AUTOMATIC POSITIONING SYSTEM FOR INDUCTIVE WIRELESS POWER-TRANSFER DEVICES AND APPLICATION TO MOBILE ROBOT CHARGING

A Thesis Proposal

by

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ABSTRACT

Wireless power transfer (WPT) has been an important topic of research for at least a century. The goal is to replace the use of wires, slip rings, brushes, or other physical contacts in electronics to allow more freedom of movement. One widely preferred method of WPT, inductive power transfer (IPT), has been implemented in numerous products, including mobile phones and electric vehicle chargers. In IPT, energy is transferred through an inductive link between coils in proximity of each other. The concentrated magnetic field created by these coils, however, still requires that they be close and aligned with each other; even small misalignments between the coils can result in serious loss of energy transfer. This research proposal outlines a plan to address this problem by developing a way to sense and correct lateral misalignments in IPT systems. The following three objectives are proposed: (1) Develop a way to sense lateral misalignment in inductive power transfer devices using sensing coils, (2) Implement an automatic two-dimensional positioning mechanism to reduce lateral misalignment, and (3) Demonstrate the use of this system on a mobile robot wireless charging application. The results of this research could be used to implement similar systems on commercial products and improve the application of IPT.

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I INTRODUCTION AND LITERATURE REVIEW

Most electronic devices today rely on wired connections for battery charging or direct power. However, wires require secure physical connections, which limit freedom of movement. Solutions for this include using flexible connections, such as brushes, slip rings, or liquid conductors. However, many of these devices are susceptible to friction and wear over time. Physical connections may also suffer from oxidation, contamination, or material fatigue.

An alternative to wired connections is wireless power transfer (WPT). This refers to any method of power transfer which does not use wires, and may include using light, radio frequency (RF), acoustics, electric field, or others. However, one of the most common methods is inductive power transfer (IPT). As the name suggests, this method relies on the inductive link between coils to transfer energy.

1.1 Origin of Wireless Power Transfer

Some of the first experiments with wireless power transfer are attributed to Nikola Tesla in the late 1800’s [1]. His experiments included highly resonant transformer circuits and inductive coils which could power electronic devices at some distance. His demonstrations provided the first examples of IPT. Today, IPT is still the preferred method for short and mid-range WPT since there are many ways to establish an inductive link between coils in proximity of each other. In a typical AC transformer, for example, the inductive link is strengthened by using an iron core and by placing the primary and secondary coils very close to each other, allowing for transfer efficiencies that commonly exceed 95%.

Other methods of wireless power transfer have not been as popular. Capacitive WPT generally requires large voltages or large surface areas. Light, RF, and acoustic-based transfer are susceptible to foreign object interference. Nevertheless, there is some notable work being done in these areas [2–5].

1.2 Inductive Wireless Power Transfer

A simplified version of a typical IPT system is shown in Figure 1 below. The main components of this setup are an AC power source, primary coil, secondary coil, and rectifier circuit. Two additional components, compensators, are shown in a lighter shade. These are not required, but are essential for increasing transfer efficiency.

The following is a brief explanation for the role of each component:

- AC power: This can be a voltage or a current source. The working frequency may vary from kilohertz to megahertz depending on the application. If powered by a DC source, this component will include an inverter.
- Primary coil: This coil is made with one or more loops of an insulated wire or conductive tube. It creates a concentrated magnetic field that alternates at the same frequency as the AC power source.

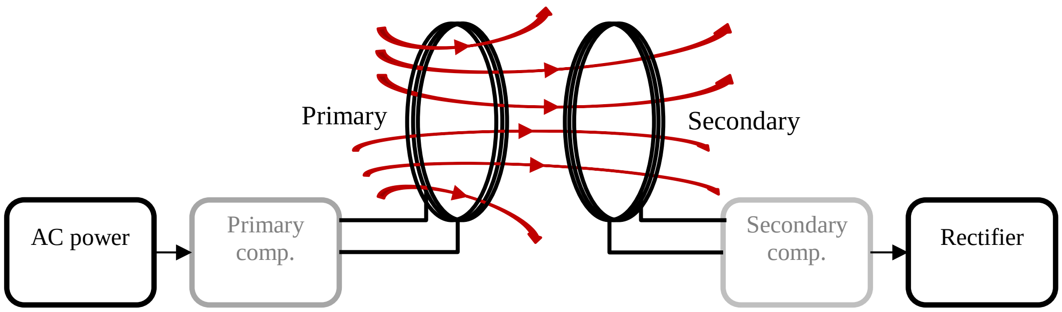


Figure 1. Simplified diagram of an inductive power transfer (IPT) system. The curved arrows represent magnetic field lines created by the primary coil.

- Secondary coil: This coil need not have the same number of loops or shape as the primary coil. It captures some time-varying magnetic flux from the primary coil. By Faraday's law of induction, a voltage is induced in the secondary coil due to this varying magnetic flux.
- Rectifier: The voltage induced in the secondary coil will alternate at the same frequency as the AC power source. The rectifier converts voltage to DC, if necessary, to power an end device.
- Compensators: These represent a variety of specialized circuits that improve transfer efficiency. For example, they may shape the resonance frequency of the coils by introducing series or parallel capacitors. They may also introduce smart control to the system, modulating the output frequency or amplitude of the primary coil depending on the demand or presence of a secondary coil.

Designs of IPT systems vary in selection of these components. For example, they may use different coil geometries, power source designs, or compensation schemes. The compensation scheme used depends on the application, and resonance based IPT has been shown to improve efficiency especially in mid-range power transfer [6]. Common compensation schemes include series-series, parallel-parallel, series-parallel, or parallel-series compensation [7, 8]. These schemes refer to the placement of resonance capacitors on the primary and secondary coils, respectively. Many wireless chargers available on the market today that charge personal devices, such as smartphones, adhere to standards that specify characteristics for all of the IPT components. One of the most popular standards, named Qi, has published specifications for wireless chargers that allow up to 15 W of power transfer and operate in a frequency range from about 100 kHz to 200 kHz [9].

1.3 Limitations of Inductive Wireless Charging

Figure 2 below shows normalized magnetic flux density vectors created by a circular loop of wire, as calculated using the Biot-Savart law (Equation 1). This loop represents a primary coil in an IPT system. Some of these flux lines penetrate the loop of a secondary coil in proximity. The rest of the magnetic field vectors are fringed into space. The magnetic field also gets weaker with distance away from the primary coil.

$$\vec{B} = \frac{\mu_0 NI}{4\pi} \int \frac{\vec{dl} \times \hat{r}}{|\vec{r}|^2} \quad (1)$$

$\vec{B}$: magnetic flux density [T]
$\vec{dl}$: wire segment [m]
$\vec{r}$: vector from wire segment to point of interest

N: number of coil loops
I: current through wire [A]
$\mu_0 = 4\pi \times 10^{-7}$ [H/m]

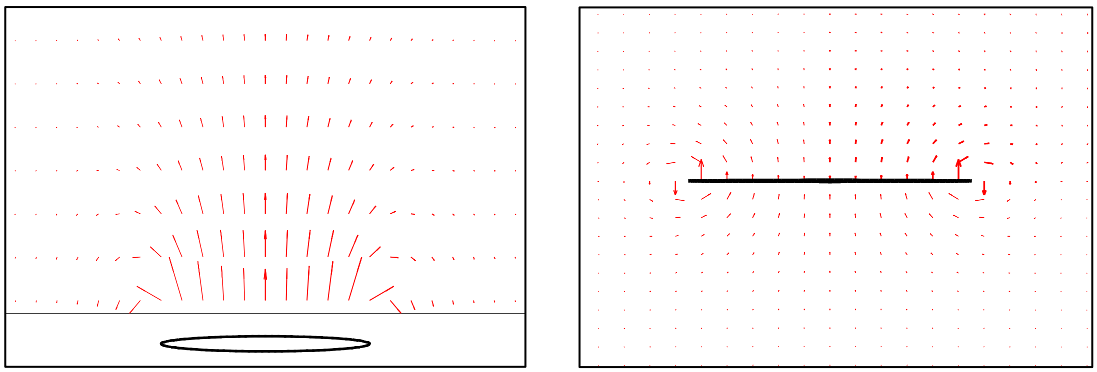


Figure 2. Magnetic flux density vectors due to a current loop. Magnitudes shown are relative.

These figures suggest that to experience the greatest magnetic flux, the secondary coil should be close to, parallel to, and concentric with the primary coil. The main issue with IPT lies here; to achieve appreciable energy transfer, the secondary coil must remain aligned with the primary coil. Much of the current research in IPT focuses specifically on increasing the working range for efficient power transfer.

Some ways to increase the working range of IPT are to increase the operating frequency, input power, or dimension of the primary coil, which would increase the magnetic flux's magnitude or its time rate of change in the space around the primary coil. However, there are many side effects to consider, such as resistive losses in the coils, skin effect, interaction with foreign objects, and power supply limitations. Much work has been done in deciding optimal coil characteristics for IPT [10, 11].

Another way to increase working range is to increase the number of coils used. For instance, there can be an array of primary coils instead of just one [12–15]. Multiple secondary coils in novel arrangements have also been used to capture more magnetic flux when there is a misalignment [16].

Still, another way to increase range is to exploit coil resonance. As mentioned before, this approach is called resonance based IPT, which involves tuning the primary and secondary coils to the same resonance frequency. Most commercially available wireless chargers use some form of resonance. In literature, there are even examples of using intermediate coils between the primary and secondary to increase the total range of power transfer [17].

Commercially, the most common solution is simply to ensure a good alignment between the primary and secondary coils and to use a tuned resonance compensation scheme of some kind. The popular Qi standard, for example, uses series-series compensation, but also relies on close alignment between the primary and secondary coils. The tolerance is only a few centimeters for 5 W chargers using this standard. To help users align their devices on these chargers, manufacturers place visual markers on the charger or construct it so that the charging device is naturally in alignment as shown in Figure 3.

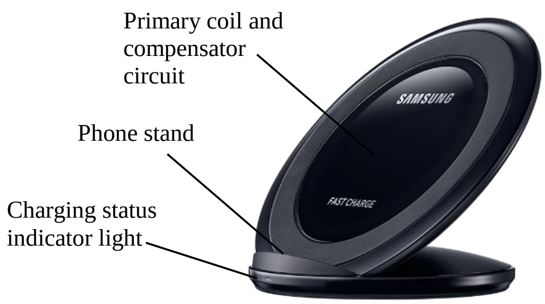


Figure 3. Example of commercially available Qi wireless phone charger, which relies on precise alignment to function efficiently (Samsung model EP-NG930TBUGUS)

1.4 Active Coil Positioning for Inductive Power Transfer

There are a few examples of active positioning for IPT. This refers to moving either the primary or secondary coil into alignment using some active mechanism. The Qi standard suggests the idea of using a capacitive touch surface or, alternatively, an array of sensing coils to detect the location of the device (secondary coil) to position the charger (primary coil). No design is given for a positioning mechanism, but the positioning resolution of 0.1 mm or better is suggested.

One notable example of active positioning can be found in the online electric vehicle (OLEV) experiments of South Korea [18, 19]. They feature the application of IPT for wireless charging of electric vehicles. In this case, the primary coils are installed in the road itself. The first generation of this experiment used a golf cart, which used an automatic positioning system to keep the secondary coil aligned with the in-road primary coil. The details of this positioning system are not made clear, but it is apparent that a camera sensor was used. Subsequent generations of this project have eliminated the alignment mechanism, focusing instead on creating a more favorable magnetic field distribution which tolerates more misalignment.

In their contribution to vehicle wireless charging research, one group recently used two small sensing coils placed next to the secondary coil on a vehicle to detect misalignment between the vehicle and the in-road wireless power transmitter [20]. These sensing coils were used to measure the difference in magnetic field between the left and right side of the vehicle. A difference indicated that the vehicle was not centered above the in-road primary coil. This information was then used to steer the vehicle and maintain a good alignment with the charger. No details are given for the inspiration of using sensing coils, and the steering control was already a function included in the vehicle.

1.5 Applications of Inductive Wireless Charging

With current advancements, and especially the release of wireless charging standards like Qi, an increasing number IPT products have reached the market. Toothbrushes with wireless charging have been available for years. Wireless charging has become standard in many high end smartphones and tablets. Wireless charging of electric vehicles has been implemented in public parking spots, and wireless chargers are available for purchase by individuals [21]. These vehicle charging systems usually include a stationary charger, a vehicle-mounted receiver, and a position-assistance device.

As mentioned before, one of the main challenges for inductive wireless charging is maintaining proper alignment between the charger and the device. The position-assistance device included with the electric vehicle chargers helps the driver park in the correct spot so that the secondary coil is directly above the charger. Misalignment leads to inefficient charging. Wireless phone chargers suffer the same problem but are considerably easier to use, since phones can easily be adjusted to align with markings on the charger.

IPT has other uses, such as wireless tracking of a rodent in a cage [22, 23]. Another application is wireless charging of implanted medical devices [17, 24]. Both of these applications suffer even more from misalignment since the location of the secondary coil is more unpredictable. Solutions may include using multiple IPT coils or smart control of electronics.

1.6 Contribution of This Thesis Research

The proposed focus of this research is to develop a method for sensing misalignment in IPT wireless charging systems and to provide a means for correcting this misalignment. Much of the focus for inductive power transfer research has been on improving the electronic circuits, coil characteristics, or control schemes of these systems to mitigate the effects of coil misalignment. The research proposed here takes a different approach, focusing instead on a mechanical solution for reducing alignment error. It is noted that most current applications of IPT use simple, single coil arrangements which could benefit from lateral misalignment reduction by an automated system. The task then is to develop the misalignment sensor, hardware, and controllers to achieve this. The result will then be implemented in a small mobile robot to demonstrate the value of this concept. The use of autonomous mobile robots has been proposed for many settings, including cleaning, surveillance, product transport, and other services [25–27]. To maximize productivity, mobile robots can benefit from autonomously recharging themselves at designated charging stations. Power transfer can be done using electrical contacts, but using a misalignment-tolerant wireless charger would reduce contact wear, risk of short circuits, and it would protect the robot electronics from the environment. If successfully completed, the misalignment reduction mechanism could similarly be applied to many other products.

II RESEARCH OBJECTIVES

To guide this research, the following three objectives are proposed:

1. Develop a method for sensing lateral misalignment in an IPT charging system.
2. Implement an automatic positioning mechanism that can reduce lateral misalignment within an acceptable range.
3. Demonstrate the use of an automatic positioning mechanism in a mobile robot charging application.

2.1 Misalignment Sensing

In an IPT system with one primary coil and one secondary coil, there are five directions in which misalignment can occur to reduce power transfer (Figure 4). These result from the magnetic field distribution of a circular current loop as shown in Figure 2. Rotation about the *z*-axis would not affect power transfer due to the magnetic field symmetry.

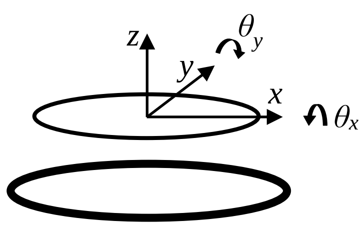


Figure 4. Misalignment directions which decrease power transfer

For this research, misalignment sensing will focus on the lateral directions only (i.e., the *x* and *y* directions). Many applications already provide planar alignment. For example, phone and electric vehicle chargers naturally place the coils on parallel planes at a fixed *z* distance. Then, the only degrees of freedom (DOFs) are in the *x* and *y* directions. The solution chosen for misalignment sensing should be contactless, to take full advantage of the wireless charging concept.

2.2 Automatic Positioning Mechanism

Given that there is a certain way to sense misalignment, a mechanical system can be implemented to reposition the secondary coil in real time if misalignment occurs. This need not be a novel design. Rather, the focus should be on reliably providing the positioning resolution required. The lateral positioning resolution of 0.1 mm or better is suggested by the Qi charging standard and can be used as a goal.

2.3 Mobile Robot Application

For demonstration with a mobile robot charging application, the automatic positioning mechanism can be implemented on an existing robot platform. The focus, then, will be giving the robot a way to reach the charging station and then evaluating the performance of the automatic IPT positioning mechanism.

III PROPOSED METHODS

The following methods are proposed for reaching each of the three objectives of this research.

3.1 Misalignment Sensing

An ideal solution for misalignment sensing is contactless. There are many sensors that can achieve contactless sensing, such as camera, ultrasonic, light, etc. However, it would be wise to take advantage of the energy already being emitted by the primary coil in an IPT system. Furthermore, it is convenient that the magnetic field emitted by a circular current loop is symmetric about its axis. Based on this, the following sensing coil concept is proposed for sensing coil misalignment:

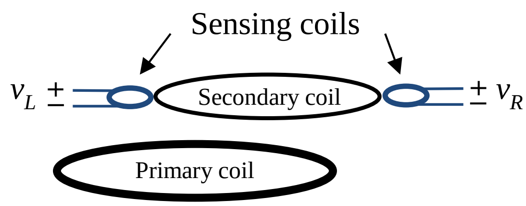


Figure 5. Proposed misalignment detection using sensing coils

In this figure, the secondary coil is misaligned slightly to the right. As a result, the magnetic flux penetrating the left and right sensing coils is not equal. The difference in magnetic flux can be quantified by measuring the induced voltage in each of the coils. In this case, the voltage in the left sensing coil will be greater than that of the right sensing coil because it lies in an area with a stronger magnetic field. The voltage difference between the two coils is expected to be a good measure of misalignment because this voltage difference should increase with misalignment. As the secondary coil continues to move to the right, the right sensing coil will decrease in voltage while the left sensing coil voltage remains high. This will be true for a limited range.

Some questions to answer through this research are: What is the misalignment sensing range? How to easily measure voltage in the coils in real time? How to compare the voltages of the coils? How will the IPT system design affect the use of this misalignment sensing method?

A preliminary experiment was conducted to test this idea. Two coils, each with 10 loops were attached symmetrically as shown in Figure 5 to a secondary coil of a Qi wireless phone charger. The two coils were made from one continuous enamel coated wire and are wound in opposite directions, such that the total magnetic flux through the coils is zero when there is no misalignment. The voltage difference can be measured directly from the two ends of the wire. Figure 6 shows the voltage measurement for zero and 5-mm lateral misalignment in one direction.

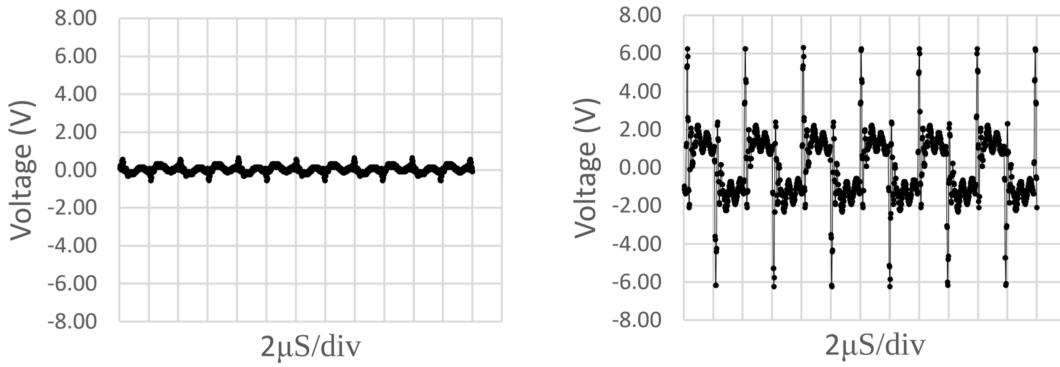


Figure 6. Voltage measurement from sensing coils for zero (left) and 5-mm (right) misalignment

As expected, the misalignment results in a measureable differential voltage increase in the sensing coils. Figure 7 shows the same measurement at various misalignment distances. These are the DC voltage measurements after adding a diode rectifier, smoothing capacitor, and shunt resistor to the output of the sensing coils.

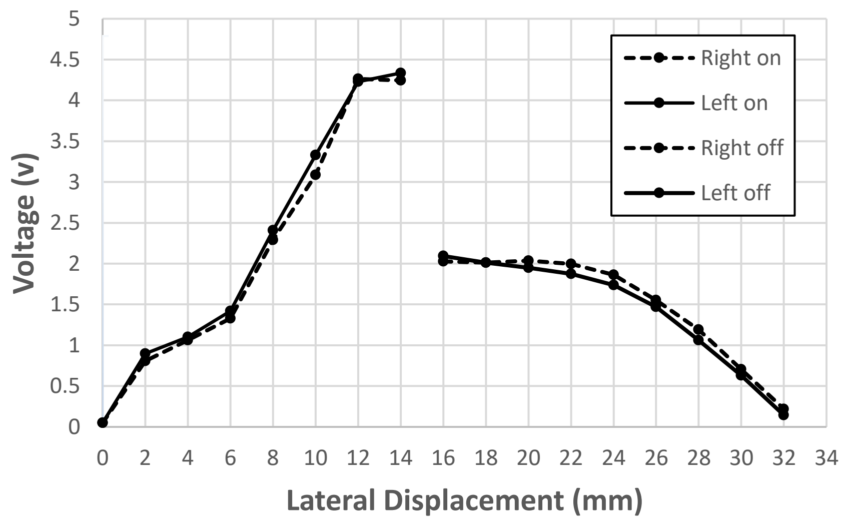


Figure 7. Measured sensing coil voltage at various sampled misalignment distances. Misalignment direction and power state of the wireless charger are labeled.

As shown here, the DC voltage reading increases for misalignment in either direction. This plot also reveals two distinct areas of operation. Between about 14 to 15 mm, the Qi charger is programmed by the manufacturer to power off and begins to send only short pulses of energy. For experimental purposes, this functionality should be disabled. Once this is done, it is expected that the positive trend of the left region would continue.

3.2 Automatic Positioning Mechanism

As previously mentioned, the automatic positioning mechanism does not need to be novel but should provide precise positioning resolution. As a suggestion, a motor, pulley, and belt system can be used (just as in 3D-printers and CNC machines). A smaller version of the positioning mechanism can be implemented on a mobile robot, and the robot movement itself can provide positioning in at least one direction.

Another important component of the positioning mechanism will be the feedback controller. For this, the use of a digital controller programmed on an Arduino board is suggested. This device is cheap, easy to use, can be used to measure DC voltage, and can command motor drivers. The sensor feedback for this controller will be provided by the proposed misalignment sensor. Further positon measurement of the motors can be provided by a rotary encoder.

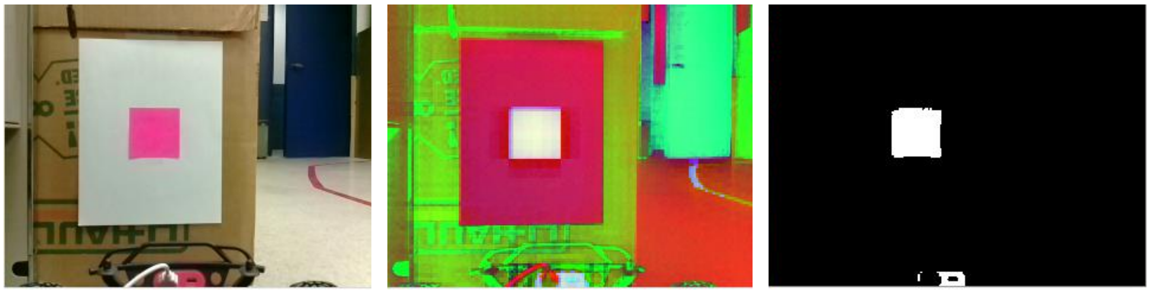
Important tasks for this research objective include dynamical modeling of the positioning system, real-time controller design, and implementation.

3.3 Mobile Robot Charging

For mobile robot experimentation, any common and easily controlled mobile robot can be used. For example, a differential-drive robot with two independently driven wheels and a ball caster roller can be used. Alternatively, a small-scale vehicle can be used. The use of a hobby remote-control (RC) car is proposed since it already has motor controllers and can be easily commanded using pulse-width modulation (PWM) signals. Once the car is selected, an automatic coil positioning system can implemented on it. The system would position the secondary coil under the car so that it aligns with a wireless charger on the ground.

Since the misalignment sensor proposed will not function at long distances, the mobile robot would need a way to find the charger location and approach it. For this task, the use of an on-board camera is proposed. This camera will identify the direction and distance to the charger in real time and feed this information to a controller on the mobile robot. Tracking of the target will be done using image processing. Since image processing is not the focus of this research, a simple tracking algorithm will be used.

To track a target using image processing, the use of a Raspberry Pi, Pi Camera, and open-source computer vision software called OpenCV is proposed. As a preliminary experiment, this setup was used to track a colored target. Figure 8 shows the results of image processing on a captured image. The pink target is successfully highlighted by filtering pixels using hue, saturation, and value (HSV) numbers.



(a) *(b)* *(c)*

Figure 8. Image filtering of for pink target: (a) original (b) HSV (c) HSV filtered

Once the image is filtered, the OpenCV software can be used to identify the target location on the image and its pixel area as shown in Figure 9.

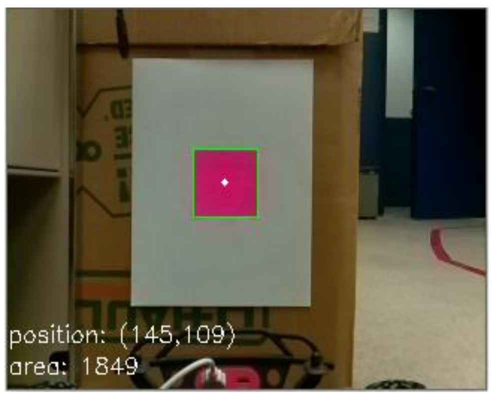


Figure 9. Target identification with location and pixel area calculated

The target location and pixel area can be used as a rudimentary way to calculate distance and heading angle error to the target as seen by the mobile robot. As the robot approaches the target, its pixel area will be larger as shown in Figure 10. To reduce the heading angle error, the robot should steer so that the target is at the center of the image.

The significance of this method is that it is simple and cheap as it only requires one camera and a cheap processor to function (the Raspberry Pi and camera together are only about $60). Furthermore, using this setup is expected to result in some final position error, which the onboard IPT automatic positioning mechanism can work to eliminate.

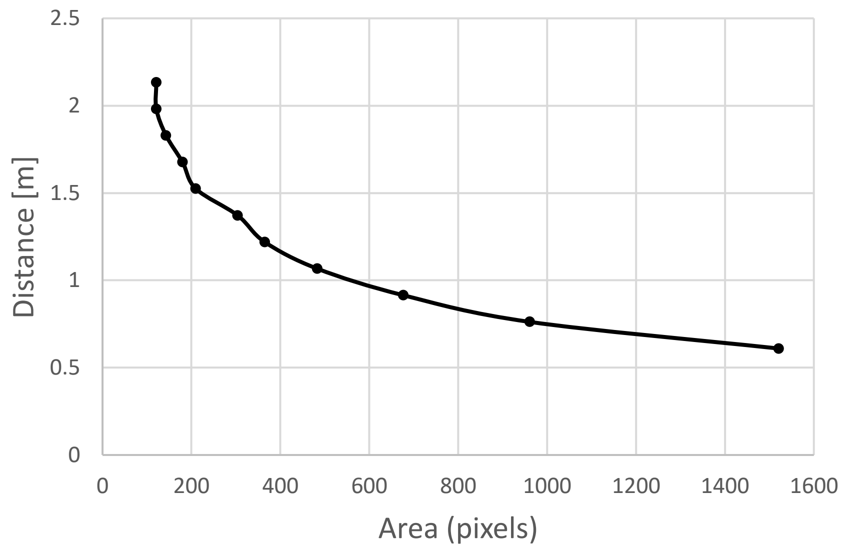


Figure 10. Plot of actual distance versus target pixel area, using a 320×240 image size

IV EXPECTED RESULTS

The following are the expected results for each objective.

4.1 Misalignment Sensing

The misalignment sensor is expected to provide a qualitative measurement of the lateral misalignment of a secondary coil in an IPT wireless charging system. The measurement is not expected to be linear (refer to Figure 7) due to the nature of the magnetic field, but the trend will still be useful for correcting misalignment.

The expected results of this objective are:

- Ideal dimensions and placement of the misalignment sensing coils
- Experimental results of misalignment sensing using an IPT charger
- Limitations of misalignment sensor (sensing range, hardware limitations, etc.)
- Recommendations on adding more sensing degrees of freedom

4.2 Positioning Mechanism

The positioning mechanism is expected to demonstrate a controller that can reduce lateral misalignment for the secondary coil of an IPT system automatically.

The expected results of this objective are:

- Design and construction of a two-dimensional positioner with sensing coils and actuators
- Design and implementation of real-time digital controller that drives the misalignment to zero
- Experimental results of position error versus time for the secondary coil

4.3 Mobile Robot Charging

The mobile robot charging application is meant only as a demonstration of the IPT misalignment sensing in action. As such, will be much room for future improvement.

The expected results for this objective are:

- Design and mounting of a secondary coil positioner on the selected mobile robot
- Implementation of a simple camera sensor with image processing on the mobile robot for target tracking
- Design and implementation of a digital controller to bring the mobile robot to the target, accepting some steady state error
- Final test: mobile robot approaches target with wireless charger on the ground, stops, and positioner places secondary coil in position above wireless charger

V RESEARCH PLAN

The following timeline and resource list outlines a plan for completion of this research.

5.1 Timeline

The timeline presented below is organized by academic semester for the duration of two years. Included are specific tasks to be completed each semester.

Table 1. Research timeline organized by academic semester

<table>
<tr><th>Objective</th><th>Fall 2015</th><th>Spring 2016</th><th>Summer 2016</th><th>Fall 2016</th><th>Spring 2017</th></tr>
<tr><td>Misalignment Sensing</td><td rowspan="3">Idea exploration and literature review</td><td>• Experiment with IPT coils (primary, secondary, Qi, sensing)</td><td>• Design, create, experiment with misalignment sensing coil</td><td>• Collect misalignment sensing data</td><td rowspan="3">Thesis defense and written report</td></tr>
<tr><td>Positioning Mechanism</td><td></td><td>• Build and test mobile robot IPT positioner</td><td>• Build and test 2D IPT positioner</td></tr>
<tr><td>Mobile Robot Application</td><td>• Investigate target tracking for mobile robot</td><td>• Implement hardware and software for target tracking</td><td>• Final mobile robot test</td></tr>
</table>

5.2 Resources and Equipment

The following resources and equipment will be used for completion of each objective.

Table 2. Resources and equipment which will be used for each objective

Objective	Equipment	Other Resources
Misalignment Sensing	• Digital multimeter • Oscilloscope • Function generator • 3D printer	• Enamel-coated wire • Commercial wireless charger (Qi) • Various electronic components
Positioning Mechanism	• 3D printer • Wood/metal machining tools	• Actuators (dc motor, stepper motor, etc.) • Motor drivers • Positioner hardware • Arduino microcontroller
Mobile Robot Application	• Mobile robot platform with motor driver and battery • Wood/metal machining tools • 3D printer	• Raspberry Pi and Pi Camera with laptop and software for communication • Arduino microcontroller • Rotary encoder

Each of these resources and equipment are available for use in the Mechanical Engineering Department at Texas A&M or are otherwise available for purchase.

VI CONTRIBUTORS AND FUNDING SOURCES

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The mobile robot to be used in this work is a RC car with a wheel encoder that was provided by Forrest Berg, who previously used the vehicle for his own research work. Forrest Berg received his master's in Mechanical Engineering under the advisement of Professor Won-jong Kim in June 2016.

Apart from the above and any other commercially available components purchased for this thesis project (Arduino, Raspberry Pi, wireless charger, etc.), all work will be the original creation of Ivan Cortes.

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