A Driver Guidance System to Support the Stationary Wireless Charging of Electric Vehicles

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Abstract. Air pollution is a problem in many cities. Although it is possible to mitigate this problem by replacing combustion with electric engines, at the time of writing, electric vehicles are still a rarity in European cities. Reasons for not buying an electric vehicle are not only the high purchase costs but also the uncomfortable initiation of the charging process. A more convenient alternative is wireless charging, which is enabled by integrating an induction plate into the floor and installing a charging interface at the vehicle. To maximize efficiency, the vehicle's charging interface must be positioned accurately above the induction plate which is integrated into the floor. Since the driver cannot perceive the region below the vehicle, it is difficult to precisely align the position of the charging interface by maneuvering the vehicle. In this paper, we first discuss the requirements for driver guidance systems that help drivers to accurately position their vehicle and thus, enables them to maximize the charging efficiency. Thereafter, we present a prototypical implementation of such a system. To minimize the deployment cost for charging station operators, our prototype uses an inexpensive off-the-shelf camera system to localize the vehicles that are approaching the station. To simplify the retrofitting of existing vehicles, the prototype uses a smartphone app to generate navigation visualizations. To validate the approach, we present experiments indicating that, despite its low cost, the prototype can technically achieve the necessary precision.

Keywords: Human-computer interaction · Visualization · Computer vision · Pose estimation · Driver guidance

1 Introduction

Electric vehicles can help to reduce air pollution in cities. Although many governments subsidize electric vehicles, they are not often bought. The reasons for this are, besides the high purchase costs, the short-range due to the battery capacity and the necessary planning of the charging intervals. For a vehicle to be charged, it must be manually connected to the charging station. This requires the driver to get out of the vehicle and physically connect the car to a charging station,

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which can be tedious. Wireless charging can help to make the process more comfortable but requires additional charging components. As described in [20], an induction plate is typically integrated into the floor and a compatible charging interface is installed on a vehicle's underbody. To maximize the efficiency of the charging process, the charging components must be accurately aligned [6]. This includes that the air gap between the charging components does not exceed a certain threshold. Moreover, there is the problem that both charging components must be aligned by moving the vehicle into the correct position. In terms of precision, the vehicle must be positioned an order of magnitude more accurate than it is required for parking. It is difficult for a driver to accurately align the charging components because they are out of the driver's field of vision. In [2], two studies show that only 5% of the vehicles were positioned precisely enough to enable efficient wireless charging. To mitigate the problem, a driver guidance system can be used to support the driver when positioning the vehicle. In this paper, we discuss the requirements for driver guidance systems to enable efficient wireless charging. We present a prototype that extends a wireless charging station with an inexpensive off-the-shelf camera system to determine the position of a nearby vehicle. Furthermore, we use a smartphone app to minimize the vehicle's retrofitting effort which visualizes supportive feedback inside of the car. A wireless charging station is being deployed as part of the TALAKO-project ("Taxi Charging Concept for Public Spaces") [1]. Since the construction work has not yet been completed, we validate the precision and usability of the prototype from a technical point of view. As soon as the charging station has been built, we will analyze whether our driver guidance system is also suitable for practical use under real conditions.

2 Wireless Charging

Wired charging of an electric vehicle encompasses several steps. The driver must park, get out of the vehicle, and use a cable to establish a physical connection between the car and the charging station. For this, a parking lot with a charging station is needed. In contrast to most gas stations, many charging stations do not have a roof to protect the driver from environmental influences such as rain or snow, which can make wired charging in bad weather a cumbersome experience. When charging wirelessly, the driver does not have to get out of the car. This means that exposition to environmental influences is comparable to regular parking and the driver can save the time that would be required to initialize the charging process. A wireless charger for electric vehicles consists of a transmitting coil and a receiving coil, compensation network, and power electronics converters [15]. Since electric vehicles and charging stations produced by many manufacturers do not support wireless charging, retrofitting may be necessary. To quickly charge vehicles, high field strengths are needed, which can be dangerous [10]. To mitigate this problem, the transmitter coil is usually integrated into the floor and the receiver coil is attached to the underbody of the vehicle. This way, the chassis can shield nearby persons from most of the radiation.

Efficient wireless charging can only take place if the vehicle's charging interface is precisely aligned above the induction plate that is integrated into the floor. To do this, the driver must maneuver the vehicle manually into an appropriate position. In comparison to regular parking, this is more complicated, because the charging interface is located under the vehicle and thus out of the driver's field of vision. When parking, it is usually sufficient to achieve a positioning accuracy in the range of a few decimeters. For efficient wireless charging, the required accuracy is in the range of a few centimeters and thus, an order of magnitude higher. It is unlikely that drivers can achieve this without further support. Thus, a driver guidance system becomes a fundamental prerequisite to enable the efficient wireless charging of electric vehicles.

3 Requirements for Driver Guidance Systems

The goal is to enable the driver to precisely align the charging interface of the vehicle above the plate that is integrated into the floor. Various approaches could be taken to reach this goal. For example, markings on the ground could be used, which can serve as an orientation during the positioning. Moreover, parking stoppers that protrude from the floor can serve as physical limitations. Alternatively, mechanical systems can be used, which automatically bring both charging components into an aligned position. The problem of markers and parking stoppers is that they are not applicable when multiple vehicle types with various dimensions should be charged. A dimension specific marker- or parking stopper setup for each vehicle type would be required. In addition, the driver's sitting position and vehicle's dimensions differ, there is no guarantee that the markings will be fully visible from the driver's perspective. Dirt or changing weather conditions such as rain or snow might also influence the visibility of the markings. On the one hand, the parking stoppers' advantage is that they are usually more visible than markings and are not quickly covered by dirt or snow because they protrude from the ground. Yet, parking stoppers can cause injuries if people trip over them. The advantage of a mechanical system is that it can be used for different types of vehicles, for example by using multiple configurations. However, buying and installing a mechanical system is expensive. In addition, complicated maintenance work may be required since vandalism or street cleaning can cause damage if, for example, parts protrude from the floor. If several vehicle types should be supported and expensive mechanical systems are to be avoided, an orientation system is required to help the driver to align the charging components. The driver cannot achieve this accuracy without any guidance. Therefore, we derive the following requirements for a driver guidance system to support wireless charging of electric vehicles:

Generic. The dimensions of vehicles can vary depending on the vehicle type. Moreover, the position of the charging interface can be attached to various positions on the underbody of the vehicle. It is necessary that the driver guidance system can be used independently of these properties so that ideally all drivers can be supported.

Cost Efficient. Adjustments of existing components or the installation of new components for driver guidance can be expensive. Hence it is necessary to minimize the number of components required to realize the system and to rely on off-the-shelf components, if possible.

Robust. Since it is difficult for a driver to properly align the charging interface by maneuvering the car, the driver guidance system is a critical part of the charging station whose down times severely affect the station's availability. As a result, it is necessary to ensure that the system is robust with respect to external factors such as vandalism or bad weather and that it relies on components that do not induce additional maintenance effort.

Precise. Efficient wireless charging can only take place, if the charging interface of the electric vehicle is aligned accurately over the induction plate which is integrated into the floor. Although, the acceptable tolerances may vary depending on the coil configuration, the accuracy requirements of current systems usually range around 10 cm.

Usable. Ideally, using the driver guidance system to initiate the charging process should be as convenient and quick as parking a vehicle with an internal combustion engine. In addition, the interactions with the driver guidance system should not distract the driver.

4 Prototype

In the following, we present a prototype for a driver guidance system that we developed based on the requirements described previously. First, we motivate the system architecture and then discuss the individual system components. An overview of the architecture is depicted in Fig. 1.

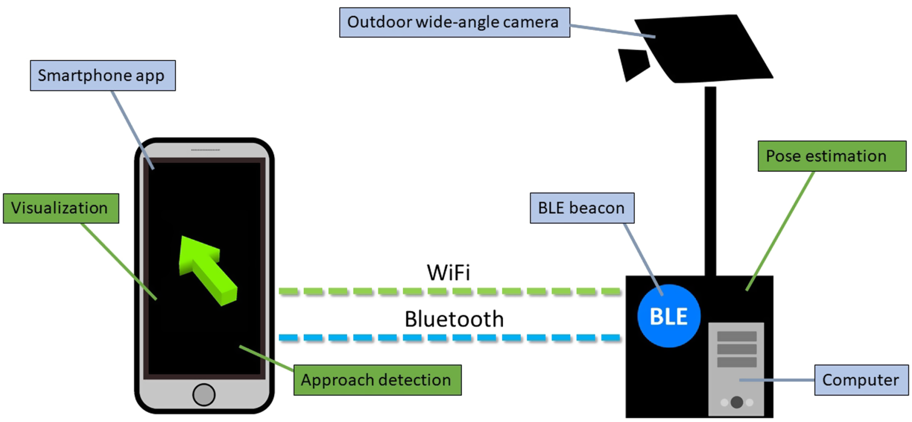


Fig. 1. Architecture of the driver guidance system. Blue squares indicate components and green squares indicate their primary functions. (Color figure online)

4.1 System Architecture

To automatically assist a driver in the alignment process, the relative position of the charging plate integrated into the floor and the charging interface installed on the underbody of the vehicle must be determined. This requires a positioning mechanism. Based on the determined positions, the driver must be informed about the current positioning situation so that the driver can counteract if misalignments occur. There are various technologies with which positioning can be carried out, such as GPS (Global Positioning System) or RFID (Radio-frequency identification). We use a camera because high accuracy can be achieved if the resolution of the captured images is sufficiently high. Cameras are inexpensive and do not require maintenance. Moreover, due to their ubiquitous use in surveillance applications, ruggedized variants, that are weather- and vandal-proof are widely available. Conceptually, there are two ways to attach the camera. The camera can either be mounted on the vehicle or attached to the charging station. When attaching a camera to a vehicle several issues must be addressed. First, without further precautions, the camera can become dirty while driving. Also, the induction plate is only visible when the camera is pointed at it. For this reason, multiple cameras may be required to be installed around the vehicle, which can lead to higher costs. If the location of the induction plate is visually not differing from the surrounding floor, additional markings may be required on it. To avoid the issues resulting from a vehicle integration and to minimize the cost, our system extends the charging station with a single wide-angle camera. To minimize the effect of environmental factors, we use a ruggedized and weather-proof case and propose to mount the camera at the top of the station so that it cannot be manipulated easily by people that are passing by. Besides from increasing the robustness, this mounting position also ensures that the

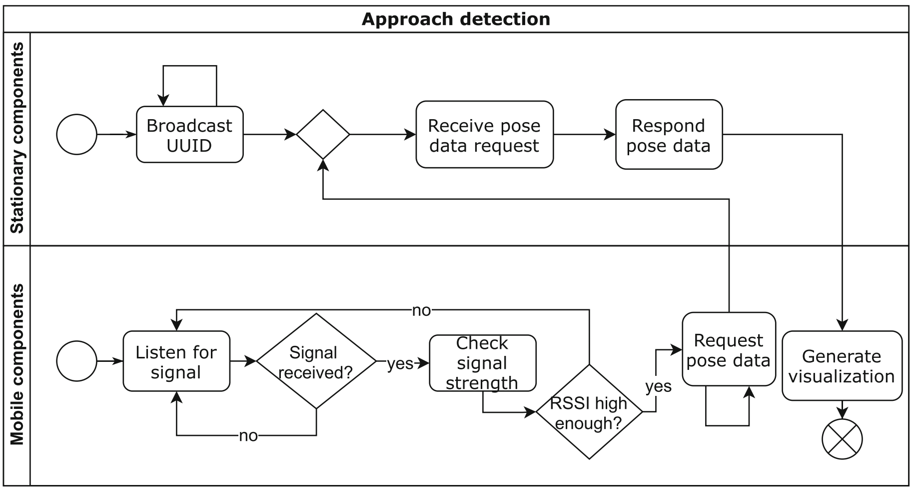


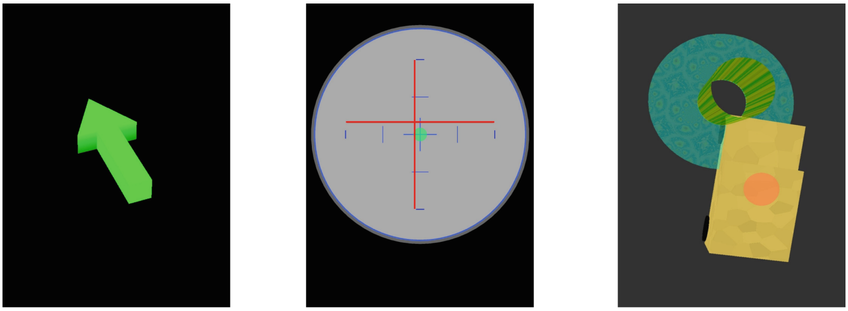
Fig. 2. Abstract overview of the approach detection process.

camera can easily detect vehicles that are approaching. Like the camera setup, there are also many possibilities to provide the driver with feedback on the current positioning situation. As with the positioning system, we pay attention to the aspect of cost-efficiency. Instead of integrating additional components into the vehicle, we propose to use a smartphone app to generate feedback for the driver using visualizations. In terms of usability, there is also the advantage that most drivers can already operate a smartphone and do not need to acclimate to new hardware devices. However, due to this combination of decisions, we have a distributed system design where the location detected by the camera on the charging station must be transmitted to the smartphone of the driver. To do this, it is necessary to establish a connection between the camera system and the smartphone app. Since this connection must be reliable and exhibit a low latency, our system does not use the cellular network but instead relies on a WiFi connection that is established, when the car approaches the station. To ensure that the driver does not have to interact with the phone while driving, our prototype fully automates the setup process.

4.2 Mobile Components

One of the two primary functions of the smartphone app is an approach detection mechanism. It automatically recognizes via a background service whether the vehicle is near the charging station to start the driver guidance. An overview of the procedure is illustrated in Fig. 2. A separate BLE (Bluetooth Low Energy) beacon in the camera system continuously broadcasts a signal with a charging station specific UUID (Universally Unique Identifier). At the same time, a background process of the smartphone app listens to whether a nearby charging station is sending a signal. If a signal is received, it is checked whether the RSSI (Received Signal Strength Indicator) has reached a certain threshold, which means that the vehicle is close enough to the charging station. Subsequently, after a WiFi connection is established, the positioning information is continuously requested to generate driver feedback.

Driver feedback is generated by displaying visualizations. In our current prototype, the driver can select from three different types, an arrow-visualization, a radar visualization, and a three-dimensional birds-eye view visualization. Arrows are minimalistic and well-known symbols. In most contexts, they are utilized to indicate the relative location of a specific object. We use a three-dimensional arrow visualization as illustrated in Fig. 3a to communicate various information. The direction where the arrow points to symbolizes the direction to be driven. The size of the arrow automatically changes according to the distance to the target. The closer the target is, the smaller the arrow gets and vice versa. The color of the arrow also symbolizes whether the driver is approaching the target. For this, we use a linear color encoding scale between red and green. As usual in other contexts, green symbolizes the right and red the wrong behavior. Moreover, our prototype provides a radar-like visualization inspired by an aircraft's primary flight display. Example screenshots are shown in Fig. 3b. There is a circular area with various distance markings and two moving red lines. The horizontal line symbolizes the distance from the vehicle's charging interface to the induction plate which is integrated into the floor. The vertical line shows the offset in the left or right direction. The goal of the driver is to arrange both lines as centrally as possible in the middle of the circle so that they cross in the green area. Our third visualization imitates the positioning area from a birds-eye view using 3D graphics. The amount of information presented has been reduced to the bare minimum. An example is shown in Fig. 3c. The location of the induction plate is indicated by a hollow cylinder, which is also delimited by a circular area. There is a circle on the vehicle that symbolizes the location of the vehicle's charging interface. The charging components are aligned if the vehicle's circle is completely inside the induction plate's hollow cylinder. To increase the level of detail, there is the possibility to change the zoom level.



(a) Arrow visualization (b) Radar visualization (c) 3D visualization

Fig. 3. Driver feedback visualizations. (Color figure online)

4.3 Stationary Components

Our camera system is composed of a ruggedized outdoor wide-angle camera that is connected to a computer, and a separate BLE beacon for the approach detection mechanism. The camera is installed at the charging station so that at least the entire positioning area can be recorded. In this way, the vehicle can already be perceived when it is several meters away from the induction plate. The captured images are retrieved by a computer vision software which is implemented using OpenCV [11] to estimate the pose of the electric vehicle. We define the pose as the three-dimensional rotation and the translation relative to the camera's position. Some preparation steps are necessary for this. The camera needs to be calibrated by determining the camera matrix and the distortion coefficients so that the recorded frames can be undistorted. Besides, the position of the induction plate, which is integrated into the floor, must be specified. Moreover, vehicle type-specific dimensions, as well as the relative offset from the car's origin of the receiver coil must be specified. Given this configuration, the steps to estimate the pose are:

Preprocessing. The image is undistorted, and it is semantically divided into foreground and background using Background Subtraction [21]. We assume that the probability is high that vehicles get classified as part of the foreground. The remaining computations are then solely performed on the foreground image.

Estimation. The vehicle's pose is determined using a wheel detection algorithm, which detects the wheels of the vehicle based on their circular shape, as illustrated in Fig. 4a. At the beginning various filters are applied to reduce noise in the image. Then the Hough circle transformation [13] is utilized to find circles that represent the wheels. To filter false positives, we reject circles that are outside of reasonable limits. Then four points of a resulting wheel pair are used to compute the object pose from 3D-2D point correspondences, using infinitesimal plane-based pose estimation [4].

Aggregation. For post-processing, we use a Kalman-filter [19], which takes past poses into account and helps to compensate strongly deviating poses. When aggregation step finishes the last computed result is continuously provided via WiFi on a REST interface so that it can be retrieved by the smartphone app.

(a) Wheels detected by Wheel Detection Estimator.

(b) ArUco markers detected by Marker-based Estimator.

Fig. 4. Illustration of the techniques being applied to estimate the pose.

5 Validation

The design of our prototype system described in the previous section is geared towards achieving a low cost and a high robustness. For the latter, we refrain from requiring any mechanical components and instead leverage a camera system that is mounted on the station. For the former, we do not require any components to be installed in the car and we solely rely on a single off-the-shelf camera with an associated computer and a BLE beacon. Given a configuration of different car models with their position of wireless charging interfaces, it is also trivial to achieve the desired genericity. To rigorously evaluate the usability and precision, measurements must be carried out under real conditions. As part of the TALAKO-project, we are deploying a wireless charging station that will be tested under realistic conditions by taxi drivers. However, since the construction work is still ongoing, we present an experimental validation which indicates that the system can achieve the necessary precision and usability from a technical point of view.

5.1 Precision

In this section, we experimentally investigate whether the precision of the camera system's pose estimation technically fulfills the precision requirement. To put the results in perspective, we compare the pose estimation through wheel detection with pose estimation based on a board of five ArUco [7] markers depicted in Fig. 4b. ArUco markers are specifically designed to facilitate a fast and precise detection, however, due to esthetic reasons, we think that they are ill-suited for practical deployments. To achieve natural illumination and reflections, the experiment is conducted in an outdoor parking area. An illustration of the experimental setup is presented in Fig. 5. For the experiment the vehicle, which is illustrated in Fig. 4, is positioned sideways at the angles of 0° and 10° at the distances of 3, 4, and 5 m in front of the system's camera. A marker board composed of five ArUco markers with different IDs each having a side length of 15 cm is being attached to the vehicle, as illustrated in Fig. 4a. A video with a resolution of 1280×720 is recorded for each pose, of which 30 images are used by the background subtractor and 20 frames are forwarded to the pose estimators to determine the distance as well as the rotation of the vehicle. We examine the Wheel Detection Estimator as well as the Marker-based Estimator which is utilizing the entire marker board as well as using the single markers individually. Table 1 shows how accurate the estimators can detect the wheels and the markers, and Fig. 6 visualizes the error in estimating the pose by each estimator. The marker board and its individual markers are found in almost all cases, but inaccurately recognized corner points lead to imprecise pose estimation. Reasons for the inaccurate detection of the corner points can be the marker size which might be too small, as well as the resolution of the recorded frames, which might be too low. Although the measurements of the Marker-based Estimator exhibit a low precision, the marker detection works consistently, even when the vehicle's rotation changes. Using bigger markers might increase the precision, but at the same time further reduces their practical applicability. In contrast to the markers, the wheels can be detected in 75.8% of all frames. In the case of the experiment at 3 m distance and 10° of rotation, no wheels were detected

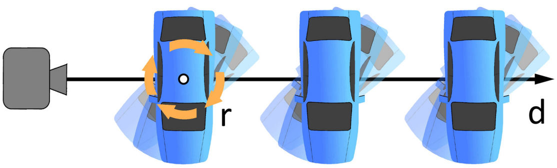


Fig. 5. Illustration of the pose estimation experiment setup.

on any frame, and therefore no pose was estimated. Due to the rotation of the vehicle, the circular shape of the wheels is distorted so that the wheels cannot be identified as circles by the Hough Circle Transform. However, when wheels are detected, the Wheel Detection Estimator can deliver a precision that meets our 10 cm requirement in most of the cases.

Table 1. Accuracy of the wheel and the marker detection. We describe the distance and rotation of the vehicle in the notation of ⟨distance⟩m ⟨rotation⟩°, e.g. 3 m 10°, meaning a distance of 3 m and a rotation of 10°.

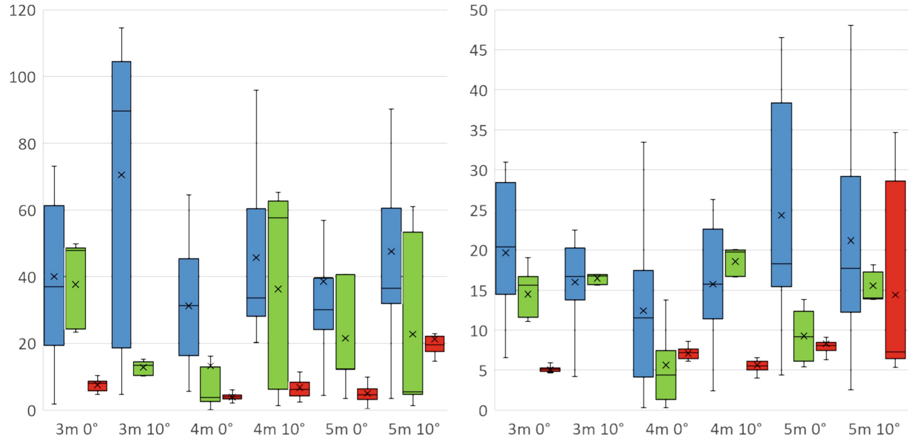
	3 m 0°	3 m 10°	4 m 0°	4 m 10°	5 m 0°	5 m 10°	∅
Marker Board	100%	100%	100%	100%	100%	100%	100%
Single Marker	100%	100%	100%	100%	100%	99%	99.8%
Wheel Detection	100%	0%	95%	80%	100%	80%	75.8%

5.2 Usability

To ensure that the system's usability is not prevented by technical limitations, it is necessary that the driver guidance is activated in a timely manner, so that driver can be supported when approaching. To validate this, we analyze the required time in the approach detection until the smartphone can retrieve the positioning information from the camera system. When entering the Bluetooth range of a BLE Beacon, it takes between 7 and 12 s for a Samsung Galaxy S7 Edge to detect the BLE advertisement and report it to the application. It takes approximately 5 s to establish the WiFi connection, which means that a total time of 12 to 17 s is required. Assuming the vehicle is approaching at a moderate speed, the overall time is acceptable. When the connection is established, it is also ideal if there is no perceivable latency in the driver feedback. We therefore analyze the update rate at which the positioning information is provided by the camera system. Our prototype system is installed on a Dell G7 Laptop with an Intel Core i7-9750H CPU and 16 GB RAM. We measure the sliding average of frames per second for a minute that will be processed and the average over the whole experiment. The resolution of the image data is 1920×1080. When executing the pose estimation the system can process approximately 7–8 frames per second. We would argue that this is sufficient because a driver's reaction time is in the range of 200–300. As a result, we would assume that the driver will usually not maneuver at a speed that would require more than a couple of frames per second.

6 Related Work

There are two categories of wireless charging, stationary as described in this paper or dynamic, whereby a vehicle is charged while it is in motion. To solve the



(a) Distance error in centimeters (b) Rotation error in degrees

Fig. 6. Box plots that visualize the error, which is the difference between the ground truth and the measurement achieved by each pose estimator. The whiskers represent the maximum and minimum values and the colored boxes show the first and third quartile. The cross stands for the average error and the horizontal bar indicates the median. Blue: Single markers; Green: Marker board; Red: Wheel Detection; (Color figure online)

misalignment problem with dynamic charging, there is a camera-based system in [14], which uses computer vision to recognize the deviation from the charging route and visualizes it to the user. An alternative approach is presented in [9], in which lateral misalignments are recognized by voltage differences, whereupon steering commands are generated for the electric power steering system to control the lateral position of the vehicle. In addition to the lateral position alignment, the air gap between the charging components is also relevant for efficient charging. For this purpose, a mechanical positioning mechanism is presented in [12] which can adjust the distance between the charging components. There are also approaches for stationary charging that use mechanical systems to adjust the position of the charging components. In [18] the misalignment of both coils is determined using wireless sensors, whereupon an electromechanical system automatically adjusts the position of the coil which is integrated into the floor. There are approaches for stationary charging that enable positioning for short distances using RFID [17] or magnetic systems [5] or combine both [3]. However, in addition to RFID, [8] also installs a camera on the vehicle to enable positioning from further distances, to visualize based on the current driving situation an optimal trajectory. In contrast to the approaches that use several hardware components for positioning, we use exactly one camera to save costs. Furthermore, the camera is installed on the charging station and not on the vehicle because we want to avoid vehicle-specific integration efforts.

7 Conclusion

At the present time, most electric vehicles are charged with a cable, which can be tedious. Wireless charging can help to make charging of electric vehicles more comfortable. Without any guidance, it is difficult for drivers to align the charging components accurately. In this paper, we discussed the requirements that a driver guidance system should meet to support the efficient wireless charging of electric vehicles. Based on these requirements, we presented a prototype, that utilizes a camera system to estimate the pose of a vehicle which in turn is used to generate visual feedback on the driver's smartphone. As indicated by our experimental validation, this system can achieve the requirements for such driver guidance systems from a technical point of view.

At the present time, we are deploying a wireless charging station as part of the TALAKO-project. Once the construction is completed, we will be thoroughly evaluating the overall usability system under realistic conditions with several taxi drivers. In the meantime, we will continue to improve the robustness of the system, e.g. by extending the wheel detection algorithm to support ellipses [16]. In addition, we are working on additional visualizations that augment the images taken by the camera with instructions for the driver.

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