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New approach of ultrasonic sensor system in inductive charging infrastructure for living object protection

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Abstract

This paper proposes an ultrasonic-based sensor system integrated into the inductive charging base pad for monitoring the edges of the vehicle's protection area so that the charging system can be switched off immediately if a foreign object penetrates the air gap. Further, signal processing techniques for surmounting the challenges resulting from the sensor application under the vehicle are presented. By eliminating the unintentional influences resulting from the vehicle's underbody, this system is able to detect foreign objects penetrating the zone between the charging coils. The provided object localization algorithms also allow to adjust the protection area size as well as to estimate the direction from which the object approaches.

Keywords: inductive charging, foreign object detection, living object protection

1 Introduction

Wireless charging is regarded as the most promising technology for automatic and convenient charging of electric vehicles in (semi-)public areas and it is developed for almost 20 years [1]. The alternating magnetic field produced for energy transfer has to pass through a large air gap between the wireless charging coils. Because foreign objects can access the air gap easily, the charging system requires additional sensors to prevent endangered objects from being exposed to the magnetic field.
This paper proposes an ultrasonic sensor system to protect living objects. This new approach exploits that the base pad containing the primary coil can be equipped with ultrasonic sensors easily. The next section presents the requirements and the proposed system concept. After that, a proof of concept for the background subtraction algorithm is shown before the following section presents measurement results for the localization of foreign objects.

2 Requirements and system concept

Especially in (semi-)public areas, various foreign objects might penetrate the air gap between the charging coils. To prevent consequential damages, the charging system has to be switched off immediately when foreign objects are detected inside of the protection area. Due to practical reasons, possible foreign objects are distinguished between metal and living objects, which is illustrated in figure 1.

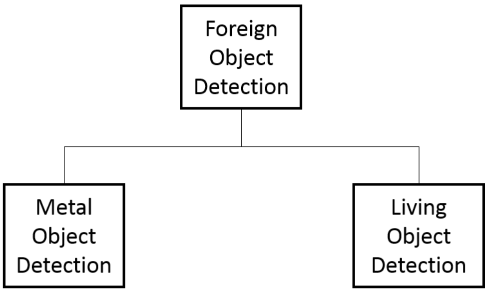


Figure 1: Distinction between metal and living object protection

Eddy currents induced by the magnetic field heat up metallic objects, such as screws or coins. As this may be dangerous for other objects in the surrounding area or the charging system itself, the charging process must be stopped immediately. There already exist several approaches to detect metal objects by measuring impedance changes using separate sensor coils or the temperature rise of the metal object itself [2, 3]. As this detection principle cannot be applied to living objects, there is a demand for other approaches for living object detection.
The International Commission on Non-Ionizing Radiation Protection (ICNIRP) published guidelines concerning the radiation safety of living objects [4]. These guidelines provide reference levels for the magnetic field strength which have to be met by an inductive charging system. The part of the radiation zone where the reference levels are not met has to be monitored to prevent endangered objects from being exposed. The properties of the protection area are further defined by DKE and SAE [5, 6].
The proposed approach uses ultrasonic sensors for monitoring the protection area edges. This enables the charging system to switch off immediately if living objects enter the area between the charging coils. Figure 2 illustrates the system setup which has been implemented prototypically.

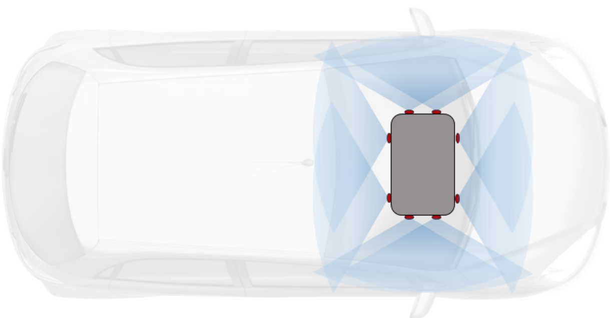


Figure 2: System setup with eight ultrasonic sensors integrated into base pad below an electric vehicle

It can be observed that eight ultrasonic sensors are integrated into the base pad housing. Their radiation direction faces away from the charging coils which makes them capable of detecting approaching objects. The usage of two ultrasonic sensors for each base pad edge allows a protection area definition with variable size as well as the localization of approaching objects. Additional benefits of ultrasonic sensors include that they are affordable, robust against dirt and environmental factors, and they are already used in automotive industry.

3 Proof of concept

Ultrasonic sensors carry out time-of-flight measurements to determine the distance of reflecting objects. Operating the sensor under vehicles, a lot of static reflections are produced by the vehicle underbody and the wheels. This section presents an algorithm to eliminate the influences of this static background affecting the measurement signals, which has been developed in [7].

3.1 Background subtraction

Before presenting measurement results, this section serves to illustrate the principles of background subtraction and object detection. Figure 3 depicts the signal flow diagram describing the signal processing.

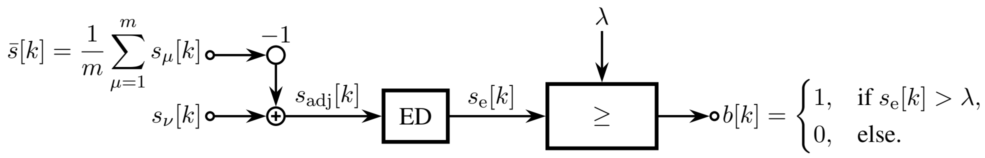
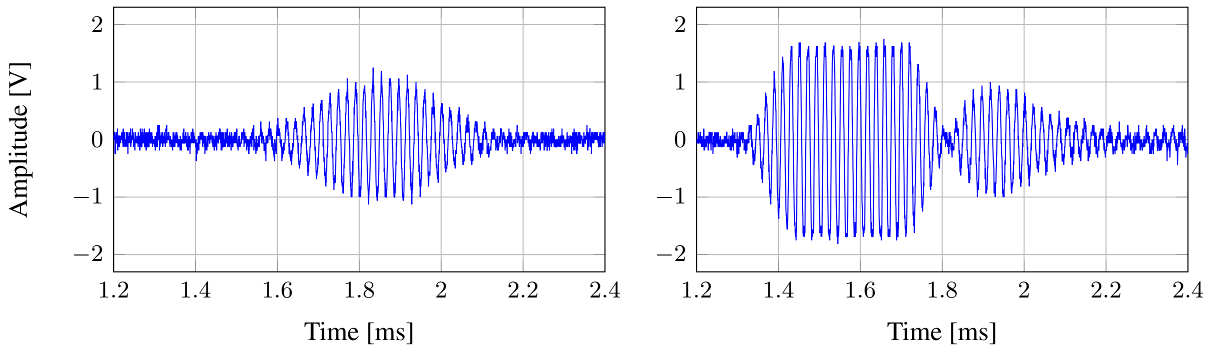


Figure 3: Signal flow diagram of background subtraction algorithm with $\nu > m$ and object detection

The first m measurements are used to record the background signal $\bar{s}[k]$ by computing the average signal. Note that the scenario is supposed to be static and no foreign objects are inside of the protection area during these measurements. This background is then subtracted from each receive signal of the following measurements $s_\nu[k]$ resulting in an adjusted receive signal $s_{adj}[k]$. To obtain information about the reflection strength, an envelope detection (ED) is carried out resulting in a signal $s_e[k]$ that contains the envelope of $s_{adj}[k]$. Consequently, $s_e[k]$ is compared to a constant threshold λ and it is received a binary signal $b[k]$ that entails data for a time of flight measurement [8].

3.2 Foreign object detection with background subtraction

The principle of background subtraction is applied to real measurements carried out using a prototypical system setup consisting of a base pad containing the ultrasonic sensors and a plain aluminum plate as an idealized underbody. Figure 4 shows the raw data of receive signals for different scenarios.

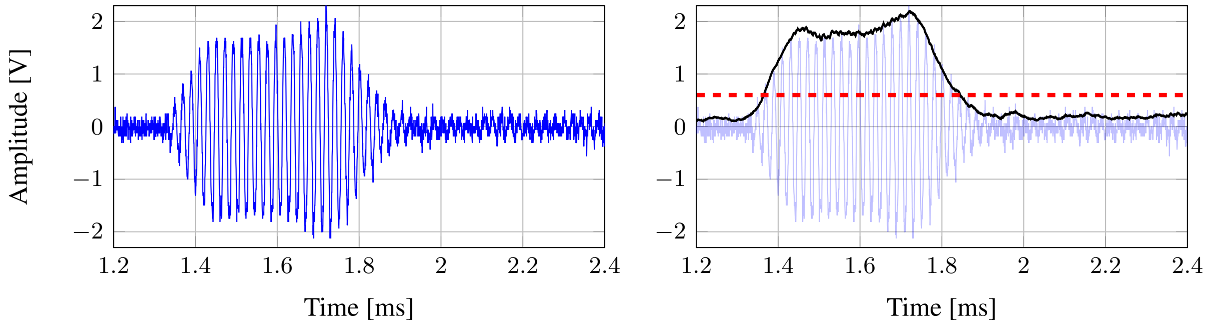


(a) Background measurement without foreign object (b) Measurement with foreign object

Figure 4: Receive signal raw data for measurements of different scenarios

The receive signal of both a measurement with and without a foreign object inside of the air gap is depicted in figures 4a and 4b, respectively. It can be observed that the background reflection cancels the reflections evoked by the foreign object at a distance corresponding to a time-of-flight of about $1.8\,\text{ms}$.

This effect is unwanted and can be avoided by applying background subtraction before carrying out the envelope detection. Therefor, the first measurement can be used as background signal $\bar{s}[k]$.
The corresponding signals after signal processing are illustrated in figure 5. Based on the adjusted receive



(a) Adjusted signal $s_{\mathrm{adj}}[k]$ after background subtraction (b) Envelope of adjusted signal $s_{\mathrm{e}}[k]$ and threshold

Figure 5: Signal processing with background subtraction and envelope detection

signal $s_{\mathrm{adj}}[k]$ depicted in figure 5a, it can be observed that the reflection of the background vanished and those of the foreign object is still present. Thus, the background subtraction allows a reliable elimination of the background's influences on the measurement signal before carrying out the object detection. Figure 5b depicts $s_{\mathrm{e}}[k]$ after envelope detection in black. Comparing this envelope with a constant threshold λ, which is depicted in red, the conventional time-of-flight measurement can be carried out.

4 Localization by using multilateration

The previous section showed that the background subtraction can be used to eliminate the background's influences on the measurement signals allowing a robust distance determination of approaching living objects. As it is illustrated in the proposed system setup in figure 2, each edge of the basepad is equipped with two ultrasonic sensors. This allows an application of multilateration techniques to estimate also the position of foreign objects inside of the protection area [7].

4.1 Localization principle

The localization principle using two ultrasonic sensors is based on the multilateration technique, which is illustrated in figure 6.

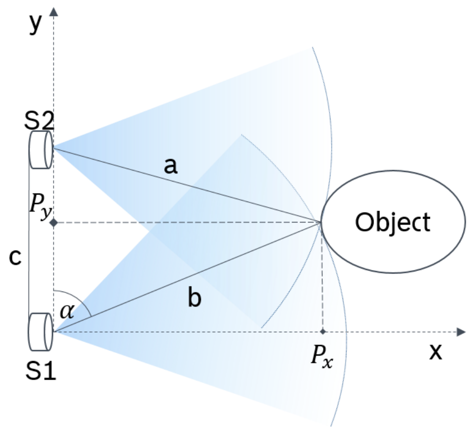


Figure 6: Multilateration technique using two ultrasonic sensors S1 and S2

The ultrasonic sensors S1 and S2 are placed at the basepad edges having a distance of $c = 13.5\,\mathrm{cm}$ at the narrow edges. The distances a and b are delivered by measurements of S1 and S2, respectively. Knowing all distances a, b, and c, the foreign object's position relative to the base pad can be computed using basic trigonometric identities.

4.2 Measurement results

Using the localization principle presented in the previous section, measurements have been carried out. For practical reasons, a beverage can is used for the measurements due to its characteristics that are favorable with respect to symmetry and reflectivity. Figure 7 depicts the original position of the beverage can and its determined one using the time-of-flight measurements of the ultrasonic sensor system.

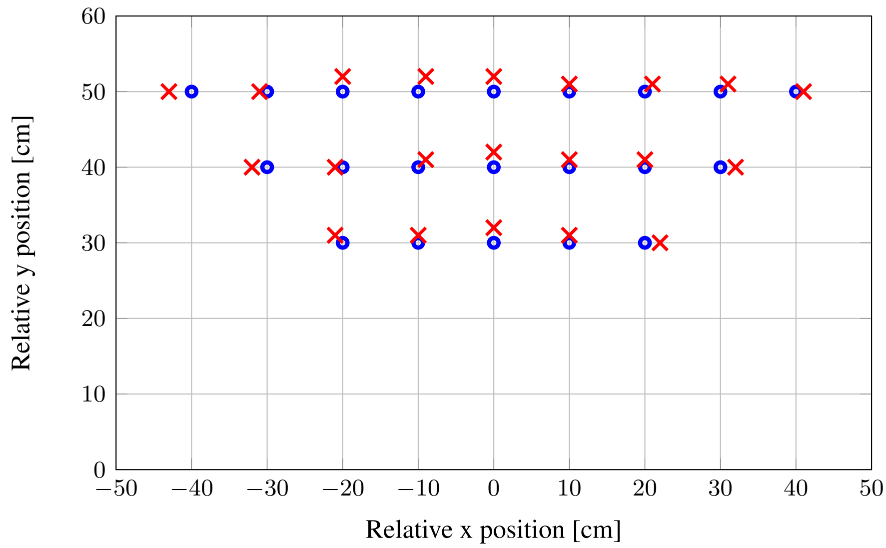


Figure 7: Measurements with original and estimated positions of the foreign object in blue and red, respectively

As the ultrasonic sensors are placed in the origin of the coordinate system, the beverage can's position relative to the base pad of the inductive charging system can be observed on x and y axis. A measurement is carried out for each position on the grid. The foreign object's position determined using the time-of-flight measurements of the ultrasonic sensors is depicted in red. It can be observed that this position complies approximately with the original object position, which is depicted in blue. Consequently, the object localization using multilateration techniques provides satisfying results within the desired range of accuracy.

5 Conclusion and Outlook

This paper proposes a new approach for protecting living objects in inductive charging using ultrasonic sensors on the infrastructure side. Furthermore, a background subtraction method is carried out to eliminate the spurious echoes from each measurement data computationally. This enables the algorithm to detect foreign objects entering the air gap under the vehicle such that the charging system can be switched off. Additionally, the object positions are computed by using multilateration techniques. The results are shown in a two-dimensional coordinate system relative to the base pad. In summary, this paper shows that living object protection using ultrasonic sensors is feasible.

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Martin Paridon was born in Waiblingen and studied Industrial Engineering at Hof University from where he received his B.Eng. in 2015. Since then, he has been studying Mechatronics at Reutlingen University. Since Autumn 2016 he is writing his Master’s thesis at Corporate Sector Research and Advance Engineering of Robert Bosch GmbH in Renningen about an ultrasonic sensor system for living object protection.

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