An Analysis of Electric Vehicle Port Design Constraints for Automated Robotic Charging

Zoltán Király[1,2], Ervin Burkus[2], Tibor Szakáll[3], Ákos Odry[2,4], Péter Odry[2,5] and Vladimir Tadić[5,6,7*]

[1] Software Engineering Institute, John von Neumann Faculty of Informatics, Obuda University, Bécsi Str. 96/B, H-1034 Budapest, Hungary, kiraly.zoltan@uni-obuda.hu

[2] Institute of Information Technology, University of Dunaújváros, Táncsics Mihály u. 1/A Pf.: 152, 2401 Dunaújváros, Hungary, {burkus@uniduna.hu, podry@uniduna.hu}

[3] Department of Informatics, Subotica Tech College of Applied Sciences, Marka Oreškovića 16, 24000 Subotica, Serbia, tibi@vts.su.ac.rs

[4] Department of Mechatronics and Automation, Faculty of Engineering, University of Szeged, Moszkvai Krt. 9, H-6725 Szeged, Hungary, odrya@mk.u-szeged.hu

[5] Symbolic Methods in Material Analysis and Tomography Research Group, Faculty of Engineering and Information Technology, University of Pécs, Boszorkány u. 6, H-7624 Pécs, Hungary

[6] Department of Mechanical Engineering, Electrical Engineering and Computer Science, Technical College of Applied Sciences in Zrenjanin, Đorđa Stratimirovića 23, 23000 Zrenjanin, Serbia, vladimir.tadic@vts-zr.edu.rs

[7] Biomatics and Applied Artificial Intelligence Institute, John von Neumann Faculty of Informatics, Obuda University, Bécsi Str. 96/B, H-1034 Budapest, Hungary

*Correspondence: vladimir.tadic@vts-zr.edu.rs

Abstract: *Automated conductive charging is a key technology, for unattended electric-vehicle (EV) operations; however, the diversity in vehicle-side charging-port designs can compromise the reliability of robotic connections. This paper systematically analyzes vehicle-side, charging-port features, that influence robotic accessibility and connection reliability, including, connector position and orientation, cover-door geometry and opening direction, protective caps, fastening elements, available clearance and sensing conditions. The analysis integrates observations from the development and evaluation of a robotic charging demonstrator with a structured review of representative vehicle-side configurations. Based on these findings, an engineering-oriented compatibility*

framework is proposed, to classify the principal physical and operational barriers to automated connection and to define measurable geometric and functional criteria for assessing robotic accessibility. The framework further distinguishes essential interoperability requirements, from desirable design improvements, thereby, providing a basis for evaluating vehicle-side charging-port designs, from the perspective of automated charging. The resulting recommendations are intended to support vehicle and charging-system designers in improving interoperability, robustness and reliability, in robotic electric-vehicle charging.

Keywords: EV charging; Robot-controlled automatic charging; Charging ports; Robotic arm.

1 Introduction and problem statement

In 2020, the University of Dunaújváros initiated the project "Research and Development Project for Automatic Charging of Electric Vehicles Using a Charging Robot" (GANZ KK 2020-1.1.2-PIACI-KFI-2020-00173), investigating robotic wired EV charging. Reliable operation requires accurate localization and 3D pose estimation of the vehicle charging port for connector insertion [1][2]. The project identified a key engineering challenge: the lack of uniform vehicle-side design principles for charging-port location, cover-door opening, protective caps, and fastening elements. Previous studies have addressed EV technology [3–6], automated charging mechanisms [5–8], and vision-guided robotic charging [9][10]. However, existing standards and guidelines do not prescribe a uniform geometric layout for EV charging-port access. Consequently, manufacturer-specific choices related to packaging, ergonomics, styling, and market practice can directly affect robotic compatibility.

1.1 Research Objective and Scientific Contribution

The objective of this study is to identify vehicle-side charging-port properties that constrain or enable robotic conductive charging and to develop an engineering compatibility framework. The study does not propose a complete charging-station architecture or formal industry standard. Its contribution comprises:

(1) A taxonomy of vehicle-side compatibility barriers

(2) Measurable geometric, sensing, and operational criteria for vehicle and robotic-station design

(3) A distinction between essential connection requirements and desirable features that improve robustness, usability, or safety. The framework is derived from robotic charging development experience and illustrated using representative production-vehicle configurations.

1.2 Why is the automatic charging of electric vehicles justified?

Robotic conductive charging has advanced rapidly, with research systems and industrial prototypes demonstrating its feasibility [10–13]. It is particularly relevant for applications where human attendance is undesirable or impractical, including autonomous taxi and private-vehicle fleets, logistics and depot operations, parking garages, and public charging facilities [14–16]. Compared with manual, pantograph, inductive, and battery-swapping approaches, robotic conductive charging can eliminate cable handling while retaining conventional vehicle-side connectors without requiring dedicated wireless hardware or standardized removable batteries [17][18]. However, reliable operation requires accurate localization, collision-free manipulation, connector compatibility, and safety supervision. As many solutions remain at the research, prototype, or demonstrator stage [19–22], vehicle-side interoperability remains an important design challenge.

1.3 Methodological Basis and Scope

Compatibility barriers were identified through structured engineering analysis based on four evidence sources:

(1) Development, operation, and testing observations

(2) Inspection of representative EV charging-port layouts

(3) Manufacturer and technical documentation

(4) Geometric assessment of robot reach, clearance, camera visibility, and connector approach.

Features were classified by their effects on reachability, sensing, collision-free access, connector insertion, and safe operation. The resulting recommendations are therefore based on repeatable engineering criteria rather than isolated examples.

The modeling approach is intentionally engineering-oriented. Previous studies have applied probabilistic, fuzzy, machine-learning, state-observer, and optimization-based models to complex robotic and mechatronic systems [35–40]. These works provide methodological context rather than direct evidence on EV charging-port geometry. Accordingly, the present model is limited to geometric reachability, pose error, clearance, and discrete compatibility attributes, which directly determine robotic access and connector engagement.

The paper is organized as follows. Section 1 presents the problem, objectives, and methodology. Section 2 reviews charging-port configurations and protective elements, while Section 3 introduces the barrier taxonomy and compatibility model. Section 4 defines engineering requirements, distinguishing essential criteria from desirable improvements. Section 5 discusses representative systems, the robotic

charging sequence, and safety considerations. Section 6 summarizes key advantages and challenges, followed by the conclusions in section 7.

2 The Placement of Electric Vehicle Charging Ports and Their Opening Mechanisms

Charging-port design is an important but often overlooked aspect of EV design. Manufacturers differ in port location, opening direction, and mechanism, affecting both aesthetics and the practical accessibility of charging [22].

2.1 The Placement of Charging Ports

EV charging-port placement varies across manufacturers, models, and sometimes model years. Locations are often influenced by conventional fuel-filler placement and generally include the front, rear, or left/right front sides of the vehicle. Additional side-mounted configurations may be positioned near the A- or C-pillar.

2.1.1 Front Placement

Some manufacturers, such as Nissan Leaf and Renault Zoe, locate the charging port at the front, beneath the hood. This configuration allows close positioning to the charging station and convenient cable access. However, access may be restricted when the vehicle is parked close to a wall or other obstacle.

2.1.2 Rear Placement

Other manufacturers locate the charging port at the rear, as in the Tesla Model S and KIA EV6, where it is positioned near or beneath the rear light, respectively. This arrangement resembles the conventional fuel-filler location and can facilitate charging when vehicles are backed into a charging station. However, access may be restricted when the rear is parked close to a wall or other obstacle.

2.1.3 Rear-Side Placement

Side-mounted charging ports, often positioned near the C-pillar, are also common and resemble conventional fuel-filler locations. For example, the BMW i3 places the port on the right rear side, while the VW e-Golf uses the left rear side. This configuration can facilitate access regardless of parking direction, but cable length and vehicle position remain important, particularly at stations with perpendicular parking.

2.1.4 Front-Side Placement

This solution has primarily spread in electric vehicles, particularly in Plug-In Hybrid vehicles, although manufacturers from East Asia tend to prefer placing the charging port near the A-pillar even in fully electric vehicles (e.g., BYD Dolphin, BYD Atto, Toyota BZ4X). The front-side placement is most commonly observed in commercial vehicles (e.g., the entire Volvo electric truck series: Volvo FH, Volvo FMX, Volvo FM, Volvo FH Aero, Ford F-150, Opel Zafira e-life, etc.). Logically, the charging port is not placed at the cargo loading area (at the rear) in these vehicles.

2.2 The Directions and Methods of the Opening of Charging Ports

The opening of the charging port also shows significant variation between different EV models, and various methods are applied by manufacturers for this process. The most common opening methods and directions are presented below.

- *Opening with a Mechanical Button*: In many EV models, the charging port is opened by pressing a mechanical button. This solution is simple and reliable, and it is similar to the opening method of traditional fuel filler ports. In the case of the Chevrolet Bolt EV, for example, the charging port is located on the left rear side and can be opened with a mechanical button, which also provides feedback to the user when the port is opened. However, this could hinder automatic charging, as this operation must be performed manually by the user.
- *Remote or Touch-button Opening*: Advances in automotive digitization have enabled remote or touch-controlled charging-port doors. For example, the Tesla Model 3 allows the port to be opened via the vehicle key, smartphone application, or touchscreen. Such software-controlled operation minimizes physical interaction and can facilitate automated charging.
- *Automatic Opening Systems*: Among the most advanced systems are those solutions where the charging port is automatically opened when the user approaches the charging station. For example, the Ford Mustang Mach-E was equipped with such a feature early on, where the vehicle detects with a sensor that the charging cable has been brought near and automatically opens the charging port. This system is particularly convenient as it eliminates the need for manual initiation of the charging process and further simplifies the use.
- *Manual, Press-down Opening*: In some vehicles, the charging port is manually opened by simply pressing the charging port cover, which then opens automatically. This solution is common, for example, in the Volkswagen ID.4, where the charging port is located at the rear right side of the vehicle and can be opened using a simple press mechanism. The cover only needs to be gently touched, and it automatically opens, allowing for charging.

However, opening the charging port is not sufficient to enable automatic charging of the vehicle. The charging port cover must also be fully extended to the maximum possible opening distance, as the robot, its cameras, and the charging gun must fit safely without damaging the charging port cover door.

2.3 Placement Examples and Opening Mechanisms of Charging Ports in Different Electric Vehicle Models

As discussed in the previous subsection, charging-port location strongly affects accessibility. Current charging-station layouts often require drivers to position the port close to the charging pillar, sometimes resulting in unusual parking configurations. For example, MOL Plugee stations in Hungary use diagonal parking, which can challenge vehicles with rear-mounted charging ports (e.g., HU-MOL 0078 – Kecskemét M5 91 E MOL2). Automated charging therefore benefits from a database containing vehicle manufacturer, model, and model-year information. Several examples are presented below:

- *Tesla Model S*: In the case of the Tesla Model S, the charging port is positioned on the rear left side and features one of the most innovative solutions. It is integrated into the rear light assembly, keeping the charging port concealed behind the taillight until it is opened. The charging port can be opened via the vehicle's touchscreen, through the application, or automatically using sensors when the charging cable is approaching.
- *Nissan Leaf*: The charging port of the Nissan Leaf is located at the front of the vehicle, directly beneath the hood. This placement is particularly practical for those who frequently use public charging stations, as these typically support head-in parking. The port can be opened mechanically by pressing a button on the dashboard. While the location is advantageous, the opening direction and size are not optimal, as discussed in later sections.
- *Audi e-tron*: In the case of the Audi e-tron, the charging port is located on the left side of the vehicle, and one of its most notable features is that it opens automatically when the cover is touched by the user. The press-down mechanism allows access to the charging port with a single touch.
- *VW e-golf*: The charging port is positioned in a conventional location, as it is placed on the right side of the vehicle in the driving direction, similar to traditional gasoline-powered vehicles.

These examples already highlight the diversity of charging port positions. However, not all possibilities have been examined, as charging ports located beneath the A-pillar or the unique charging solutions for commercial vehicles have not yet been discussed.

2.4 Protective Covers in Electric Vehicles

2.4.1 Connector Protection Cap

In most EVs, a protective cap must be removed after opening the charging-port door to prevent contamination and weather exposure. These caps are typically removable and tethered to the vehicle, although some are integrated into the door. In CCS2 systems supporting both Type 2 AC and DC charging, AC and DC contacts may also have separate protective caps, as in the VW e-Golf.

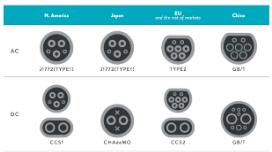


Figure 1

Types of charging ports [23]

In some models, the function of the connector protection cap is performed by a hinged, snap-open door (e.g., Nissan Leaf, Renault Zoe, MG ZS EV). These snap-open covers almost make robot-based charging impossible.



Figure 2

Protective Covers of Nissan Leaf [24] and Renault Zoe [25] respectively

2.4.2 Fastening Elements

Protruding plastic or metal fastening elements under the cover door can obstruct charging-gun connection, particularly when oversized. Examples include the BMW i3 and Hyundai Ioniq. Manufacturers may compensate by increasing the cover-door dimensions; in the BMW i3, the larger door provides sufficient clearance for both manual and automated charging despite the relatively large fastening elements.



Figure 3

Built-in fastening elements of BMW I3 and Hyundai Ioniq respectively

2.4.3 Connection Indicator Elements

In many EV models, the charging connection can only be monitored on the vehicle's dashboard or at the charging station.



Figure 4

Connection Indicator Elements of Opel e-Corsa [26] and KIA EV6 respectively

In several models, feedback—most often provided by LED lighting—is also available under the fuel cap.

3 Analysis of the Charging Ports

3.1 The Opening Direction of the Charging Port Door

In the case of automatic, robotic arm-based charging, the first obstacle is posed by the charging port. For different models, the charging port is variable depending on the vehicle's model year. Here are the examples:

- Horizontally to the left (Renault Megane E-tech, Kia Soul, Skoda Citygo)
- Horizontally to the right (Mercedes EQB 350, Kia EV6)
- Upward tilting (Nissan Leaf N-Connecta)
- Upward sliding (Dacia Spring)
- Diagonally to the left and upward (Opel Corsa Electric)
- Diagonally to the left and downward (Renault Zoe)
- Downward sliding (Zeekr X)

Designing a robotic gripper that accommodates different door positions while enabling reliable connector insertion is challenging. The main constraint is camera placement: a camera, and potentially a distance sensor or light source, must detect the charging port without being obstructed by the charging gun. Although prototype systems typically position the camera above the gun, side- and below-mounted configurations have also been demonstrated (Aiways Automobile Europe GmbH [27]). Notably, most reported prototypes use vehicles with side-opening charging-port doors.

3.2 The Opening Angle of the Charging Port Cover Doors

EV charging-port doors have varying opening angles. Although an angle of at least 90° relative to the port surface may facilitate manual connection, some models, such as the Renault Megane Electric, provide smaller openings that can prevent robotic connection. Internal door elements may further restrict the available clearance. Sliding doors are advantageous for automated charging because they do not obstruct the approach from the sides, top or bottom.



Figure 5

Opening Angles for Renault Megan Electric [28] and ZEEKR X respectively

3.3 The Size and Shape of the Charging Port

Charging-port door size depends largely on the number and arrangement of connectors. For example, Nissan Leaf models commonly place Type 1/CHAdeMO and Type 2 connectors side by side, while the ZEEKR X uses a large door covering multiple connectors.

CCS2 access doors also vary considerably. Some resemble those of conventional vehicles (e.g., VW e-Golf vs. VW Golf VIII), while EV-specific models show greater variation. The BMW i3 has a large, nearly square door that facilitates robotic access, whereas the smaller elliptical Fiat Hatchback and circular Škoda Citigo doors provide limited clearance. The Dacia Spring's upward-sliding door may improve access, but can obstruct the charging-port camera; its side-opening variant places the hinge close to the CCS2 connector.

3.4 The Position of the Charging Port on the Vehicle

As noted above, EV charging-port configurations are considerably more diverse than those of conventional fuel ports. For robotic systems with limited local degrees of freedom, the vehicle must be positioned so that the charging port is accessible from the robot's operating area. Accordingly, front-, side-, or rear-mounted ports require corresponding vehicle positioning and sufficient space at the charging station. Examples include systems developed by Doosan [29] and Hyundai Motor Group [30].

3.5 Systematic Taxonomy and Measurable Compatibility Criteria

For systematic assessment, the vehicle-side barriers can be classified into nine categories:

(1) Port location on the vehicle
(2) Port orientation and surface normal
(3) Cover-door opening mechanism
(4) Cover-door opening direction and angle
(5) Protective-cap design
(6) Locking and fastening elements
(7) Required approach corridor and physical clearance around the port
(8) Sensing conditions, including visibility, illumination, and occlusion
(9) Human-safety and operational constraints

A vehicle configuration is considered robot-compatible only when all essential categories allow the complete approach–insertion–release–withdrawal sequence without collision and while preserving the required sensing field of view. This taxonomy is used in Section 4 to distinguish essential and desirable requirements.

A compact geometric model can be used to make the assessment quantitative. Let p_c denote the charging port position, p_r the robot-base position, and R_{eff} the effective reachable radius after accounting for the required manipulation reserve m_r. Reachability requires the next distance:

$$d = ||p_c - p_r||_2 \leq R_{eff} - m_r \tag{1}$$

Let $\hat{p}_c$ and $\hat{n}_c$ be the estimated connector position and approach-direction unit vector and p_c and n_c their reference values.

Position and orientation errors can be expressed as:

$$e_p = ||\hat{p}_c - p_c||_2 \tag{2}$$

and

$$e_\theta = arccos(\hat{n}_c \cdot n_c) \tag{3}$$

respectively, where e_p denotes the position error and e_θ denotes the orientation error. These errors must remain below system-specific acceptance limits of e_p maximum and of e_θ maximum.

Collision-free access requires the minimum distance δ_{min} between the end-effector swept volume *E(q)* and the vehicle/door obstacles set *O*, and the following condition should be satisfied:

$$\delta_{min} = min\ ||x - y||_2 \geq \delta_{safe}, \qquad for\ x \in E(q)\ and\ \ y \in O \tag{4}$$

where δ_{safe} denotes the minimum safe distance at which collision is avoided and q denotes the obstacle. For side-opening doors, the experimentally motivated geometric requirement used in this research is an opening angle of at least 90°. These quantities convert qualitative recommendations into testable acceptance criteria; the numerical tolerances for pose error and safety clearance must be validated for the selected robot, gripper, connector and vehicle set.

4 Essential Requirements for Automated Charging

EV charging-port placement and opening mechanisms affect both user experience and robotic feasibility. Accordingly, vehicle-side designs should satisfy explicit criteria for robot reachability, unobstructed approach, sufficient cover opening, sensor visibility, collision-free insertion and withdrawal, and safe fault behavior. The following requirements translate the observations from Sections 2 and 3 into verifiable engineering criteria, for design and validation.

4.1 The Location of the Charging Port

For an automated EV charging station serving side-by-side parked vehicles, the charging ports must remain accessible to the robots. Perpendicular parking provides a straightforward configuration, as it is already widely used in manual charging stations. The charging port must be within the robot's reachable workspace while maintaining a safe clearance between the vehicle and the robot or charging station. In Fig. 6, the blue circles denote the robot bases, the blue line indicates the minimum reachable path, and the red areas mark the charging-port locations.

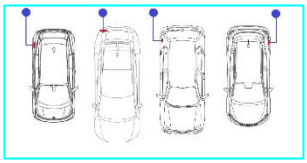


Figure 6

Electric vehicles' charging port locations

4.2 The size of the cover door and the appropriate distance of the connector from the cover door

The size of the cover door determines the size of the device that can be used for connecting the charging cable. Since, in robotic charging systems, not only the gripper (claw) is attached to the end-effector, but also sensor devices such as

cameras, distance sensors, etc., a cover door of sufficient size is required to accommodate these tools.

4.3 The shape of the cover door, its opening direction, and its opening angles

Charging-port door size, opening angle, and direction are critical for robotic access because the door can interfere with end-effector-mounted cameras and other components. Since cameras are typically positioned above the end effector, the upper robot workspace must remain unobstructed. Side-opening doors, the most common configuration, must also provide sufficient clearance for the connector, cameras, wiring, gripper, and cables. Fig. 7 illustrates representative door configurations, including the solution developed in the project.

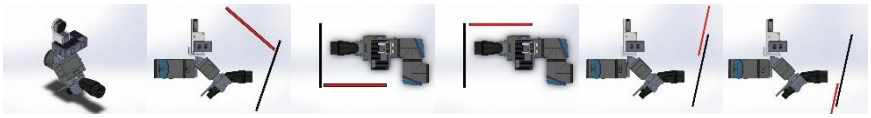


Figure 7

The cover door opening positions relative to the components mounted on the robot's end-effector

As illustrated in Fig. 7, top-hinged doors may interfere with end-effector-mounted cameras. For side-opening doors, an opening angle of at least 90° and sufficient clearance between the charging port and door are desirable, as the camera may be wider than the gripper or end effector.

4.4 The Charging Port Cover Cap

As previously explained, it is not ideal for the charging port cover cap to be attached to the inside of the cover door. Vehicles where the driver hangs the cover cap on a hook provided by the manufacturer are also difficult or impossible to charge, as this creates the same obstruction as a charging port cover cap attached to the cover door.

4.5 The Position of the Vehicle

Previous studies have addressed vehicle positioning at automated charging stations [22]. For robotic charging, vehicles should be positioned with the charging port within the robot's workspace while minimizing angular deviation from 90° in perpendicular parking to facilitate reliable camera-based localization. Practical solutions include guiding vehicles with physical lane markers and sensors, together with flexible barriers to prevent contact with the robot, in its default position.



Figure 8

Vehicle positioning at the automatic charging station

To ensure correct vehicle positioning, each parking space is equipped with two self-developed pressure sensors and an industrial radar sensor. The strain-gauge pressure sensors detect when the vehicle's front or rear wheels are correctly positioned, while the radar sensor provides vehicle detection and additional safety monitoring. The sensors are controlled by a PLC. Their placement must ensure sufficient vehicle proximity for connector insertion while maintaining adequate clearance for robot maneuvering.



Figure 9

Sensors for vehicle detection and positioning: the strain gauges-based pressure sensors; the radar sensor; the sensor in action are presented respectively

4.6 The Distance of the Charging Gun from the Vehicle Body

In some vehicles, the charging port is recessed deeply beneath the cover door, causing the camera or gripper to collide with the vehicle body before full connector engagement. Increasing the distance between the gripper and connector could mitigate this issue; however, project experiments showed that this configuration can obstruct the charging-port recognition camera by entering its field of view.

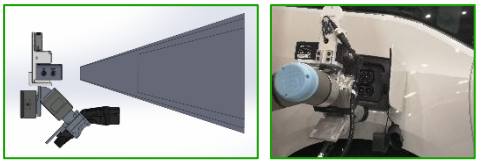


Figure 10

The field of view of the mounted camera: the model and the camera in action are shown respectively

4.7 Essential and Desirable Requirements for Robotic Compatibility

The recommendations can be separated into essential requirements, without which automatic connection cannot be guaranteed, and desirable improvements that increase robustness or simplify automation. This distinction is intended as an engineering prioritization rather than a formal standard.

Essential requirements:

(1) The port must lie within the robot's validated and reachable workspace, for the defined parking tolerance.
(2) The port and its approach corridor, must remain free of rigid obstructions, throughout insertion and removal.
(3) The cover-door must open sufficiently width in order to avoid collision with the end-effector and sensors, with at least 90° opening angle used as the baseline for side-hinged doors in this study.
(4) Any protective cap or lock that blocks insertion must be automatically actuated or absent during robotic charging.
(5) The ports 3D pose, must be detectable, with validated position and orientation accuracy.
(6) The vehicle and station must support a safe stop and recovery sequence after failed localization, failed insertion, unexpected motion, or obstacle detection.

Desirable requirements:

(1) Standardized or manufacturer-declared port position data.
(2) Visual or geometric references that improve machine perception.
(3) Simplified, self-opening, or sliding cover-door geometry.
(4) Local connection-status indicators visible to the perception system.
(5) Generous clearance around the port beyond the minimum end-effector envelope.
(6) Software-accessible port-opening and charging-state signals.

These features are not strictly necessary in every robotic architecture, however they can reduce cycle time, sensing complexity, and failure probability.

5 Robots and Automatons

The widespread adoption of EVs has transformed transportation while creating new challenges for charging infrastructure. Advances in robotics and automation have led to solutions for automated cable charging, aimed at improving convenience and facilitating everyday EV use.

- *Tesla Charging Robot*: One of the most well-known examples of automatic EV charging is the robotic arm charger developed by Tesla, which was first introduced as a concept in 2015 [31]. This snake-like robotic arm is capable of automatically connecting the charging cable to the vehicle's charging port.
- *Volkswagen Robotic Charger*: Volkswagen has also developed an automatic charging system that uses a self-moving robotic charger [32]. This robot is specifically designed for use in parking garages and is capable of connecting to the vehicle's charging port and starting the charging process.
- *ROCOS and Halodi Robotics*: Another innovative approach is presented through the collaboration between ROCOS [33] and Halodi Robotics [34], which involves the use of humanoid robots for electric vehicle charging.

The proposed charging system comprises a UR10e industrial robot mounted on a motorized cart that travels along a rail positioned in front of parallel vehicle parking spaces. The robot is equipped with a 3D camera and an industrial gripper for securely handling the charging gun. The modular rail-mounted design facilitates installation in locations such as shopping-center parking areas and temporary event sites, including transport containers.



Figure 11

Images of the developed automated robot-based charging system

The operation of the system and the charging process consists of the following steps:

- Following vehicle detection, identification, and charging authorization, the rail-mounted robot is directed to the charging port using its stored position and orientation in the system database. Vehicle detection verifies that the vehicle is correctly positioned. As described above, this is achieved using two pressure sensors with an intervening radar sensor for additional safety.
- Vehicle identification is carried out in two ways: firstly, the license plate is read using a camera and license plate reading algorithm at the charging station, and secondly, the vehicle owner's identification is obtained via a mobile application.
- Charging authorization takes place after the charging gun, placed into the socket, is released by the robot and it moves away from the vehicle. Charging authorization is carried out by the charging station.

- The precise position and orientation of the charging gun holder pillar, the charging gun, and the vehicle's charging socket are determined by the camera located on the end-effector of the robotic arm.
- The charging gun is grabbed by the robot using a special gripper, inserted into the charging socket, then released, and the robot moves away from the vehicle.
- Following this, the charging process is launched by the charging station.
- After charging is completed or interrupted, the charging gun is removed from the vehicle by the robot in a manner similar to the steps above and returned to the charging gun holder pillar.
- During robot motion, workspace clearance is continuously monitored. If a person or obstacle is detected, the robot stops and resumes operation only after the workspace is clear.

5.1 Safety and Reliability Considerations

Automated conductive charging introduces system-level hazards, including collisions, foreign objects, contamination, connector damage, misalignment, incomplete insertion, unexpected vehicle movement, sensor or communication loss, power interruption, and emergency-stop activation. The control system should prevent charging until secure mechanical connection is confirmed and place the robot in a safe state whenever required sensing, communication, or authorization conditions are unavailable.

Reliability should be evaluated by logging each connection attempt and classifying failures by stage, from vehicle detection and port localization to insertion, charging authorization, and withdrawal. Acceptance testing should include nominal trials and fault-injection cases such as occlusion, unexpected obstacles, communication loss, localization errors, and power interruption. Following failed insertion, the robot should return to a collision-free recovery position and perform limited retries; persistent failure should terminate the sequence and request manual intervention. This provides traceable evidence of safe unattended operation beyond successful nominal demonstrations.

6 The Advantages and Challenges

Automated EV charging improves convenience by eliminating manual cable handling, particularly under adverse weather conditions. It can also support fully autonomous vehicle operation, enabling autonomous EVs to charge without human intervention and potentially improving the efficiency of urban transportation and logistics.

All automated charging systems face significant technical and economic limitations. Interoperability depends not only on the port standard but also on port location, door geometry, protective elements, approach space, sensing conditions, parking tolerance, and fault handling. Thus, a robot designed for one vehicle geometry may fail with another using the same connector. The following recommendations are therefore proposed, as design requirements derived from the compatibility analysis, not established standards.

1. Connector location and parking geometry: the port position should be declared and should remain inside the validated robot workspace for the allowed parking tolerance. A consistent front or side zone is desirable since it reduces required rail travel and manipulator reach, however the essential criterion is the quantitative reachability condition defined in Section 3.5.
2. Cover-door geometry: the door must not intersect the required end-effector and sensor/camera envelope. For side-hinged doors, an opening angle of at least 90° is used as the baseline criterion in this study. Larger side-opening or sliding doors are desirable since they increase clearance and reduce camera occlusion.
3. Protective caps and locking elements: any element that physically blocks the port must be absent from the approach corridor or actuated automatically before robot insertion. Eliminating a manually removable cap is desirable, however the essential requirement is that no manual action be necessary for the robot to complete the charging sequence.

Furthermore, the high development and manufacturing costs of automated systems may also hinder widespread adoption. Although the advancement of technology allows for the creation of such systems, the costs are still high, making this solution not necessarily accessible to users.

7 Conclusions

Robotic conductive charging can support unattended EV operation, but universal interoperability requires more than port standardization. This study systematically classifies vehicle-side geometric and operational barriers, including port location and orientation, cover-door configuration, protective elements, clearance, sensing visibility, parking tolerance and safety constraints.

An engineering compatibility framework translates these factors into measurable reachability, pose-error, clearance, and door-opening criteria and distinguishes essential requirements from desirable improvements. The analysis further emphasizes validation of the complete charging sequence, including localization or insertion failures, obstacle detection, emergency stops, and recovery. The study focused on vehicle-side robotic accessibility and does not propose a formal industry standard.

Future work should validate the criteria across a larger vehicle set and quantify success rates and tolerance limits for different robotic configurations.

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