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# Modular, Vision-Based Control of Automated Charging Systems for Electric Vehicles

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**Abstract:** Contemporary vehicle fleets include a variety of both manually and automated operated vehicles. A significant shift involves the increasing use of electric powertrains. However, the current electric charging infrastructure predominantly relies on manual processes. There is an opportunity to automate the charging process for these cars, with the intent to enhance convenience, aid people with accessibility needs, to support MW charging where EV cables are heavy, and finally to enable autonomous driving. The charging standards are common but the mechanisms to access the charging ports are not i.e., lids and protectives. This could be a challenge in the automation process given the complexity of the manipulation task at hand. With the increasing variety of electric vehicle models, standardizing charging mechanisms becomes imperative to streamline the charging process and enable broader adoption. In summary, this paper presents a holistic approach to addressing the evolving needs of electric vehicle charging infrastructure, emphasizing the importance of automation in enabling efficient, accessible, and future-ready charging solutions.

**Keywords:** automated charging system; charging infrastructure; charging technology; electric fleet solutions; electro-mobility; megawatt charging; plug-and-charge

## 1 INTRODUCTION

Electrifying transportation has become a critical strategy for mitigating climate change and reducing dependence on fossil fuels. In this development, automated charging systems for electric vehicles (EVs) play an important role in improving comfort, efficiency and autonomous processes. The vast majority of vehicles registered today have a conductive side coupling system [1]. The approach taken here is complete automation of the charging process by use of the standardized interfaces, based on previously carried out research [2]. The use of modular, vision-based control systems promises positive prospects for improving the charging infrastructure ecosystem for certain applications, be it charging commercial vehicle fleets, industrial vehicles or passenger cars. Fig. 1 shows the prototype automated charging system including standardized CCS connector, sensors and actuators and lighting system.

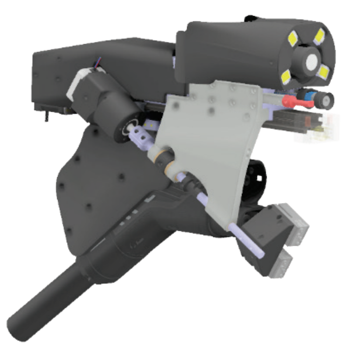

**Figure 1** ACCS modular end-effector

The aim of this paper is to investigate and analyse the application of modular vision-based systems in the context of automated charging for electric vehicles. By using a wide range of sensors and intelligent control algorithms, these systems offer the potential to optimize charging processes and improve the user experience. It also enables easier access to e-mobility, for example for people with disabilities who may have difficulties with the current charging infrastructure.

In the first section, the key components, functionalities and operating principles are introduced and their roles in charging infrastructure are elaborated. In addition, the performance characteristics, advantages and limitations of these systems are examined in various real-world scenarios ranging from indoor charging facilities to outdoor environments with different lighting conditions. Through empirical evaluations, valuable insights are provided into effectiveness, reliability and adaptability. In addition, the effects of research findings on the further development of electromobility are discussed as well as innovation and optimization potential are illustrated in view of future development of the charging infrastructure.

### 1.1 Abbreviations

**Table 1** Abbreviations

| Abbreviation | Meaning |
| --- | --- |
| ACCS | Automated Conductive Charging System |
| CAD | Computer Aided Design |
| CCS | Combined Charging System |
| DC | Direct current |
| EV | Electric Vehicle |
| EVSE | Electrical Vehicle Supply Equipment |
| LIDAR | Light Detection and Ranging |
| ToF | Time of Flight |
| VSC | Vehicle Side Coupler |
| VW | Volkswagen |

## 2 METHODS AND KEY RESULTS

Based on process- and design analyses of a pre-defined electric vehicle fleet of five mass production cars that were different in their design of the charging port, a robotic system was developed that completely automates the charging process. Laser scans, CAD space analyses and sensor tests were carried out to find a suitable setup. The process analysis has shown that the critical process steps are strongly related to the quality of image recognition. Based on experiments, Tab. 2 provides an overview of the current assessment of individual process steps.

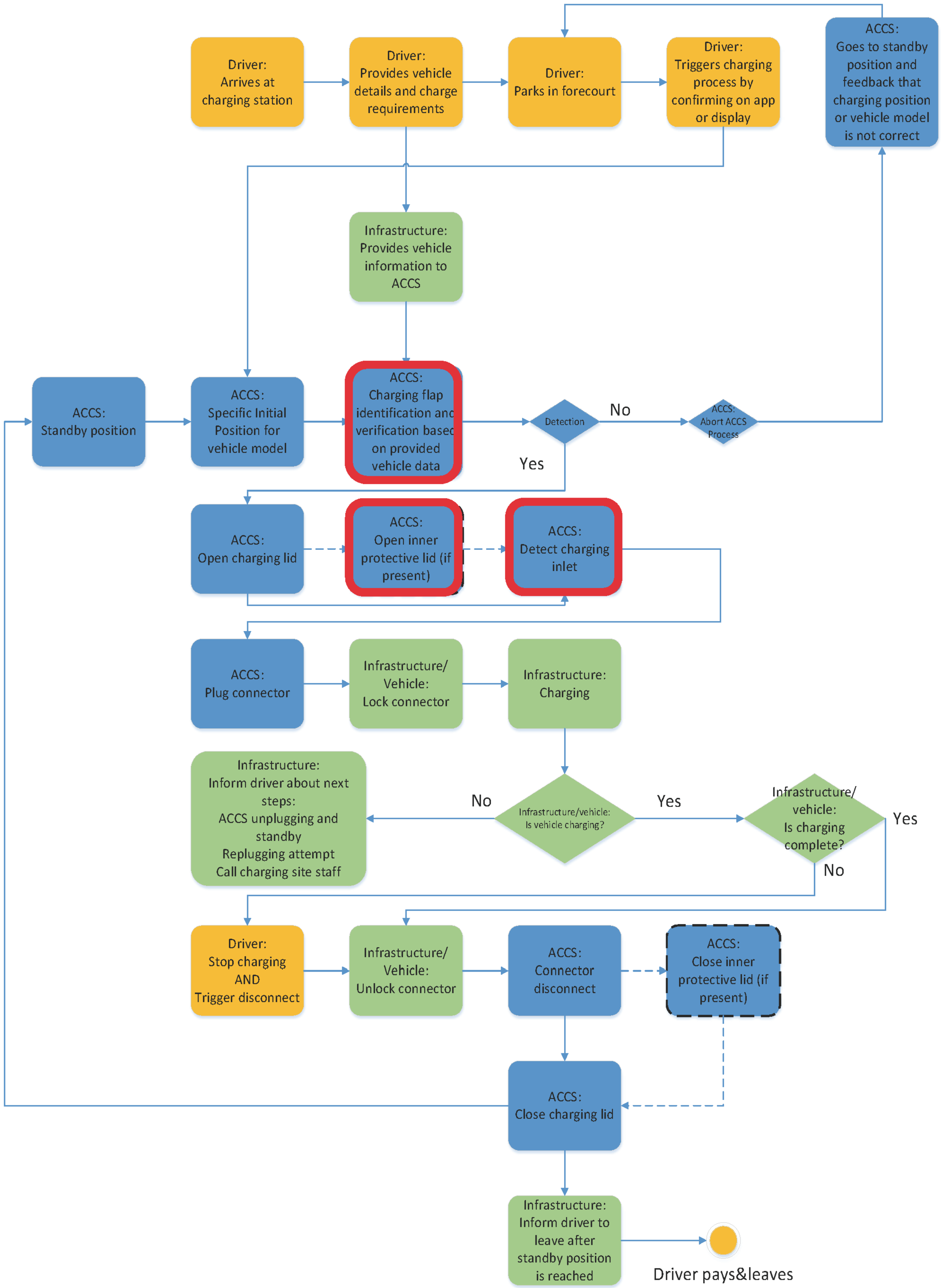


**Figure 2** Exemplary ACCS process [4]

CAD space analysis have resulted in a modular design of the end-effector, which is shown in Fig. 3. To support efficient testing, each component of the prototype can be replaced and functionalities can be added or reduced if necessary. A test plan was created for system validation. Two electric vehicles were tested for robustness with different test subjects on four consecutive days. The process was closely based on a manual loading process. Each individual process step was evaluated for successful implementation and data such as time, positions, images and user feedback were recorded. The system validation has shown that complete automation of the charging process using a cost-efficient 2D camera is possible under the condition of controlled lighting influences.

## 3 THE AUTOMATED CHARGING PROCESS IN DETAIL

Fig. 2 shows the operational sequences of the fully automated charging process from start to end, and Fig. 3 shows the design and main components of the experimental setup of the robotic actuation system. In the displayed ACCS sequence, the focus lies on the process within the defined system boundaries, which is represented by the blue blocks. In addition, the steps in which image recognition is involved are marked in red.

The ACCS waits in standby position until a wake-up trigger from the infrastructure is received. The robotic system (1) with its end-effector moves into a pre-defined location that enables charging lid position determination utilizing its camera system (2). The light system (3) supports in difficult light conditions. After the charging lid is correctly identified and crosschecked with the expected vehicle type, its position is determined and the charging lid is opened with the charging lid opening device (4). Optional, the authentication of the vehicle type can be managed by communication technologies, e.g., according to the communication standard (ISO 15518) [3]. Depending on whether inner protectives are present or not, the system continues with identification and the corresponding position determination (2). In case that the inner protection are protective plugs, the inner protectives handling device (6) is used to remove them. In case that protectives lid are present, the universal pusher (5) is used for opening. After the inner protectives are removed or opened, the position determination of the charging socket starts (2). Following the exact position determination, the ACCS moves into a position for plugging the connector (8) by use of a rail system (7) to connect the vehicle for charging. After the charging process is finished or aborted, the system carries out the process backwards to place the inner protectives and closed the main lid. All positions and movements are stored in the controller, so that no additional position detection is required for the closing procedure.

A detailed analysis of the charging process showed that all steps could be automated. Tab. 2 indicates the ACCS process steps including a rating of their complexity level from low (+) to high (+++) in relation to automation. The complexity per step is rated as a combination of:

- Robustness of image recognition
- Required logics
- Required actuators.

**Table 2** Complexity of automated steps [4]

| Step | Description | Complexity per step |
|---|---|---|
| 1a | Detection and position determination of charging lid | + |
| 1b | Opening charging lid | + |
| 2a | Detection and position determination of protectives | +++ |
| 2b | Removal of protectives | ++ |
| 3a | Detection and position determination of charging socket | +++ |
| 3b | Plugging of connector | ++ |
| 4 | Removal of connector | + |
| 5 | Re-attaching of protectives | ++ |
| 6 | Closing of charging lid | + |

## 4 MAIN COMPONENTS OF AUTOMATED CONDUCTIVE CHARGING SYSTEMS

In the preceding chapter, the fundamental functionalities required to automate the charging process of electric vehicles were elucidated based on the procedural workflow. This chapter now shifts focus towards delineating the primary system components necessary to enable this process.

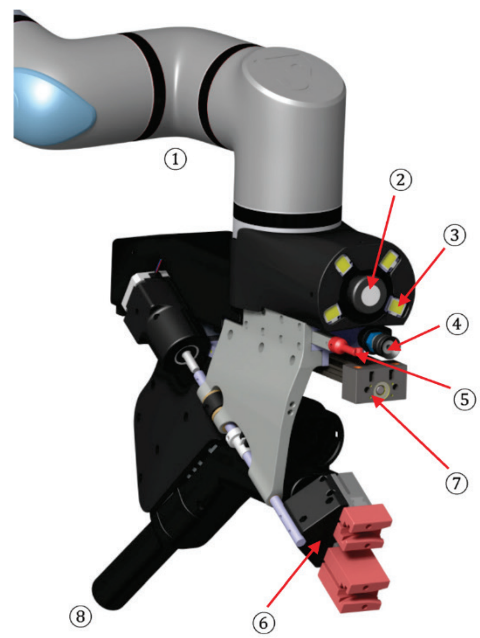


**Figure 3** ACCS System components [5]

Fig. 3 shows the setup of the ACCS including following key components:

- Control unit
- Robotic system (1)
- Camera system (2)
- Light system (3)
- Charging lid opening device (4)
- Universal pusher device (5)
- Inner protectives handling device (6)
- Rail system (7)
- Connector (8)
- Various sensors
- Interface to charging infrastructure.

## 5 MODULARITY OF THE AUTOMATED CHARGING SYSTEM

The modularity of the automated charging system is an important part of its design philosophy and enables quick adaptation to a wide variety of application scenarios during experimental investigations. Each component within the system architecture is designed with a high degree of modularity, software as well as hardware. This modular approach extends to all functions of the system and ensures that individual components can be replaced or reconfigured to adapt to the respective requirement.

An important aspect is the ability to quickly adapt the system's functionalities to the specific requirements of different environments. Regardless of whether the charging system is used in a parking garage, on a public street or in a fleet management depot. This agility is particularly advantageous in dynamic urban environments, where the requirements for the charging infrastructure can vary greatly, as confirmed by inquiries in the industry. The sensors, which serve as eyes and ears of the system, play a critical role in accurately detecting and responding to the presence and positioning of electric vehicles. By adopting a modular sensor architecture in the research prototype, the system can easily integrate different sensor technologies and configurations. Whether LiDAR, ultrasonic sensors or camera-based solutions – the modular sensor system ensures adaptability and reliability, depending on the intended use. Using modular software modules and flexible programming interfaces, the system can be easily integrated into existing infrastructure and third-party applications. This interoperability promotes scalability and futureproofing and enables seamless upgrades and expansions as development occurs.

In summary, the modular design of the automated charging system emphasizes its adaptability and robustness in tackling the complexities of electric vehicle charging. It enables stakeholders to efficiently respond to evolving requirements, enhance operational efficiency, and effectively utilize sustainable transportation infrastructure.

## 6 THE ROLE OF THE VISION SYSTEM

The vision system plays a pivotal role in the operation and efficiency of an automated charging system for electric vehicles. This chapter examines the profound influence of the vision system on various aspects of the charging process, encompassing detection, localization, and monitoring functionalities.

As covered by Walzel, et al. [6], basic computer vision functionality, referred to as machine vision, is employed for detecting predefined features or object characteristics such as edges, corners, motion, and distance estimation. This functionality aids in tasks such as identifying objects and estimating distances and orientation. More advanced computer vision techniques enhance object recognition accuracy but require complex approaches involving machine learning to teach artificial intelligence (AI) systems to recognize and classify objects with high precision.

For the application of automated charging, depth information is essential to define the position of the target object sufficiently precisely. This depth information can be obtained by using different sensor systems: 2D cameras that provide only positional and size information of objects, and 3D cameras that offer depth information. Two methods for generating 3D information are highlighted here: structured light and time-of-flight (ToF) technology. ToF technology, in particular, is noted for its ability to provide accurate depth information with less sensitivity to lighting conditions and reflections. This technology is increasingly integrated into automotive applications for driver assistance, emergency braking systems, and pedestrian protection. Current research aims to combine 3D ToF technology with 2D image recognition to improve the accuracy of object identification and differentiation.

One of the primary functions of the vision system is the detection and recognition of electric vehicles within the charging environment. The vision system can accurately identify the presence of vehicles, distinguish between different vehicle types, and detect relevant features such as charging lids and ports. This capability is essential for initiating the charging process and ensuring compatibility between charging infrastructure and the vehicle. Tab. 3 compares common sensor systems in the automotive industry.

A majority of car charging ports are made of black plastic material with little texture. In this way, it is difficult to obtain useful characteristics in the camera image [7]. The working distance in the current process is between 0.25 m and 1.2 m. In this area, a very high level of accuracy is required because the plug-in tolerances of standardized charging interfaces are very small and in the range of ±0.4 mm in the translational part. Fig. 4 shows technologies suitable for this purpose to enable position determination with the required accuracy. Cameras are evolving into a dominant positioning technology that covers a wide range of applications across all levels of accuracy [8].

**Table 3** Comparison of different sensor technologies [6]

| Sensor | Bright light performance | Low light performance | Outdoor | Weather robustness | Vehicle classification | Vehicle adaptation | Material costs |
|---|---|---|---|---|---|---|---|
| Ultrasonic | Good | Good | Yes | Good | No | No | Low |
| Magnetic | Good | Good | Yes | Good | No | Yes | High |
| 2D-camera | Good | Weak | Yes | Weak | Yes | No | Low |
| Laser and lidar | Good | Good | Yes | Good | Yes | No | Very High |
| 3D-camera | Good | Weak | Yes | Weak | Yes | No | Low |
| Structured light | Weak | Good | No | Weak | Yes | No | Medium |
| Tof-cameras | Good | Good | Yes | Good | Yes | No | High |

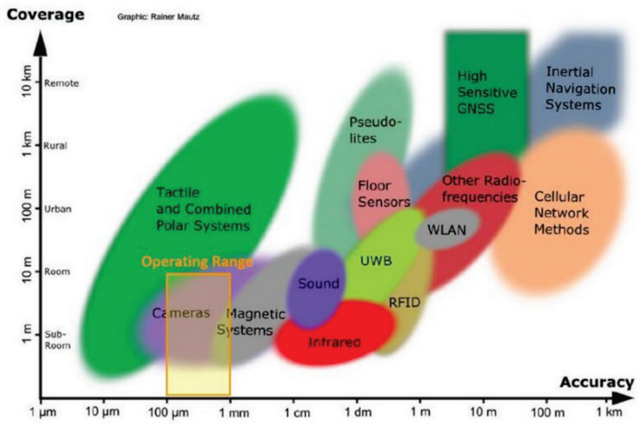


**Figure 4** Accuracy and coverage of different sensor technologies [1]

### 6.1 The Influence of Use Cases

The selection of the optimal camera system for a fully automated charging system for electric vehicles crucially depends on the specific use case. In particular, the use of a 2D camera system requires careful consideration of the requirements and challenges.


**Figure 5** Position determination of a VW ID3 charging lid

Monochromatic 2D cameras offer several specific advantages that can be beneficial. The choice of a camera system depends heavily upon the specific requirements of the application. 2D cameras offer notable technical advantages that warrant careful consideration in this context. Their primary allure lies in their cost-effectiveness, which is a huge factor for scalability, attributable to simplified hardware and reduced computational demands. This renders them particularly suitable for deployments where budget constraints are paramount. Furthermore, owing to their monochromatic nature, these cameras exhibit heightened sensitivity in low-light conditions, facilitated by their ability to capture information without the complexity of colour processing. Additionally, the absence of colour processing overhead streamlines data acquisition and reduces computational load, enhancing overall system efficiency. Despite their apparent simplicity, they have advanced imaging capabilities and feature high-resolution sensors and sophisticated algorithms that deliver exceptional image sharpness and contrast. This enables precise object detection and localization, which is crucial for the accurate operation of charging systems. In Fig. 5, the position determination of the charging lid of a VW ID3 is shown as an example.

The utilization of a monochromatic 2D camera proves to be sufficiently precise and robust, particularly in tightly controlled lighting conditions. However, when faced with fluctuating, uncontrolled lighting environments, such as outdoors, the monochromatic camera system within its current configuration might be no longer robust enough, and alternative solutions should be considered [9].

### 6.2 The Influence of the Vision System on the Process

Precise localization and positioning of the EV relative to the charging station are critical for seamless and efficient charging operations. The vision system facilitates this by analysing captured images to determine the exact position and orientation of the charging port. Using sophisticated algorithms and geometric analysis, the vision system can calculate the optimal alignment of the charging connector, minimizing misalignments and maximizing charging efficiency. Additionally, the vision system can assist in obstacle detection and avoidance, ensuring safe manoeuvring of the robotic system during the charging process.

In an outdoor test series with two vehicles, 114 completed test runs were recorded and evaluated. Of the 114 test runs, 60 were conducted on a VW ID3, with a success rate, i.e., successful plugging and charging, of 90%. 54 test runs were carried out with a BMW iX40, with a success rate of 87.5%. All vehicles in this test series have a standardized CCS type 2 [10] charging socket. A HPC CCS connector from Phoenix Contact [11] was used at the charging infrastructure. Plugging was possible in 100% of cases, although the latching mechanism did not trigger in the failed test runs. It should be noted that outdoor tests were chosen because the limitations of the 2D camera system were to be examined. Fig. 6 shows the relative contribution of image recognition to the overall process. The grey part of the pie chart represents the temporal triangulation part of the overall process. The timing of the triangulation starts with reaching the first position until after the successful calculation of the combined pose from the previous 5 positions. The 5-point triangulation is shown in Fig. 11.

One can see that the proportion of triangulation is very large at 15.6% for the VW ID3 and 25.8% for the BMW iX40. On the one hand, this means that a relatively large amount of time must be invested in order to get sufficiently accurate and precise results and, on the other hand, this process step probably offers the most potentials in view of process time optimization.

Commercial image processing software is used to determine the position of the target object using a 2D camera by shape-based 3D matching. To do this, a CAD model of the object is made available. The 3D shape model consists of 2D projections in selected positions. This results in characteristic features such as edges, corners or similar structures, which are detected by the image processing software. An SBM algorithm is then used for the matching sequence. Calculated parameters include the distance and orientation of the object that result in a 3D pose, which then is used further in the process [12].

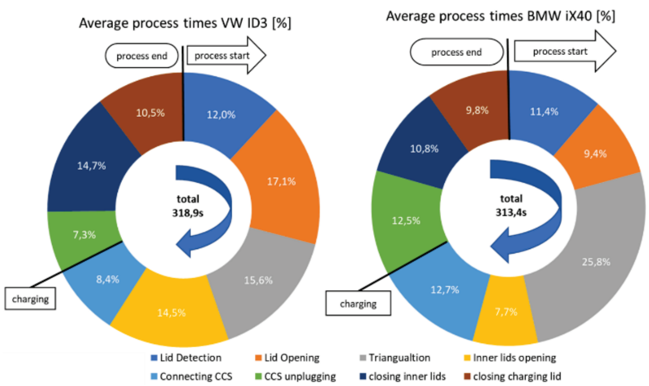


**Figure 6** Relative proportion of triangulation using the example of two test vehicles

Fig. 7 shows the result of the image recognition of the inner protective plug of a VW ID3. Interesting to see in Fig. 8 is the constant duration of the triangulation of this detection. The number of tests is plotted on the abscissa and the duration of detection of the inner protectives is plotted on the ordinate. Over the course of all test runs, there were only a few outliers that indicate significantly changed lighting situations. On the other hand, it can also be deduced that the edges of the specific plug are relatively easy to process for the edge detection algorithm.

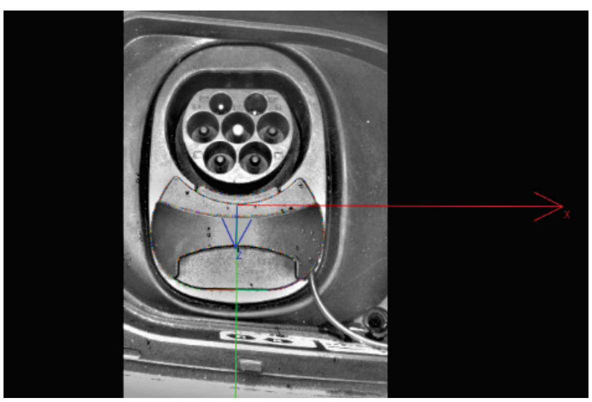

**Figure 7** Position determination of the inner protective lids of a VW ID3

In comparison, the image recognition of the inner flaps of the BMW (Fig. 9) shows a significantly higher fluctuation in the detection times (Fig. 10) over the course of all test runs. The number of tests is plotted on the abscissa and the duration of detection of the inner lids is plotted on the ordinate.

This can be explained on the one hand by different lighting conditions, but on the other hand also by the design features of the orientation of the flaps (no shielding of light from above due to the orientation of the CCS socket). In general, it can be stated that the inner lids of the BMW took longer in the position determination process and show greater temporal variance than the protective plugs of the VW.

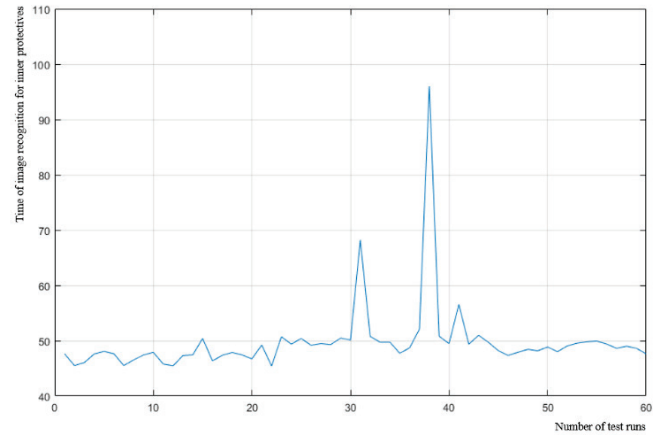


**Figure 8** Detection time VW ID3 inner protectives

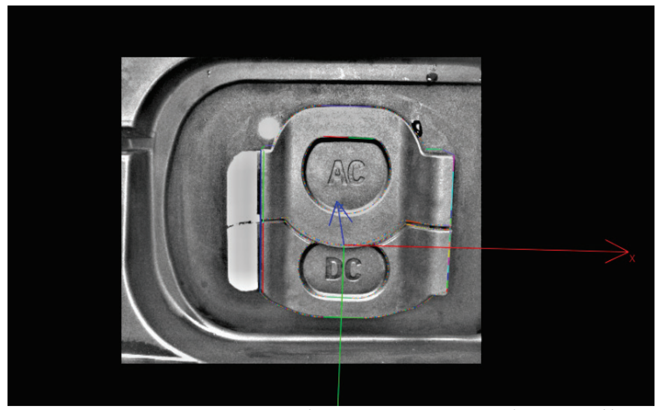


**Figure 9** Position determination of the inner protective lids of a BMW iX40

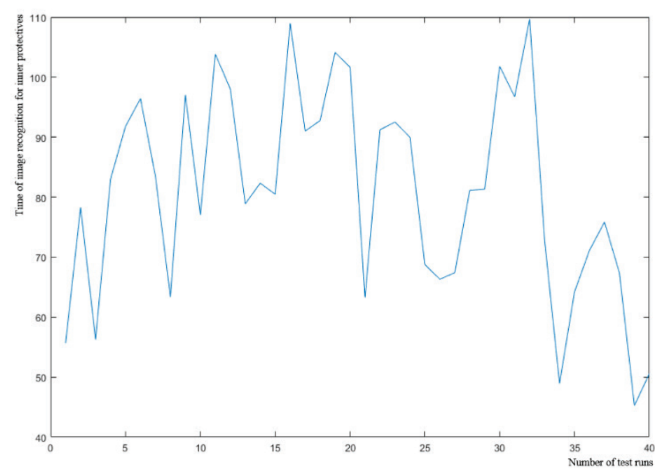


**Figure 10** Detection time BMW iX40 inner protectives

### 6.3 Improved Position Determination Process

This chapter focuses on enhancing the position determination process using a monochrome 2D camera.

Through a specific process adaptation, the camera's performance limitations could be extended. This was achieved by implementing triangulation, analysing images from several different positions to compute a combined position. A cross method has proven particularly effective, varying only one angle. This methodological adjustment significantly contributes to increasing the accuracy and robustness of the position determination process, enabling more precise results across various application scenarios. The triangulation process is illustrated in Fig. 11.

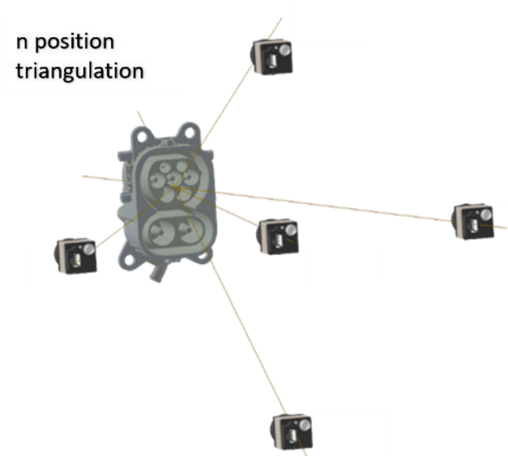


**Figure 11** Example triangulation

In each of these positions, several images were taken and combined into one. This results in a total of *n* positions, which are ultimately calculated into a combined one. This is based on a weighted, iterative averaging procedure. With this process, the influence of lighting can be significantly mitigated and both accuracy and precession increase.

### 6.4 The role of artificial lighting

Artificial lighting plays a critical role in facilitating image recognition and precise position determination within the framework of a monochromatic 2D camera system.

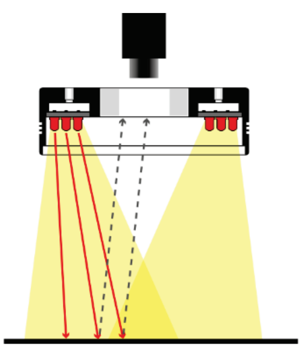

**Figure 12** 2D camera setup with artificial direct light [13]

Artificial lighting is a fundamental tool for improving the quality of images captured by 2D cameras. Providing consistent and even lighting minimizes shadows reduces glare and improves contrast, improving the visibility of objects in the camera's field of view. This improved image quality is important to enable accurate object detection and positioning, especially in an environment with changing lighting conditions. Additionally, the use of directional lighting can aid in the precise localization of objects by providing depth cues and increasing the contrast between objects and their surroundings. This precise position determination is essential for the automated connection of charging plugs by robotic systems. An exemplary setup is shown in Fig. 12.

In outdoor or indoor environments with fluctuating ambient light levels, artificial lighting serves to mitigate variations and ensure consistent illumination for image processing. By supplementing ambient light with controlled artificial lighting sources, the camera system can maintain optimal visibility of objects and minimize the impact of unpredictable lighting fluctuations. This stability in lighting conditions is crucial for the reliability and robustness of edge detecting image recognition algorithms, enabling consistent performance across diverse operating environments. However, it should be noted that restrictions are to be expected in outdoor areas, as the artificial light intensity is simply not sufficient in many cases. Overall, artificial lighting plays an important role in expanding the application limits of 2D cameras and, under certain conditions, sufficiently ensuring the reliability of 2D camera systems for image recognition and positioning applications. Particularly noteworthy here is the provision of accuracy, precision, efficiency (related to the detection time) and robustness in the fully automated charging process.

**Figure 13** LED light ring FLDR-i90A-W [14]

However, it must be taken into account that there are strong limitations due to the available installation space of the end effector. The lighting system must not be wider than a standardized CCS connector. This severely limits the lighting setup and, due to the working distance, only allows for direct, diffuse reflected light, although other configurations would probably deliver better results.

In conclusion, artificial lighting can cost-effectively expand the application limits of 2D camera systems. However, there are application scenarios in which other sensor systems are superior and should be considered, e.g., 3D points clouds combined with deep learning [15].

## 7 OUTLOOK TO FUTURE RESEARCH

The modular, vision-based control approach presents a fertile ground for further research, offering opportunities to address existing challenges and to unlock new capabilities. This chapter delineates the potential directions for future investigations in this domain.

Advancements in computer vision techniques hold significant promise for improving the perception capabilities of automated charging systems. Future research will focus on integrating state-of-the-art vision algorithms, such as deep learning-based object detection and tracking, to enhance the system's ability to accurately identify charging connectors and vehicle interfaces under diverse environmental conditions, including low light and adverse weather. This also includes research of further sensor systems or combinations in order to achieve possible synergetic effects. The goal is to reduce costs while improving accuracy and precision. Further refinement of the modular architecture is essential to enhance system scalability, flexibility, and compatibility with diverse EV models and charging infrastructure. Future studies will explore innovative approaches to modular design, including standardized interfaces and protocols to facilitate seamless integration and interoperability across different charging scenarios and platforms.

Ensuring the robustness and reliability of automated charging systems is paramount to their widespread adoption and acceptance. It is important to focus on developing robust control algorithms and fault-tolerant mechanisms to mitigate uncertainties, disturbances, and hardware failures, thereby enhancing system performance and safety.

## 8 CONCLUSION

In conclusion, the findings of this paper shed light on the efficacy of modular, vision-based systems for automated charging systems in the realm of electric vehicles. The investigations have demonstrated that monochromatic 2D camera systems exhibit promising potential in certain application scenarios, particularly indoors where lighting conditions are well-controlled. Within such environments, these systems can deliver sufficient accuracy and precision to facilitate effective charging operations.

However, it is crucial to understand the limitations of 2D camera systems, particularly when confronted with variable lighting conditions, especially in challenging outdoor settings. Fluctuating illumination can compromise the reliability and robustness of these systems, potentially leading to performance degradation and operational inefficiencies.

While monochromatic 2D camera systems represent a viable solution indoor applications, their suitability for outdoor use must be carefully considered. Future research will focus on developing adaptive strategies and integrating complementary sensor technologies to mitigate the impact of changing lighting conditions and enhance the overall robustness and versatility of automated charging systems for electric vehicles. By addressing these challenges, the evolution of modular, vision-based control systems will be realized towards greater effectiveness and applicability in various real-world scenarios, supporting an ultimately implementation of automated charging technologies in the electric mobility landscape.

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