29 W maximum power transfer the Load Coil is able to provide. This result is further examined in Section 3.5.
3.5 Chapter Summary

Before implementing a UAV-based wireless power transfer system, it is first necessary to build a working ground system utilizing the best and most practical methods currently available in research. In Chapter 3, successful mid range power transfer through the use of strongly coupled magnetic resonances has been demonstrated and shown to be superior to standard inductive power transfer. Using resonant power transfer, more than 2.4 W was transferred with a distance of 0.4 m between the transmitting and receiving coils, and power transfer was sustainable at many different configurations. Other methods of wireless power transfer do have some advantages, but from a practical standpoint these pale in comparison to resonant power transfer’s adaptability to dynamic environments for operation from a UAV.

During testing, interesting results were found using the resonating coil directly to power a device. This method of power transfer has not been found in any other literature, yet in these experiments it was be able to transfer slightly more power compared to the more practiced secondary load coil loading, and requires one less coil. However, there are multiple disadvantages to taking power directly from a resonant coil. One disadvantage of this system is that the device receiving power must be capable of handling the high alternating voltages produced in the resonating coil. Many sensors run off of DC sources, and rectifying the power off the resonant coil directly could also prove impractical for maintaining resonance and thereby sufficient coupling with the transmitting power source. Another disadvantage comes from a drop in efficiency, although in some applications the source power may be of relatively less significance in comparison to the amount of power realized at the receiving end of the wireless power system.

Throughout this chapter many important accomplishments have been realized,
and for each new success, another tangent of potential research has emerged: coils of different geometries, using more than two resonant coils, or even exploring what benefits exist by powering objects directly from a resonant coil. Although each of these new project ideas are exciting, promising advancements are made through novel application of this technology as well. Utilizing this foundation of research, Chapter 4 follows with the design and development of a UAV capable of providing wireless power to remote locations.
Chapter 4

Wireless Power Transfer from a UAV

4.1 Introduction

After producing a working model for wireless magnetic resonant power transfer, we chose a specific path of research to make contributions to UAV and wireless power research. This objective, which is the remaining content of this thesis, is developing a UAV which is able to provide power to remote locations through the use of wireless power. In this chapter a working prototype for this application is completed, and by implementing a power receiver board which autonomously optimizes power transfer, nearly 5 W of power is transferred to a grounded sensor. This is significant as no other system like this is known to exist. Section 4.2 begins by describing the system design for demonstration and experiments. The control algorithm for optimizing power transfer to the receiving node during flight is covered in Section 4.3. Next, Section 4.4 explains the experiments and their results. Finally, Section 4.5 provides a summary of Chapter 4.
4.2 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 infeasible. For this reason, this system is designed to operate during flight. To begin this section, a general description of the overall system is given, followed by in-depth information on the power transfer coils, helicopter, and receiver node.
4.2.1 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 Drive Coil (Fig. 4.1). The Drive Coil then generates an alternating magnetic field that drives the neighboring resonant 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 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. A more in-depth explanation of how this technology works is provided in Section 3.2.

4.2.2 Power Transfer Coils

The two primary factors for resonant coil performance are that they resonate close to the same frequency and that they have a sufficiently high quality factor. Two ways to increase the quality factor are to lower capacitance or resistance as seen in Eq. (3.8). 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 Eq. (3.7), which limits significant currents due to voltages having less time to overcome magnetic momentum. In our implementation of raising the Q 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. The other method of raising the
Q 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. For weight reduction the inductors on resonant coils are limited to two wraps of 16 gauge copper coil. This is just one example of many iterative design decisions that are made with the whole system in mind.

The inductors for the resonant coils are made to a specific radius of 0.265 m to mount directly to the UAV’s frame. Inductor coils can be made larger, but this would start limiting the environments the UAV can traverse. These coils are used with 0.1 uF capacitors to form the resonant coils. Using these parameters along with Eq. (3.6), Eq. (3.7), and Eq. (3.8), the resonant frequency is approximately 189 kHz and the Q factor is about 90. This Q factor is lower than that of the coils from initial experiments in Chapter 3 which have a much thicker gauge of wire. However, a lower Q factor also increases the bandwidth in which the coils will resonate, even if not with as high of a peak. Since the proximity of transmitting and receiving coils affects the resonant frequency of the system as a whole, this wider bandwidth has advantages. These equations work well as a starting point for designing coil and capacitor combinations, but final values are sensitive to physical parameters such as bends in the inductor coil and variability between manufactured capacitors.

4.2.3 Helicopter

An Ascending Technologies Hummingbird quad-rotor helicopter [1] is used to carry the transmitting coils and power system as seen in Fig. 1.2, left. This quadrotor has a 200 g payload. The power transmitting coils are each 38 g and the Drive Board is 51 g for a total of 127 g of added mass. With this payload the flight time is between 15
and 20 minutes when using a 2.1 Ah, 11.1 V LiPo battery. This battery also powers the Drive Board mounted on the UAV, which uses 50 A, 40 V 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 at 190-210 kHz dependent upon the exact configuration. In future work, signal generation will be placed on-board, eliminating the need for this cable.

The Hummingbird uses approximately 80 W of power and the Drive Board peaks at about 45 W. The battery can supply more than 550 W continuously, so this 125 W total is not an issue, but the UAV does lose as much as 1/3 of its flight time when providing power transfer. In future work, it will be possible to implement a power switch for the Drive Board to extend flight time when the UAV is not actively transferring power. Despite carrying all of these components, the helicopter is extremely stable and still has significant power for dynamic motions.

### 4.2.4 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. 4.2) 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 50 V peak-to-peak, although some configurations reach 150 V). Diodes in a standard high-speed, full-wave rectifier configuration rectify the AC voltage into a DC voltage. A large 1 mF, 100 V capacitor stabilizes the rectified voltage. An LM5005 switching power supply then converts this high, variable voltage into a stable 5 V supply and is capable of driving a load at up to 2.5 A. The LM5005 has a minimum input voltage of around 7 V, so the rectified voltage must stay above this level to maintain power transfer.

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

The processor is an 8 mHz, low-power Atmel ATMega1284p processor. The processor monitors the rectified voltage, as well as the output of the 5 V 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 5 V 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 2.5 A, the maximum power the Rx Board can draw from the Load Coil is 12.5 W, more than enough for our applications.
4.3 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 are 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 7 V input required for keeping the switching power supply operating.

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 diminish. 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 5 V supply which will draw up to 12.5 W at full current. The processor uses a PWM signal to quickly switch a MOSFET on the Rx Board which in turn controls the current running through the resistor. The less current allowed to run through the resistor, the less power transfer. In this way, feedback control is enabled by monitoring the rectified voltage across the input capacitor and then varying the amount of current allowed to run from it to the resistor. Similarly, the battery charge rate can be controlled through current to vary the power draw from the Load Coil.
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, a Proportional-Derivative (PD) controller is implemented to adjust the power usage.

The PD controller tries to maintain a rectified voltage of 9 V, which gives a suitable safety margin above the minimum 7 V allowed by the switching regulator. It was found, a purely proportional controller oscillated too much as the UAV moved, and adding the derivative term resulted in a stable controller. Figure 4.3 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 9 V and a power draw of over 5 W. This overshoot is acceptable and is, in fact, preferable to a more aggressive controller, which may result in larger oscillations below 9 V and could result in the rectified
voltage dropping below the 7 V minimum.

4.4 UAV Power Transfer Experiments

Numerous experiments are performed to characterize the power transfer system. Presented first are the results of static experiments used to analyze the system without the UAV. Then results of experiments performed with a UAV wirelessly transferring power to a ground sensor are given.

4.4.1 Static Power Transfer

Before beginning any aerial power transfer experiments, static tests are performed on the ground to tune the to-be-flown system and establish what levels of power transfer can be achieved over various distances. To do this, the same flat shelf system which can hold individual coils at set distances for testing from Section 3.4 is used. 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 [23] [24].

The optimized conditions used for data collection are with 3.5 cm between the Drive and Tx Coils, 4 cm between the Rx and Load Coils, and a drive frequency of 207 kHz. This drive frequency is 9.5% greater than our theoretical resonant frequency calculated in Section 4.2.2, but this is due in part to the frequency being affected 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. 4.4 depicts measured power transfer and 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 [21]. More importantly, there is significant power transfer when the Tx and Rx Coils are separated vertically 0.2-0.3 m with a radial tolerance up to 0.1 m. 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 is 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 [21, 5]. With stationary energy transfer tests complete, the system designed for the UAV

Figure 4.4: Power transfer and efficiency for various distances between the Rx and Tx Coils.
finally took power transfer to the air.

### 4.4.2 Aerial Power Transfer

After demonstrating that power transfer works with the designed system on the ground, tests are 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. 1.2, left. The Rx Board controls the power draw using the PD controller described in Section 4.3 and the results are logged. After a few test flights, data from a single manual flight is plotted in Fig. 4.5. 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 0.2-0.3 m target range described in Section 4.4.1, but due to manually flying with ground effect and drift, power transfer often took place between from 0.15-0.4 m.

The peak power transferred was 5.41 W, with an average of 4.43 W 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 tries 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 are performed on adjustable shelves, all the distances between coils are 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 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.
4.5 Chapter Summary

Chapter 4 demonstrates that wireless power transfer from a UAV to a ground sensor is possible and practical through experimental results. This is a significant contribution to both UAV and wireless power research as no other system like this is known to exist. This has numerous and exciting applications for powering sensors in remote locations without access to grid or solar energy. We achieved this by building and improving on established methods to account for the challenges that come with transferring power from a moving UAV. Wireless power transfer through strongly coupled magnetic resonances was chosen because of its inherent flexibility in changing environments. 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 also light and efficient enough for the UAV to carry and operate without a loss in mobility.

Our experimental results show that the aerial transmission does not achieve as much power transfer as the static case. This is in part due to the relative motion of the Drive and Tx Coils on the helicopter and the deformations of these coils. This issue has been addressed by constructing a new light-weight fixture for maintaining the proper circular shape and distance between the coils on the UAV as shown in Fig. 1.2, right. Another obstacle that reduces overall power transfer is maintaining an exact position over the Rx Coil. This issue creates additional motivation for autonomous navigation to provide more accurate relative localization between the UAV and receiver. Autonomous navigation, however, begins with sensor feedback. Chapter 5 develops a sensor which is able to measure high frequency alternating magnetic fields. Despite these problems, nearly 5 W continuous transfer occurred from the UAV to the ground sensor.
Chapter 5

High Frequency Alternating Magnetic Field Sensing

5.1 Introduction

In Chapter 4 we found many parameters that affect UAV power transfer, but chief among them is the UAV’s position. During these manually guided flights, power transfer stability is limited by the pilot’s skill and ability to retain visual contact with the UAV. To overcome this limitation, we are developing an autonomous localization and navigation system. This requires sensing, and we choose magnetic field sensing as a means for control feedback. It would be possible to use a camera or other alternative, but we do not want to add more weight and processing, so we take advantage of the magnetic fields provided by power transfer. Existing magnetic field sensors are too heavy or cannot sense the high frequency alternating magnetic fields with sufficient accuracy, so we needed to design our own sensing board to meet our needs. In this chapter we perform experiments with these sensors and determine that we can locate receiving coils from a power transmitting UAV. In future work, this information will
be used for autonomously locating nodes and optimizing UAV position for power transfer. There are three iterations of sensor boards designed in Section 5.2, 5.3, and 5.4 respectively. Section 5.5 presents tests of the final sensor for receiver localization and Section 5.6 provides a summary of Chapter 5.

5.2 Magnetic Field Sensor Alpha

Magnetic Field Sensor Alpha (Sensor A) is the first sensor board design (Fig. 5.1). Section 5.2.1 covers initial design and simulation, Section 5.2.2 describes the components used and the printed circuit board (PCB) layout, and Section 5.2.3 covers the experimental results for Sensor A.

5.2.1 Initial Design & SPICE Simulation

From early testing, it was discovered that a small wrap of coil produces an AC voltage when it is located in the alternating magnetic fields used for wireless power transfer. This voltage is the result of the changing fields causing alternating current to run
through the coils, and therefore an alternating voltage that can be read by an oscilloscope. After studying differences in signal strength based on positioning of the Tx and Rx Coils (varying between 50 mV and as high as 1 V depending on proximity), it was determined that with multiple inputs at different points on the UAV, a control algorithm can be developed for locating nodes and positioning for maximum power transfer. The next requirement is a board which can read these voltages, put them into digital form, and send the information to a central processor for decision making.

This is where the first magnetic field sensor comes in. The primary design component for reading the AC signal is a precision rectifier, also known as a super diode. This consists of an amplifier, two diodes, and two resistors which work together to amplify the negative half of an AC signal (Fig. 5.2). The benefit of a precision rectifier is that it can be used with other electronic components to act as an adjustable peak detector on an AC signal without needing any kind of switch.

The limiting factor of this design is that the amplifier must have a high enough slew rate to overcome two diode voltage drops in a half cycle’s time. For this reason, SD103AWS Schottky diodes with low voltage drop and quick reverse recovery time (10 ns) are used in conjunction with an LMH611 Op-Amp which has a particularly
high slew rate (460 V/µs). For simplicity, this design is implemented with only a 5 V source and GND (Fig. 5.3), which works well in theory since amplification is only needed on half of the signal for an amplitude or peak value.

After the amplifier circuit, a low-pass filter is implemented to keep a stable voltage which can be read by an analog-to-digital converter (ADC) on a microprocessor. The cutoff frequency can be calculated as follows:

$$f_c = \frac{1}{2\pi RC}$$  \hspace{1cm} (5.1)

where \(f_c\) is the cutoff frequency (Hz),
\(R\) is the resistance of R5 (Ω) (Fig. 5.3),
and \(C\) is the capacitance of C1 (F).
The theoretical cutoff frequency for the simulated circuit is 637 Hz. This value allows the ADC to act as a sensor picking up changes as quickly as 100 Hz, while filtering out any effect from the 300 kHz oscillations which take place from the amplified field signal. As with many other parameters such as gain on the amplifier, the response of the system can be easily changed by soldering components with different values on the PCB.

Two slight modifications are made to the low-pass filter to improve performance. First, another Schottky diode is added to be sure when the amplifier cycles down to a lower voltage that there is no current that flows back to the amplifier from the output. The second modification is an additional resistor which is placed from the output to ground and can be changed to tune the amount of time it takes the peak signal to drop once a signal is lost.

For simulation the input signal from the coil is represented by inductive coupling to another circuit loop with an alternating voltage (Fig. 5.3). Since tests on the oscilloscope indicated that the incoming coil signal amplitudes vary between 100 mV
and 1 V, the simulated input is tested through this range. With a $5 \times$ gain on the amplifier set by R4 and R2, this design utilizes the full range of the 5 V power supply to the amplifier fairly linearly through the tested input range and flattens out when exceeding it (Fig. 5.4).

There is a slight drop in voltage on the capacitor due to limited exposure time to peak amplifier oscillation, and since the resistor to ground always draws some current when a voltage is present. The relationship between incoming signal, half-wave amplification, and capacitor charge can be better understood by directly studying an output plot of the simulator (Fig. 5.5). Simulation is performed using a SPICE program developed by SIMetrix Technologies [26].

### 5.2.2 Sensor A Printed Circuit Board Layout

Once simulation and design of the components to produce a linear, measurable voltage from an AC signal was complete, the next step in design is bringing in the other
components and completing the PCB design. The main constraint for this board is to keep things as compact as possible since multiple sensors will have to be mounted on the UAV for the system to work.

Additional chips brought in include an ADP3330 voltage regulator to create a stable 5 V supply, an SN65HVD1781D RS485 chip for communication to the main board through a noisy alternating magnetic field, and a quad-flat no-leads package (QFN) Atmel Atmega328P microprocessor to handle the ADC conversion and sending packets of information. Three Hirose connectors are used: a DF3A-6P for processor programming, a DF3A-4P for communication and power supply, and a DF3A-3P in case a power supplied sensor needs to be tested. The rest of the space is taken up by surface mountable passive capacitors, resistors, and LEDs (0603 packages in all cases aside from two 0805 capacitors for main power supply), and a drilled through hole for mounting via a fastener. Fig. 5.6 and Fig. 5.7 depict Sensor A’s schematic and layout completed with CadSoft’s EAGLE software [27].

Overall, the board is completed with less than a 3/4 in$^2$ footprint using two layers, the bottom layer being used primarily as a ground plane. This means that the board and the wind of coil take about the same amount of space when overlapped, so there is little benefit to shrinking the design any further. The only real draw back of this design layout is the difficulty in soldering and changing components in a such a dense space, but with practice this becomes much easier.

5.2.3 Sensor A Experimental Results

In implementation, this board does not work as simulated in tests using the signal coil in alternating fields. This is due to low input impedance and unplanned voltage biasing on the amplifier input. However, a lot of important discoveries were made
from this first sensor.

First, when measuring the coil in the alternating field with the oscilloscope, the peak to peak voltage was able to reach significant levels for measurement because of the high input impedance of the oscilloscope. Something that was not taken into
account in the simulation is the limited current that the signal coil would be able to supply. This severely limits performance with a low input impedance on the amplifier. The impedance can be raised by changing the values of the resistors on the amplifier; however, higher resistance values also slow down the response of the system. This proved detrimental at 300 kHz. The result is that either the signal is too low to be meaningful due to the limited current it can supply, or the response of the amplifier is too slow due to high resistor values.

Another issue that compounded with the first is that the amplifier has a biased voltage on its input of a few hundred mV. Because the coil is in space and essentially has no ground, it will only oscillate about the voltage at the input of the amplifier. Since the amplifier only outputs an inverted signal and has only a positive supply, the coil needs to go below ground to cause an output. However, the signal coil’s amplitude voltage was already limited by the first problem of a weak signal with low input impedance. With both of these issues combined, only extremely high magnetic fields raise a voltage across the ADC capacitor. These results are not sufficient for weaker field reading during node searching.

However, great results do occur when sourcing the signal with a function generator as opposed to the signal coil in a magnetic field. Not only does the function generator source more current to the amplifier, it has a ground and is unaffected by the voltage biasing problem of the amplifier. In essence, the function generator acts exactly like the SPICE simulation because it more closely matches the conditions of the input signal in simulation.

Using the function generator, the board is able to utilize the full 5 V range over the capacitor for ADC on the Atmega processor. The Atmega328P is programmed to collect the ADC value, and successfully publishes this information using RXD and TXD. Learning from the good and bad of Sensor A, we design a second board to
overcome low input impedance and voltage biasing for the signal coil while keeping all the aspects that worked well for the function generator tests.

5.3 Magnetic Field Sensor Bravo

Magnetic Field Sensor Bravo (Sensor B) is designed after the first board ran into issues with tests using the signal coil in live magnetic fields (Fig. 5.8). Section 5.3.1 covers the design of Sensor B, Section 5.3.2 describes the PCB layout, and Section 5.3.3 covers the experimental results.

5.3.1 New Design Capabilities

The first major change in design from the first board is the use of a buffer amplifier, or more specifically a unity gain buffer. The unity gain buffer eliminates the low input impedance issue for the signal coil on the first board. By running the signal through an additional preliminary amplifier which can imitate the signal voltage with a $1 \times$ gain without any other resistors in the loop, the theoretical input impedance to
Figure 5.9: Sensor B complete amplifier schematic.

the signal coil becomes infinite. Furthermore, since the input to the original precision rectifier is now an amplifier, all necessary source current can be supplied. This is the same condition as with the successful function generator experiments. As opposed to incorporating an additional amplifier chip the LMH6612 is used. This chip consists of two internal amplifiers that each have the same performance as the original LMH6611.

One significant improvement to the coil signal input is the ability to offset the voltage bias on the amplifier input. The motivation for this is to be able to control the voltage about which the coil signal oscillates as opposed to being at the mercy of the buffer amplifier. For instance, it was found that Sensor B biases the input voltage to the buffer amplifier to oscillate about 4.15 V as opposed to the theoretical ground. This means that the half-wave amplification on the next amplifier would only cause a positive voltage on the ADC capacitor if the coil signal had an amplitude voltage greater than 4.15 V to generate a negative output from the buffer amplifier. Since very few tests to this point have generated that level of voltage on the coil signal, the only possible way of moving forward is to bias the buffer amplifier input to ground, or even better to below ground to compensate for diode loss later in the circuit for weak signals.
This is accomplished first by supplying both plus and minus 5 V to the board using a new LT3032EDE-5#PBF voltage regulator, and then by connecting the input to the buffer amplifier to the high and low supply voltages through resistors (R23 and R24 in Fig. 5.9). Adding these resistors to the signal input does lower the theoretical infinite input impedance to the buffer amplifier; however, using high resistance values for R23 and R24 kept this effect to a minimum and still biases the voltage.

If the value of these resistors is the same, the voltage will be biased to ground, which works well for the design. However, the voltage can be biased to be below ground which causes an offset in the output of the half-wave rectifier to a higher peak oscillation over the ADC capacitor. The benefit of this is that even very weak coil input signals will cause noticeable differences on the ADC values since the new nominal will stay above the diode voltage loses that occur before the ADC. For greater resolution, the gain on the second amplifier can always be increased by soldering new resistors with a greater ratio between R22 and R21 (Fig. 5.9). The ADC on the Atmega processor has a 10 bit resolution which on a 5 V scale can pick up voltage changes less than 5 mV after amplification, and 1 mV before amplification on the signal coil with the current 5 × gain.

The second design improvement to the coil signal input is a high-pass filter. A high-pass filter will separate any transfer of current from a DC or low frequency offset between the now biased input voltage of the buffer amplifier and the signal coil, but allow high frequency oscillations from magnetic field measurement to pass through. Although the layout of a high-pass filter is different than that of a low-pass filter, the calculation for cutoff frequency is still the same (Eq. (5.1)). In this case, the capacitance is of C21 and the resistance is the equivalent resistance of R23 and R24 (Fig. 5.9). The experimental results of this new dual-amplifier circuit with voltage biasing and high-pass filtering on the signal coil will be discussed in Section 5.3.3.
It should be noted that many of the methods for implementing signal amplification with a plus and minus 5 V supply can be applied to a circuit with only a 5 V supply (Fig. 5.10). The main drawback to this is that since the second amplifier is inverting, voltages have to be biased and compared to 2.5 V instead of ground which uses less of the range on the Atmega ADC. The benefit of this is that a plus and minus 5 V supply is no longer necessary, and the same voltage regulator from Sensor A which requires less additional capacitors can still be used.

To make sure that all outlets are available for testing on this board, this circuit version is completed and mapped into a separate ADC channel on the Atmega board for testing along with a third circuit path which has no ground plane. The complete
top level schematic of Sensor B is shown in Fig. 5.11. Unfortunately, exact simulation of Sensor B’s two-amplifier circuit is too intricate for the free version of SPICE used for Sensor A simulation.

5.3.2 Sensor B Printed Circuit Board Layout

![Altium PCB layout for Sensor B.](image)

Figure 5.12: Altium PCB layout for Sensor B.

One of the primary changes between the PCB design of the first and second sensor is the size of the board (Fig. 5.12). With Sensor A the idea was that if the board worked well it would immediately be ready to implement as a sensor on the UAV.
Learning from the mistakes of the first project, rather than trying to do it all in one shot, space is used much more liberally to test multiple designs with one board for Sensor B.

It is only necessary to use a two layered board, but much more care is taken into utilizing well designed ground planes. One section of the board is designed with no ground plane to measure differences from not having a ground plane in a circuit area when operating in an alternating magnetic field. Also, where the analog circuits run out to their respective signal coil input locations from the processor ADC inputs, ground planes and power connections are bottlenecked to avoid current loops that can affect measurements.

Altium is used in place of EAGLE for the design of Sensor B and Sensor C. This program allows for multiple paged schematics during the design phase for better abstraction and also more intuitive component building and PCB layout. With Altium it is also possible to see what Sensor B will look like before ordering (Fig. 5.13).
5.3.3 Sensor B Experimental Results

The high-pass filter used for the incoming measurements on the signal coil works very close to theoretical values. With C21, R23, and R24 (Fig. 5.9) set with 0.012 \( \mu \)F, 76.2 k\( \Omega \), and 90.9 k\( \Omega \) components respectively, the theoretical cutoff frequency is 320 Hz using Eq. (5.1). A range of incoming signal frequencies were tested through
Figure 5.15: Comparison of simulated and actual data for ADC voltage.

The plotted gain rises steadily at approximately 10 dB/decade until just past the cutoff frequency where higher frequency signals start to be passed through with a 0 dB gain. At a decade before the cutoff frequency the phase begins to shift from the filtered signal lagging the incoming signal by 90° to having almost no difference in phase a decade after the cutoff frequency. This accounts for a 45°/decade change on both sides of the cutoff frequency. It should be noted that at the lower frequencies the measured gain does not drop off as sharply as it should due to noise in the filtered signal measured with the oscilloscope. At lower frequencies the increasingly noisy signal also made it more difficult to measure the phase differences between the incoming and filtered signals. With these two slight errors aside, it can be seen that the data closely follow the calculated plots based on component values. The main sources of error are noise and the manufacturing error of the capacitor.

The most important achievement of Sensor B is the ability for the signal coil to
produce high enough voltages directly from the alternating magnetic field to read out
to the ADC. This is due to the significantly increased input impedance offered by the
buffer amplifier, and the ability to offset the input voltage to allow measurement of
even the most insignificant field strengths. It was discovered that live coil signals from
alternating magnetic fields correspond to the same ADC values as equal amplitude
signals that originate from the function generator. Because of the difficulty in running
the alternating magnetic field, keeping the board in the same location relative to the
power transmitting coils, and then measuring different nodes on Sensor B with an
oscilloscope probe, much of the data characterizing Sensor B are collected using the
function generator.

For ADC measurement resulting from the varying incoming coil signal strengths,
R23 is 20 kΩ and R24 is 22 kΩ. The resulting nominal buffer amplifier input is -
150 mV which corresponds to a nominal 0.52 V on the ADC capacitor. A plot of the
collected data compared to simulated results is shown in Fig. 5.15. The two sets of
data follow the same linear trend, with the actual measurements being slightly higher
due to the voltage biasing on the input which was not done in simulation. Due to
design improvements over the original board, Sensor B is a success. Since Sensor B
is a large prototype board which is impractical for use on a UAV, further steps must
now be taken toward re-implementing the same effective design on a smaller board
for Sensor C.
Figure 5.16: Compact and functional Magnetic Field Sensor C with signal coil and power supply and communications cable attached.

5.4 Magnetic Field Sensor Charlie

Magnetic Field Sensor Charlie (Sensor C) is the last iteration of sensor board design (Fig. 5.16). Section 5.4.1 presents the final design iterations of Sensor C, Section 5.4.2 depicts the condensed PCB layout, and Section 5.4.3 briefly covers the initial testing and tuning for Sensor C.

5.4.1 Final Design

Because of the success of Sensor B, the only fundamental change in design for Sensor C is using the plus and minus 5 V path for ADC production without the other two prototype paths. Without the other two experimental analog circuits, Sensor C can be more compact. However, there are two other minor design improvements.

First, an extra resistor is added between the plus 5 V source and the voltage biased input to the unity gain buffer amplifier (Fig. 5.17). This allows Sensor C to be tuned
Figure 5.17: Final ADC design layout for Sensor C. Aside from minor design improvements, this circuit is much the same as its counterpart on Sensor B.

more accurately and consistently for voltage biasing on multiple builds of the board. Instead of performing trial and error experiments with two different resistors to get the correct voltage bias, two identical resistors with the correct level of impedance are used as a baseline (R24 & R23) and then a third resistor is brought in to fine tune the voltage below ground for weak field sensing (R25). The other design improvement is removing the power and ground connections from the signal coil input. No powered sensor has been implemented on the previous two boards and this allows additional space saving.

5.4.2 Sensor C Printed Circuit Board Layout

Although Sensor C is similar to Sensor B in circuit design, Sensor C’s PCB layout resembles Sensor A in its compact design (Fig. 5.18). The board is completed with just over a 3/4 in² footprint using two layers, the bottom layer being primarily used as a ground plane. The analog circuit ground plane is isolated from the rest of the board except for one bottleneck where the ADC and power traces connect to avoid measurement affecting current loops. There is a single through hole for a #4 fastener
as the board is intended to be mounted in an array for operation.

Additional room is saved by changing to 1.25 mm pitch connectors. Power and communication are now connected through a compact Hirose DF13-5P-1.25DSA connector (H5). A DF13-6P-1.25DSA connector is used as the serial port for the Atmega328p processor, but since the connection is only temporarily used to program the board a portion of the complete connector mounting area is used to save space (H4). Finally, without the additional power and ground connections that are on previous boards, the signal coil is connected to a single pin (H2).

5.4.3 Sensor C Experimental Results

Since the primary design elements of Sensor C are already known to work from live experiments with Sensor B, most of the initial experimental effort is put into choosing final component values for peak operation. Once a standard configuration is chosen it will be replicated across multiple sensors to build an array of magnetic field sensors for locating receiver coils in Section 5.5.

The primary goals of the final configuration are to allow a consistent field mea-
surement between multiple sensors and to maximize the resolution on the ADC for weak field measurements. We found that using 100 kΩ resistors for R23 and R24 and a 20 kΩ resistor for R25 (Fig. 5.17) kept the coil signal input at a low enough voltage that small measurements can be read on the ADC, but not so low that the nominal ADC readings are artificially high. In some experiments a 15 kΩ resistor for R25 does achieve the same result and with a slightly greater range for ADC measurement. However, since it is cutting margins close for being able to perform weak signal measurement, we decided to use the 20 kΩ resistor to account for small manufacturing differences that occur between boards.

To increase the resolution of the ADC, R22 is changed from 5 kΩ to 10 kΩ to make the half-wave rectifier gain $10 \times$ the output of the buffer amplifier. This results in a 0.5 mV resolution from the signal coil to the Atmega328p ADC, which is twice the resolution of the previous boards. Even with the higher gain, maximum ADC values are only reached when the signal coil is directly overlaid on a resonating coil, which is impractical for UAV operation where this would mean a near collision. Higher gain configurations are possible, but we found that these also cause less amplifier stability and therefore varying ADC values.

With this final configuration Sensor C is accurately biased below ground and is able to pick up weak magnetic field signals on the Atmega328p ADC with a 0.5 mV resolution. This design is replicated across four different boards, which are identified as ID0, ID1, ID2, and ID3 (Fig. 5.19, left). The nominal ADC values of these four sensors are 187, 161, 192, and 157 for ID0 through ID3 respectively. A non-biased input voltage equates to about 60 on the 10 bit ADC, so up to 130 of the effective ADC range is taken away from the default voltage biasing resistor configuration. However, each of these sensors is well within range to measure weak alternating magnetic fields and never climb over the remaining 800 ADC measurement range in
practical experiments. Additionally, each of these sensing boards are found to respond consistently to the same conditions of magnetic fields. With an array of four reliable sensing boards, experiments for locating a receiving coil based on measurements is achieved in Section 5.5.

5.5 Magnetic Field Sensing Experimental Results

With an array of sensors that can read the alternating magnetic fields used for power transfer, information about the relative location of the receiving coils to the transmitting coils is deduced. This is possible to do with one sensor if absolute positioning of the UAV is known, but this system is intended to operate outside without exact positioning and the UAV will inevitably drift [28]. For this reason, an array of sensors is chosen which makes the system more robust against uncertainty in UAV position with both redundant and directional information from multiple sensors. In the future
this information will be used as feedback to the UAV for locating nodes, and then optimizing its position for power transfer.

The primary attribute of the resonating coils that makes this localization possible is when driving the resonant coils pre-resonance, they produce a stronger magnetic field from the inductive coil counter clockwise from the resonating capacitor. The same is true of the portion of inductive coil clockwise from the capacitor post-resonance due to a change in phase from lagging to leading the driving source. For the experiments presented in this section, we use resonant coils identical to those on the UAV in Section 4.4 with the exception of using 0.15 \( \mu \)F capacitors instead of 0.1 \( \mu \)F capacitors. These modified resonant coils oscillate at a slightly lower frequency (Eq. (3.7)) and resonate consistent enough that they break the capacitors if operated at peak resonance without a dampening load. Pre-resonance operation for experiments is done at 150 kHz, with critical peak resonance taking place in the 160s of kHz.

For simplicity and practicality the sensor array is held at a constant distance of 12.5 cm above the Tx Coil with each sensor about 12.5 cm radially shifted from the center at 45°, 135°, 225°, and 315° (Fig. 5.19, right). This proximity configuration between the Tx Coil and the sensor array is representative of how they will operate when mounted to the UAV. For the experiments we perform the Rx Coil moves in a 40\times40 \text{ cm} plane 25 cm above the Tx Coil in 10 cm increments. This emulates data collection that would occur if the Rx Coil was stationary and the sensors and Tx Coil moved in incremental sweeps to locate it. In actual implementation more data can be streamlined for better resolution than with manual movement and measurement, and with additional lower ADC values outside of the tested grid.

Since the pre-resonant Tx and Rx Coils each have stronger and weaker areas of magnetic field, the orientation of the sensor array relative to the coils is critical
Figure 5.20: Three rotational orientations between the Tx and Rx Coils used for testing localization. The blue field represents the half of the resonant coil which produces greater magnetic fields and ADC readings on the magnetic field sensors for pre-resonant experiments.

(Fig. 5.20). The three primary experiments in this section are performed with the Rx Coil parallel and then rotated with respect to the sensor array (0°, 45°, and 90°). Because sensors require information about the location of the Rx Coil field alone, data are normalized by subtracting the baseline ADC measurement that each sensor generates from the nearby, resonating Tx Coil. This experimental method works well for data collection and examination to locate the Rx Coil.

When a load is introduced on the Load Coil it diminishes the amount of field the Rx Coil produces. This causes the changes in sensor ADC values from the Rx Coil to be less evident. This same effect happens when the Rx Coil is elevated further from the sensor array. However, the same trends occur and the same methods for locating the Rx Coil can still be implemented. It should also be noted that with the Rx Board from Section 4.2.4 it is possible to eliminate the load on the receiving coils until the UAV is in a good position for power transfer. For the purpose of demonstrating the
Figure 5.21: Individual sensor field measurements for the parallel 0° Rx Coil. A more meaningful peak ADC is obtained from sensors ID0 and ID3 which are located in a stronger portion of Rx field when the Rx Coil is centered over the Tx Coil.

abilities of the sensor array with more meaningful data, a load is not used in the following experiments.

In the first 0° experiment the most indicative data for locating the Rx Coil are gathered from sensors ID0 and ID3, which are located in the stronger Rx field when the Rx Coil is centered over the Tx Coil (Fig. 5.21). The peak ADC value of each of
Figure 5.22: Total sum of field measurement on sensor array for various $0^\circ$ Rx Coil positions. Peak ADC readings take place between where the Rx Coil is perfectly aligned over the Tx Coil and where the strongest pre-resonant portion of Rx field is centered over the sensor array.

these sensors is much greater than the corresponding weak field sided ID1 and ID2, and comes to a point from both horizontal directions. The ID0 and ID1 peaks take place in an area between where the Rx Coil is centered over the Tx Coil and where the peak Rx field is over the sensors. This is intuitive to the nature of the system since when the Rx Coil is centered over Tx it will resonate with the greatest amount of energy but when it is offset more of the field is directed toward the sensors. It is also evident that evaluating the total sum of ADC values for the entire array of sensors generates a peak in a similar location (Fig. 5.22).

If all we did for implementation was center the UAV on the peak values of ID0, ID3, or the sum total of the array for navigation, this system would work. The power transmitting UAV would position within the 0.1 m radial window of significant power transfer found in Section 4.4. However, it is also possible to observe these trends, which are repeatable, and make a set correction in position from the peak value for even better results. It would even be possible to create a table of data that
can be referenced during operation for approximating position to the receiving coils with sensor data. The primary challenge of an approach like this is dealing with any ambiguity a measurement can have to multiple positions.

Although the data from ID1 and ID2 do not have an identifiable and consistent center peak along both axes for the $0^\circ$ configuration, some trends can still be derived from them as individual sensors. In both cases, the ADC values of these two sensors are lower when the Rx Coil is further from them laterally, and higher when the Rx Coil is located closer to them. This information can be used in conjunction with ID0 and ID3 data during a horizontal sweep of the UAV carrying a sensor array (Fig. 5.23). The differences in peak ADC values among sensors can also be used as an indicator of the orientation of the Rx Coil relative to the Tx Coil.

For the next experiment, the Rx Coil is rotated $90^\circ$ to ensure that the same localization techniques will still work for a rotated receiving coil (Fig. 5.24). We find that sensors ID0 and ID1 produce the most identifiable peaks. This is expected as these two sensors are located in the strong Rx field when the $90^\circ$ Rx Coil is centered. Likewise, the use of all of the ADC sensors combined still generates a center peak
Figure 5.24: Individual sensor field measurements for the 90° Rx Coil. A more meaningful peak ADC is obtained from sensors ID0 and ID1 which are located in a stronger portion of Rx field when the Rx Coil is centered over the Tx Coil. This is the same observed trend as with the previous 0° Rx Coil experiment.

that is offset in the direction where the greatest Rx field is centered above the sensor array (Fig 5.25). This is not surprising since the conditions of this experiments are much the same as the previous, only rotated to transfer the peak ADC values from one sensor to another.
Figure 5.25: Total sum of field measurement on sensor array for various 90° Rx Coil positions. Peak ADC readings take place between where the Rx Coil is perfectly aligned over the Tx Coil and where the strongest pre-resonant portion of Rx field is centered over the sensor array.

The third experiment observes the effect of rotating the Rx Coil 45°, which will cause an alignment of sensors to peak fields unlike the two previous experiments. The ID0 sensor provides the most detectable peak (Fig 5.26). This sensor is most associated with the strong field side of the Rx Coil when it is rotated 45°. ID1 provides more useful data than ID3, likely since ID1 is closer to the inductive coil located directly counter clockwise from the resonating capacitor when the Rx Coil is in a position to receive significant power from the Tx Coil. Last, ID2 actually provides a centered peak despite being on the weaker side of the Rx Coil.

The question of whether localization can be done with a finely rotated Rx Coil is answered on the merit of the ID0 sensor data alone. This sensor is most positioned in the stronger Rx field side and behaves consistently with the expectations formed in previous experiments. However, the sensors which are now located in fringe areas of stronger and weaker fields act differently than in previous cases. One solution to this is to study these cases in greater detail and for more angles of rotation. Another solution
Figure 5.26: Individual sensor field measurements for the 45° Rx Coil. The most detectable peak ADC is obtained from sensor ID0 which is located in a stronger portion of Rx field when the Rx Coil is centered over Tx. This is the same observed trend as with the previous experiments; however, the other sensors produce mixed results compared to previous experiments due to being located in border regions of strong and weak fields in the 45° Rx Coil configuration.

is to implement more sensors in a denser array that provide redundant information and offer sensors in positions similar to the previous two experiments for all rotation angles. As another merit for the current four sensor array, the collective ADC readings
Figure 5.27: Total sum of field measurement on sensor array for various 45° Rx Coil positions. Peak ADC readings take place between where the Rx Coil is perfectly aligned over the Tx Coil and where the strongest pre-resonant portion of Rx field is centered over the sensor array.

Figure 5.28: Total sum of field measurement on sensor array for various 0° Rx Coil positions with 25 cm (left) and then 30 cm (right) between transmitting and receiving coils. Peak ADC readings take place in exactly the same region despite altitude differences.

still provide a reliable peak for locating the Rx Coil within a slight offset (Fig 5.27).

A final experiment is performed to validate the robustness of this localization technique for a new altitude. For this last set of data, the distance between the
transmitting and receiving coils is increased from 25 cm to 30 cm. This is not a significant difference in height, and is intended to be representative of a slight change in elevation. However, the similarity of new data to previous experiments is undeniable (Fig. 5.28). This means that the UAV does not need to be at an exact height to use this method of localization. Furthermore, the similarity in data between the two experiments validates the repeatability of this method of measurement. The only significant difference between the two sets of data is the magnitude of the ADC changes. This is expected as the UAV is further from the Rx Coil it is measuring field from in the second experiment.

After successful ground testing of the magnetic field sensors, we suggest a method for implementing this information from a UAV for node finding. The UAV should perform scans back and forth over the area where it expects to find the receiving coil at one elevation. Once a meaningful ADC difference is detected in any one of the sensors, the UAV immediately switches from a searching algorithm to an optimization algorithm. This second algorithm will consist of a scan in one lateral direction until a peak ADC value is detected, in which case the UAV will move back until it reads a value close to the initial peak, and then scan in the other horizontal direction. If at any point the ADC sum is dropping significantly the UAV will react. If this happens while optimizing its position, the UAV will simply change the direction of its scan. If this happens after the UAV is in a good position and is transferring power, it can re-implement the optimization algorithm to get back in position. It may be possible with more testing to determine the direction and elevation to the Rx Coil from individual sensor readings as well. Finally, if at any point the sensors drop to their nominal ADC values, the original search algorithm will be performed again.
5.6 Chapter Summary

After successfully transferring power from a UAV to ground sensors, we found many parameters affect UAV power transfer, but most significant among them is the UAV’s position. Motivated by the significance of positioning and the end goal of having UAVs that can locate nodes on their own, we are developing autonomous navigation. This goal requires sensing, and we choose magnetic field sensing as a means to obtain control feedback.

At the outset of this task, it was uncertain whether or not a sensor can be made which produces meaningful data from the alternating magnetic fields used for wireless power transfer. This uncertainty came from an extensive search of literature and testing of Hall effect sensors currently available on the market. From testing we found a wrap of coil can produce a significant voltage (100s mV) to be measured when located in an alternating magnetic field. This knowledge manifested itself into the development of Sensor A.

Starting from the concept of a precision rectifier, Sensor A was simulated and then incorporated on a small PCB (less than a 3/4 in² footprint). Other integrated circuits like the RS485 and the Atmega microprocessor were included and programmed for communication and reading the ADC voltage. Although Sensor A works extremely well for signals produced by a function generator, it did not work well for live tests. This is due to a low input impedance compared to the oscilloscope originally used for the signal coil tests.

The second project produced Sensor B which evolved from more advanced design concepts. Having the ability to shift the signal input voltage bias, adjust gain on the primary amplifier, and change the frequency response of the inputs and outputs makes the board quite customizable for a large range of magnetic field strengths.
Sensor B was successfully implemented with live magnetic field experiments, and is the basis for Sensor C which uses the same successful design components, but on a smaller PCB to be mounted in the form of multiple sensors in an array on the UAV transferring wireless power.

After building an array of novel sensors that measures the alternating magnetic fields used for power transfer, information about the relative location of the receiving coils to the transmitting coils was finally deduced in live experiments. These experiments were conducted successfully on the ground for many different rotational orientations and distances from the sensor array and power transmitting coils to the receiving coils. The trends in collected data are robust and consistent with our understanding of the magnetic fields used for power transfer. We found in all instances that the peak collective ADC value occurs when the transmitting coils are near center alignment with the receiving coils, where the most meaningful power transfer follows. An approach is suggested for the power transferring UAV to locate nodes, and then optimize its position for power transfer. This will allow the UAV to transfer power without human pilot interaction.
Chapter 6

Conclusion

In this thesis we develop a wireless power transfer system that can be operated from a UAV for the purpose of being able to supply power to sensors and other electronic devices in remote locations. We did this first by developing a ground-based wireless magnetic resonant power transfer system, similar to existing systems, to test operation in a controlled environment. Then, we outfitted a UAV with a redesigned version of the wireless power transfer system, which is light enough to be carried by an AscTec Hummingbird without any significant loss in mobility. By implementing a power receiver board which autonomously optimizes power transfer, we transferred nearly 5 W of power to a grounded sensor from a UAV. Since the power transfer stability is limited by the pilot’s skill and ability to retain visual contact with the UAV, we began developing autonomous navigation. We started by designing and then building an array of novel sensors which are able to measure the alternating magnetic fields used for wireless power. Using this sensor array, we performed multiple experiments which proved robust and consistent for indicating the location of receiving coils from the power transmitting coils.

The primary contributions of this thesis are as follows: 1) development of a res-
onant power transfer system which can be carried and operated from a UAV, 2) implementing a power receiving board that uses sensors for autonomous optimization of power transfer, 3) experimentally demonstrating the ability to transfer nearly 5 W of power to ground-based sensors, 4) completing a sensor board design which is able to measure high frequency magnetic fields, and 5) demonstrating the ability of these sensors to collect data with sufficient resolution and accuracy to, in the future, implement an autonomous flight control algorithm for node finding and optimizing location for power transfer.

These contributions are significant as no other system like this is known to exist. By successfully outfitting a UAV with a wireless power transfer system, we can effectively deliver power to any location that is accessible to a UAV. This has numerous and exciting applications such as: sensors placed under bridges for structural monitoring, underwater sensors that surface intermittently to send data and recharge, underground sensors, sensors that are only activated when the UAV is present, and sensors in locations where security or aesthetic concerns prevent mounting solar panels. It is also possible to deploy sensors from a UAV, making this system even more effective. To limit upkeep the same coils that the UAV uses to transmit power could even be used to recharge the UAV at a power station. The unique sensors we developed make it possible for the UAV to locate nodes and optimize position for power transfer autonomously. This will allow UAV power transfer application without human pilot interaction. This same magnetic field sensing technique can be used to direct UAVs for recharging at a power station, or even in non-UAV applications such as positioning an electric car for recharging [29].

We are exploring other parameters that will improve both the efficiency and amount of power transferred. These include: raising the Q factor of the coils, exploring different operation frequencies, increasing the input voltage, further optimizing
the receiving board, and storing received energy in super capacitors instead of batteries. This progress can be augmented with a theoretical model that is better suited for actual resonance. This can be done through the derivation of equations, similar to what was done in Section 3.2, or with computerized simulation, which has improved by leaps and bounds in the past decade. By completely simulating the power transfer system prior to build, it would be possible to maximize parameters without having to double efforts as far as cost of materials and time for experimentation.

Moving forward, more intricate programming will take place on a primary board connected to all of the magnetic field reading sensors. This primary board will use the ADC data from each individual sensor, and incorporate it with higher level ROS architecture to control the UAV for node finding and power transfer optimization. From here we hope to deploy sensors in an outdoor environment with loose GPS coordinates, and have the UAV autonomously seek out and recharge these sensors (Fig. 6.1). This will complete our vision of autonomous wireless power transfer from a UAV, and bring the breadth of applications that lie on the horizon within our grasp.
Bibliography


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