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Simple Relative Positioning 3-Axis Alignment Sensors for Wireless Power Transfer for Electric Vehicles

Thomas Stout[1]

[1]*Evatran Group, Inc., 2521 Schieffelin Rd #128, Apex, NC, 27560, USA, tstout@evatran.com*

Summary

Wireless charging of electric vehicles (EVs) is an enabling technology that makes EVs easier to use and can help accelerate EV adoption. Proper alignment of the vehicle over the wireless charger is critical for the operation of this technology, and the positioning must be easy to accomplish in order to maintain the convenience offered by wireless charging. A vehicle alignment sensor capable of meeting these requirements is presented here. The 3-axis sensor presented is an improvement over the planar sensing coils previously used in these types of applications.

Keywords: control system, EVSE (electric vehicle supply equipment), wireless charging

1 Introduction

The number of electric vehicles (EVs) worldwide is growing rapidly, with EV sales counting for approximately 1% of all vehicle sales in 2015 [1]. The total number of electric cars grew by 70% between 2014 and 2015 [1], with that trend likely to proceed or even accelerate into the foreseeable future. Wireless charging is an enabling technology that can accelerate the adoption of EVs [2] [3]. Wireless charging works by using a resonant air-core transformer with the primary and secondary windings physically separated from each other. The orientation of the secondary coil mounted on the vehicle with respect to the primary coil resting on the ground is critical to the operation of the system [4]. Since these systems transfer power using magnetic fields, it is an obvious choice to use magnetic field sensors to detect the alignment of the system [5] [6]. There has been extensive work done in the past to use magnetic sensors for determining positioning information, but these systems are generally very complex and attempt to solve for precise positional and rotational information using multiple field generators and/or sensors [7] [8] [9]. Due to the limited number of controllable variables in the alignment of the vehicle, it is not necessary to determine precise positioning information. Relative positioning information is all that is needed to direct the vehicle operator towards correct alignment. Final alignment determination can be completed by detecting the coupling between the primary and secondary coils [10]. Determining the relative position of coils in wireless charging has previously been done using planar sensing coils [5] [11]. The use of planar positioning coils, however, presents problems for a vehicle charging application making them difficult to use. Instead, an alternative method is presented that uses a multi-axis detection coil to determine power transfer coil relative positions.

2 Alignment Information Requirements

Alignment is completed by relying on two different measurements. The first measurement uses a set of magnetic field sensors to determine the relative position of the vehicle with respect to the primary coil. The second measurement is made to determine the coupling between the primary and secondary coils to indicate when adequate alignment for charging has been reached.

The relative positions of the two power transfer coils are determined using sensors that detect a field being generated at a known level by the primary coil. The magnetic field sensors only needs to provide positional information in two dimensions. This is because the operator of the vehicle only has control over the position of the vehicle in two dimensions. With the height of the vehicle off the ground maintaining a fixed value, the system cannot provide any useful guidance information based on the Z-axis gap between the two coils. Because the Z-axis gap is not a variable that can be controlled, the alignment system can be simplified by excluding this dimension from measurement. Since the secondary coil is fixed to the bottom of the vehicle, the vehicle operator also has no control over the pitch of the secondary coil in any direction. Determining the angular tilt of the coil also provides no useful information to the vehicle operator, and by not determining this information the positioning system can be further simplified.

While providing two dimensions of information is sufficient to guide a vehicle operator into the correct location, another measurement is needed to determine when an acceptable final location has been reached. Since the primary coil is already energized at a known level to enable the operation of the alignment sensors, the induced voltage on the secondary coil can be measured to determine the coupling coefficient and determine when the vehicle has reached a suitable charging location.

3 Alignment Sensors

The magnetic field sensors are located symmetrically around the secondary coil, which allows for pairs of sensors to provide relative positional information along one axis. Only two pairs of sensors are needed to obtain the required information to provide relative guidance to the vehicle operator. Fig. 1a and Fig. 1b show two possible alignment sensor arrangements that provide two dimensions of information. The direction of movement needed to improve alignment in each axis is equal to the direction with the sensor that has the higher output value. The secondary coil is itself used as a sensor for detecting coupling to determine when the system is in an acceptable location to transfer power.

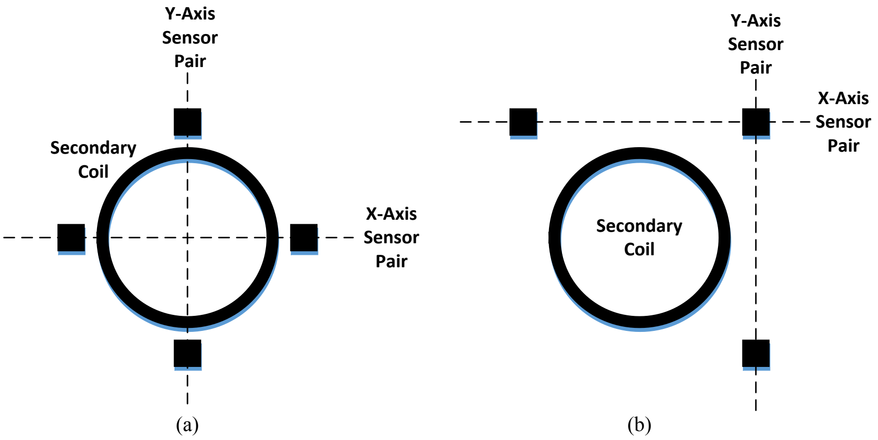

Figure 1: (a) Alignment sensor positions for 2-axis relative positioning information using 4 sensors. (b) Alignment sensor positions for 2-axis relative positioning information using 3 sensors.

3.1 Secondary Coil Sensing

Throughout the alignment process the primary coil is used to generate a magnetic field of a known magnitude. The voltage induced in the secondary coil is measured continuously during alignment. This voltage is proportional to the level of coupling between the two coils. This voltage can be compared to a fixed threshold value that indicates when the coupling is sufficient for the charging process to begin. Fig. 2

shows a typical topology for a wireless power transfer system along with the measurement points needed to determine coupling between the two halves of the system (V_P and V_S).

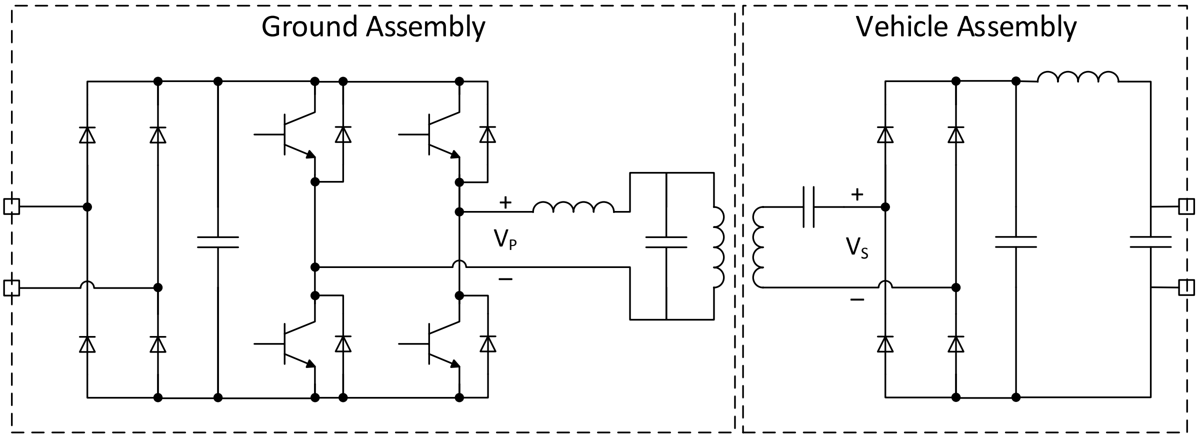

Figure 2: Typical Wireless Power Transfer Topology with Measurement Points for Coupling Coefficient

3.2 Planar Alignment Sensors

A planar alignment coil is often proposed as a solution for sensing magnetic field strength, and therefore relative position in a wireless charging system [5] [11]. In practice, this sensor type does not work well. The issue is that a planar coil only captures flux in a single axis. Along any line that moves straight out from above the primary coil the total magnitude of the magnetic flux does drop as a function of distance. However, the magnitude in any one axis does not have a purely monotonic relationship between position and flux. The results of the field strength from a simulated circular coil are shown in Fig. 3.

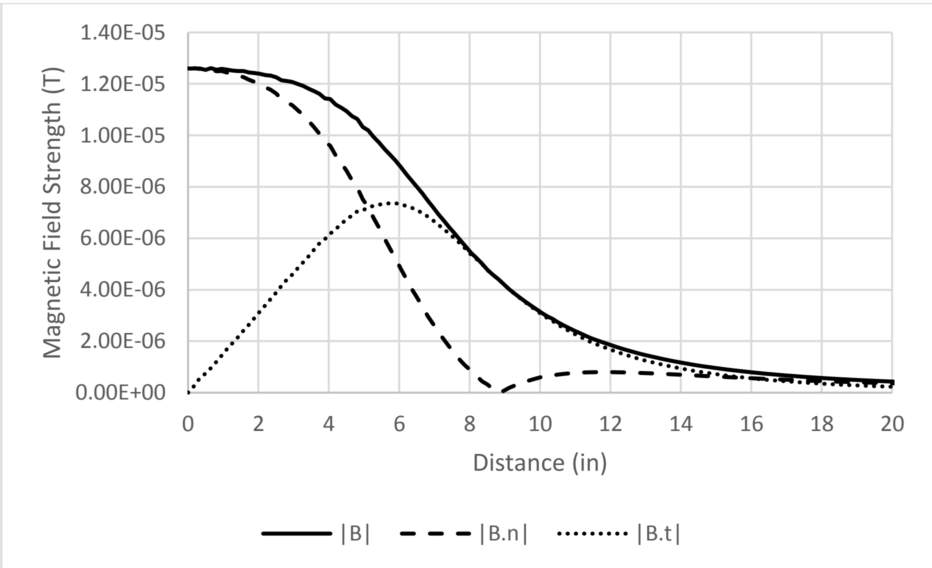

Figure 3: Simulated Magnetic Field Strength vs. Distance at 4" Gap for a 6 Turn 13" Round Coil at 1 Amp

Using a planar coil guarantees that for any given orientation of the sensor there will be a location where the sensor is tangent to the magnetic field. The point where this happens will always have a sensor output that goes to zero. Fig. 4 shows the orientations of a planar coil that is tangent to the magnetic field in different locations, and shows that any chosen orientation will be tangent to the field at some location.

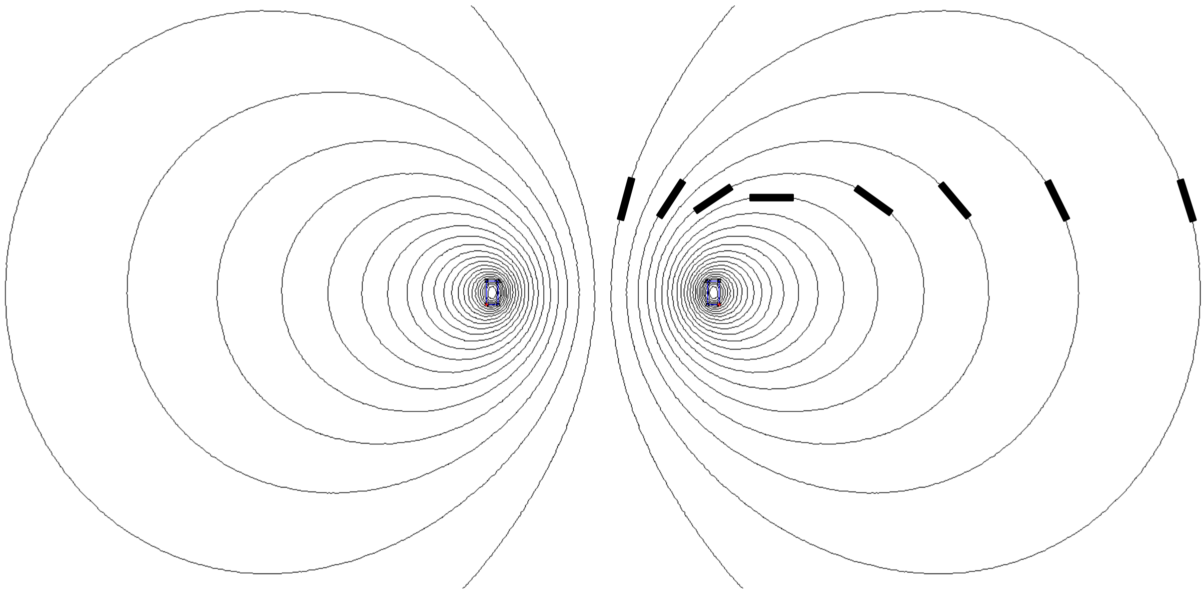

Figure 4: Locations Where Sensor is Tangent to Field for Various Planar Sensor Orientations

If the planar coil is perpendicular to the secondary coil then the output will be that of |B.t| in Fig. 3. The output will have a zero point right at the center of the primary coil. If the planar sensor is placed in the same plane as the secondary coil then the output will be that of |B.n| in Fig. 3. The flux captured in this orientation has a zero point just outside the radius of the primary coil.

These zero points make accurately determining the relative position of the power transfer coils impossible. On either side of these points there will be locations where the sensor outputs are equivalent. This means that the location of the sensor is ambiguous between at least two locations, one on either side of the zero. This ambiguity leads to positions where the system cannot determine which direction the secondary coil assembly needs to move in order to improve alignment. Fig. 5 shows an example of ambiguous sensor locations where the spacing between the sensors is fixed, and the output from the sensors is identical.

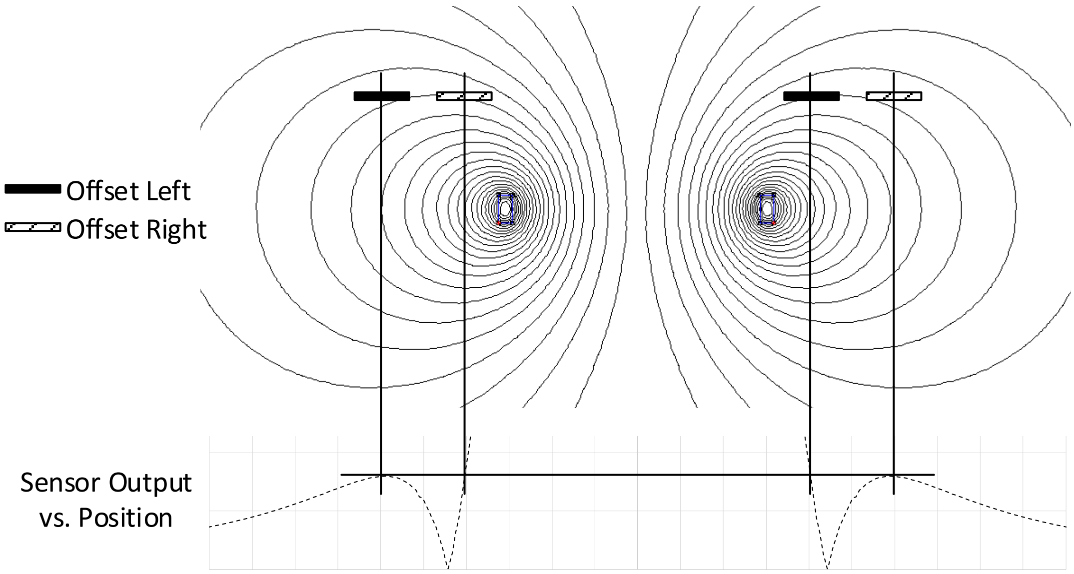

Figure 5: Example Planar Sensor Ambiguous Positions

For some wireless power applications it is possible to constrain the space over which the sensors must operate to provide feedback to avoid these zero points. For example, a handheld device would be much easier to achieve initial alignment, and the sensors could be spaced in such a way to avoid these zero points over normal use cases of the system. However, this does not work for a vehicle. The vehicle will be unconstrained in its initial positioning, and the system will need to provide guidance feedback over the full range of possible orientations between the sensors and the primary coil.

If a simple comparison between the two sensor outputs is used to determine which direction to move the coil, then these zero points lead to incorrect guidance information. When one sensor is near the zero point, it will be possible to find locations where that sensor's output has a lower value than the other sensor, even if the other sensor is farther away from the primary coil. Methods to compensate for this add significant complexity and still can't correct for the locations where the output is ambiguous and identical, as previously outlined.

3.3 3-Axis Alignment Sensors

An alignment sensor that measures all three axes can be used to determine the total magnetic field strength using equation (1). This measurement produces a monotonic output, where the output drops as the sensor is moved farther away from the primary coil. This allows for a pair of sensors to be directly compared for determining relative positioning information.

$$|B| = \sqrt{B_X{}^2 + B_Y{}^2 + B_Z{}^2} \tag{1}$$

A further simplification can be made to this sensor arrangement that eases implementation. Instead of solving for the value of the magnetic field precisely, an approximation can be used as shown in equation (2). The output of this modified sensor is shown as B Approx in Fig. 6.

$$|B| = |B_X| + |B_Y| + |B_Z| \tag{2}$$

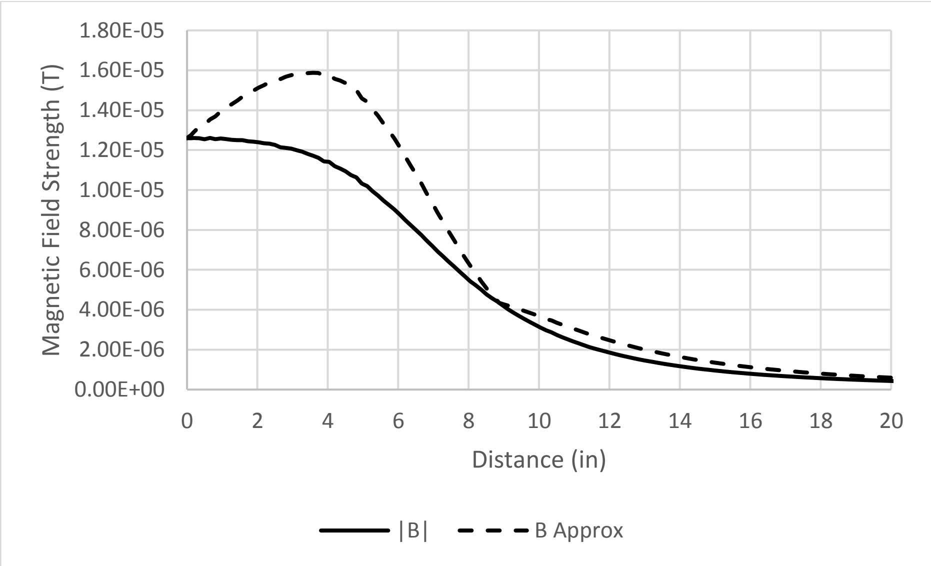

Figure 6: Simulated Magnetic Field Strength vs. Distance at 4" Gap for a 6 Turn 13" Round Coil at 1 Amp

This approximate solution to the field strength can be implemented using the very simple passive circuit in Fig. 7. Because this circuit is passive it allows for the sensor to be constructed in such a way that it does not require external power, and because of the simplicity it can be constructed for a low cost. The physical construction of this sensor requires the three sensing inductors to be oriented orthogonally to each other.

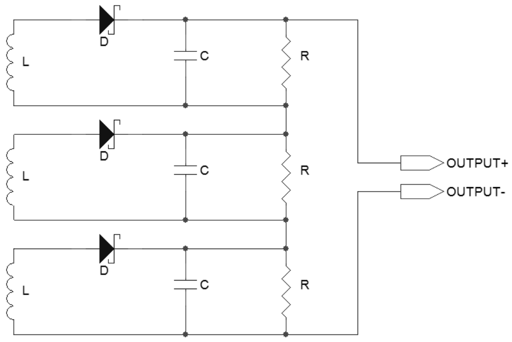

Figure 7: 3-Axis magnetic field approximation sensor schematic.

With this simplification to the sensing requirements, as long as the sensors are placed at an appropriate width, a direct comparison of sensor values can still be used to give relative positioning information. While the actual magnetic field strength has a single peak directly above the center of the primary coil, the approximate signal has two peaks that are on either side of the primary coil. These two peaks occur near the edge of the coil.

There will be a local minima at the center of the primary coil for the approximated signal. The output of the sensor will be below this local minima value for all points outside a region roughly the size of the primary coil. In order to use a direct comparison between two sensors for determining guidance information the sensors must be spaced far enough apart to prevent an inversion of sensor values around this point. Fig. 8 shows the local minima and the minimum required spacing this creates between the two sensors.

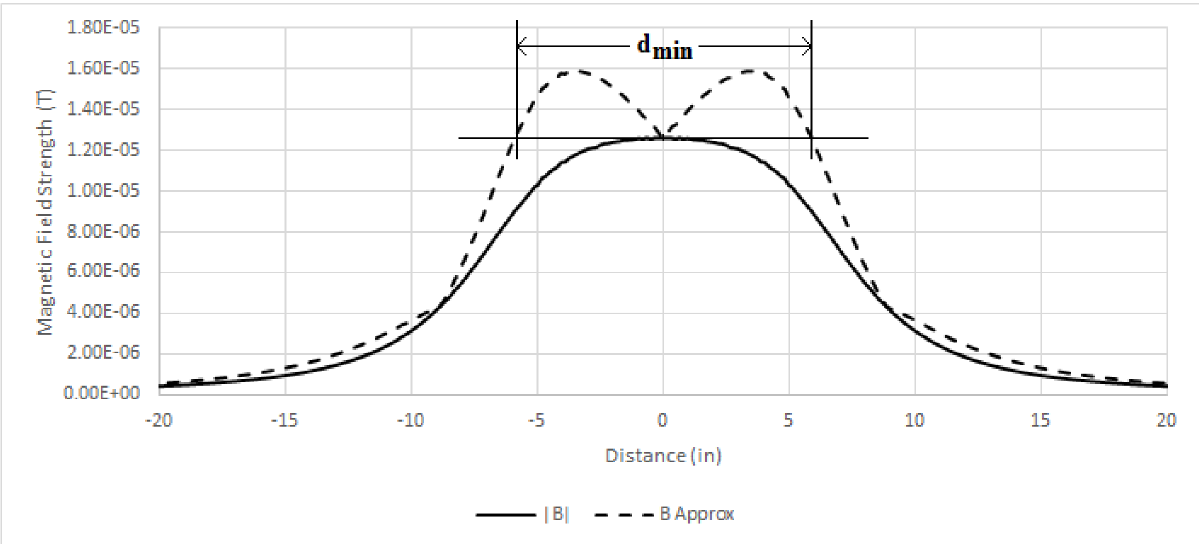

Figure 8: Simulated Magnetic Field Strength vs. Distance at 4" Gap for a 6 Turn 13" Round Coil at 1 Amp

4 Example Sensor Comparison

An example planar coil is shown in Fig. 9 (a), while an example 3-axis sensor is shown in Fig. 9 (b). The planar coil was implemented as traces on a PCB. The 3-axis sensor was implemented using wire-wound ferrite core inductors. Note that the three inductors that make up the sensor are physically arranged to be as close to each other as possible, and all orthogonal to one another, which allows for the best approximation of measuring the field strength at a single point.

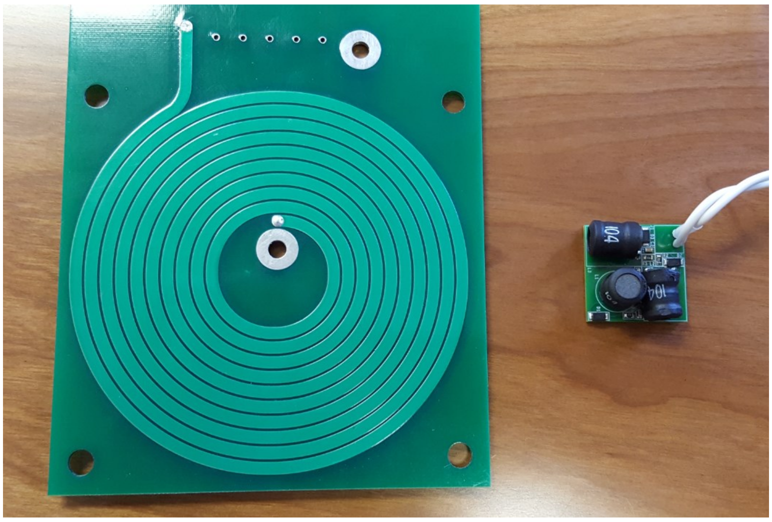

Figure 9: (a) Example Planar Sensing Coil (b) Example 3-axis Sensor

Data was captured using a 13" primary coil with a 4" Z-gap between the sensors and the primary coil. The data has been normalized for a zero-offset value of 1 so that the shapes of the output from the sensors can be readily compared. The raw data scales are different due to different self-inductance values, and would require different front-ends on the analog signal measurement stages of an actual design. The data from simulations is shown in Fig. 10, with the actual data shown in Fig. 11.

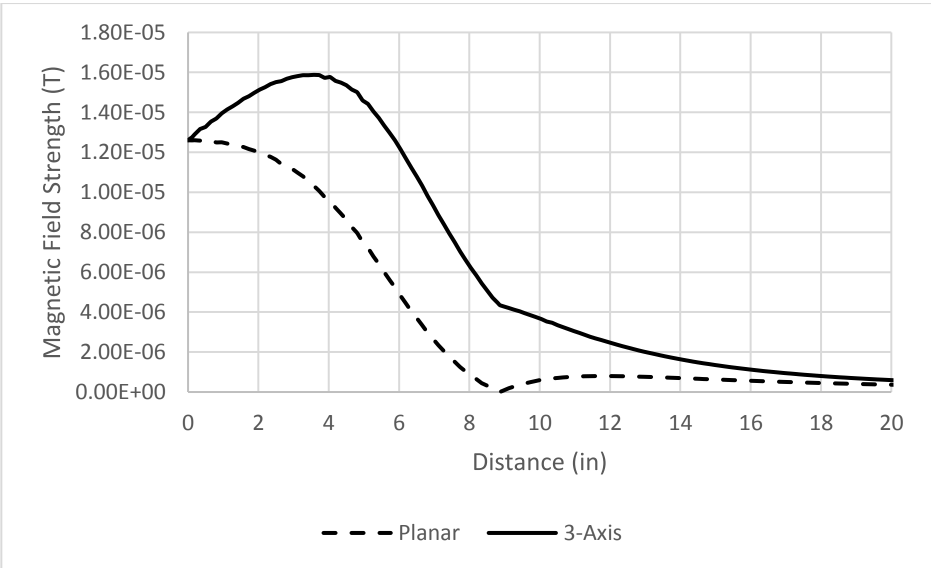

Figure 10: Simulated Sensor Output vs. Distance

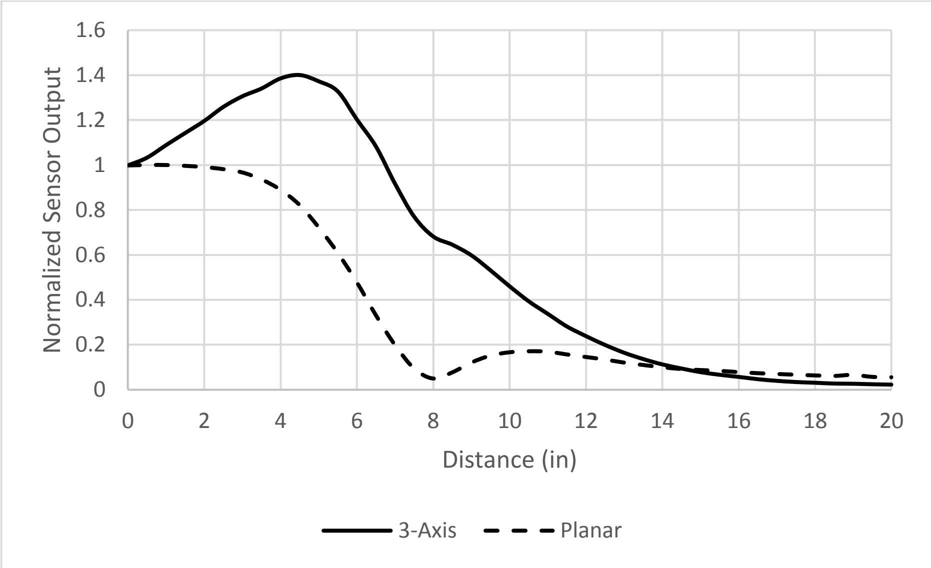

Figure 11: Example Sensor Normalized Output vs. Distance

It can be seen that the real-world performance of these sensors matches the expected behaviour very well. There are some variations in the real implementation due to non-ideal characteristics of the sensor that were not considered for the simulated data. For example, the diodes used to generate the absolute value of the three individual axes have a small forward voltage drop in a real implementation. Until the output from any one axis surpasses this value, the diode will not conduct and the output will remain low. This subtracts a small amount from the value measured on each axis. However, as can be seen from the captured data, this effect can be minimalized when the diode forward drop is small compared to the full scale output of the sensor.

5 Alignment System Based on 3-Axis Sensor

These alignment sensors are currently used in the Evatran Plugless line of wireless electric vehicle chargers. The control algorithm for determine feedback to the vehicle operator is very simple. With a pair of sensors in each axis under operator control, the system uses a simple comparison to determine which direction the vehicle should be moved to improve alignment. A small dead-band is implemented around the comparison, such that left/right guidance is not given when the outputs from the two sensors are very close. When the difference between the sensor values goes outside this dead band the operator is guided to move towards the sensor with the higher output value (which is the sensor closer to the primary coil). For front/back alignment the system will always indicate which direction the vehicle must be moved in order to improve alignment.

The alignment system is capable of determining when left/right adjustments must be made when the vehicle is still approximately two feet away from the primary coil. This distance is based on the sensitivity of the sensor and the strength of the magnetic field being generated by the primary coil during alignment. Tests have shown that this distance is adequate for directing a vehicle operator correctly into the parking space above the primary coil. With the steering wheel of the vehicle fully turned towards one direction the cars that have been implemented are capable of moving one foot left or right for every one foot travelled forward.

The alignment system uses voltage measurements on the primary and secondary coils to determine the coupling coefficient of the system in real time while the vehicle is aligning. When an acceptable coupling level is reached the operator is guided to stop. The system will resume providing directional guidance if the coupling is reduced below an acceptable level due to the vehicle operator not stopping in time.

Experience has shown that this is level of guidance provides enough control to allow an operator to correct their positioning within just the last few feet of travel when parking. Most vehicle operators are able to use the alignment system for the first time with minimal training, and becoming fully comfortable with the operation of the system after just a few uses.

6 Conclusion

Planar sensing coils for determining alignment in wireless power transfer applications are not well suited to vehicles. Due to the large range over which guidance must be given, the output characteristics of these sensors make them difficult to use. Using a 3-axis sensor with an approximation of the total magnetic field gives an output that can be easily used to provide alignment guidance, and a sensor design that is easy to implement. This solution has a low complexity and very low computational overhead. The final determination of alignment is based off of the coupling measured between the primary and secondary coils. Coupled with the fact that a vehicle can only be controlled in two dimensions, it is very easy to create a guidance system that can determine the relative position of the two power transfer coils in these two dimensions and provide the required guidance feedback to the vehicle operator.

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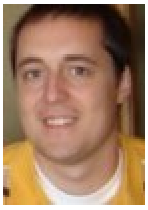

Dr. Thomas Stout received his Ph.D. in Computer Engineering from North Carolina State University in 2015. He has been employed by Evatran Group, Inc. since 2012. He is currently the principal engineer and system architect for their vehicle wireless charging systems. In this role he leads the research and development activities for technologies related to wireless charging and the development of commercial wireless charging systems.