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REGULAR PAPER

A review of robotic charging for electric vehicles

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Abstract

This paper reviews the technical aspects of robotic charging for Electric Vehicles (EVs), aiming to identify research trends, methods, and challenges. It implemented the Systematic Literature Review (SLR), starting with the formulation of research question; searching and collecting articles from databases, including Web of Science, Scopus, Dimensions, and Lens; selecting articles; and data extraction. We reviewed the articles published from 2012 to 2022 and found that the number of publications increased exponentially. The top five keywords were electric vehicle, robotic, automatic charging, pose estimation, and computer vision. We continued an in-depth review from the points of view of autonomous docking, charging socket detection-pose estimation, plug insertion, and robot manipulator. No article used a camera, Lidar, or Laser as the sensor that reported successful autonomous docking without position error. Furthermore, we identified two problems when using computer vision for the socket pose estimation and the plug insertion: low robustness against different socket shapes and light conditions; inability to monitor excessive plugging force. Using infrared to locate the socket yielded more robustness. However, it requires modification of the socket on the vehicle. A few articles used a camera and force/torque sensors to control the plug insertion based on different control approaches: model-based control and data-driven machine learning. The challenges were to increase the success rate and shorten the time. Most researchers used commercial 6-DOF robot manipulators, whereas a few designed lower-DOF robot manipulators. Another research challenge was developing a 4-DOF robot manipulator with compliance that ensures a 100% success rate of plug insertion.

Keywords Automatic charging · Electric vehicle · Robot manipulator · Systematic literature review

1 Introduction

Improvements in Electric Vehicle (EV) technology have multiplied in recent years, including technology related to the EV and its supporting facilities. EV development is leading to autonomous Electric Vehicles (AEVs). Alawadhi et al. (2020) consider that AEV technology substantially has the potential to mitigate many negative aspects. Magid et al. (2021) stated that pandemic conditions were a driving factor in using autonomous technology to help humans. Golbabaei et al. (2020) claim that AEV technology can create new opportunities for realising intelligent and sustainable urban mobility and offer fair and inclusive opportunities for young people, people with disabilities, and senior citizens. Kassens-Noor et al. (2021) identified a significant mobility gap between ordinary people and people with disabilities. People with special needs (blind, limited mobility) rely heavily on public transportation, and AEV has the potential to increase the mobility of this population. McLoughlin et al. (2018) stated that AEV has the potential to extend independent living for the older people, thereby increasing the overall quality of life. This statement aligns with Siegfried et al. (2021), who mentioned that AEV acceptance depends on the ability to interact with the vehicle and its facilities. The importance of this has been explained in a review article by Hersh (2015), that robots can help serve the needs of human life, especially people with disabilities and older people.

Several review papers discuss EV from perspectives of technology development (Sun et al. 2019; Un-Noor et al. 2017; Yong et al. 2015) and adoption (Coffman et al. 2016; Sun et al. 2019; Un-Noor et al. 2017). Un-Noor et al. (2017)

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describe the EV configuration, battery, electric machines, charging systems, and EV technology. The paper by Sun et al. (2019) provides an overview of developments in EV technology such as batteries and charging infrastructure. Technical challenges for increasing efficiency, reliability, and safety are also presented. Yong et al. (2015) comprehensively review EVs' development and the impact and deployment opportunities. According to Un-Noor et al. (2017), one of the problems with EVs is the adequate availability of charging stations. Similarly, Sun et al. (2019) argue that charging infrastructure is essential in EV deployment. Coffman et al. (2016), who identified external factors influencing EV adoption, agreed with these review results. The above references cover the technological development of EVs and underline the vital role of EV charging in promoting their adoption.

Review papers on EV charging have been reported by several researchers (Banguero et al. 2018; Leijon & Boström, 2022; Narasipuram and Mopidevi 2021; Rahman et al. 2016; Rajendran et al. 2021; Un-Noor et al. 2017; Yilmaz and Krein 2013). Un-Noor et al. (2017) also mentioned international charging standards and describe levels and characteristics for charging and various types of charging systems. Rajendran et al. (2021) present a detailed EV charging system, including power converters, structure, incentives for its development, standards, charging technology, and technology quantitative assessment. Narasipuram and Mopidevi (2021) provide an overview of various charging station designs categorised by the power used with diverse methodologies and optimisation techniques. It also discusses the off-grid mode of renewable energy, which is combined into the charging station infrastructure. The existence of storage and renewable energy can decrease the high loads on the grid, especially during peak-load periods. The review by Leijon and Boström (2022) explains several different EV charging strategies. Three existing types of charging include conductive charging, inductive charging, and battery exchange. The charging designs can comprise fixed or mobile scenarios. EV charging must consider the safety factor. It is critical to maintain the battery so that it does not overheat or fail. Yilmaz and Krein (2013) reviewed the application of charge levels, battery chargers, and EV infrastructure. Charging currents are categorised as DC or AC, whereas charge levels are categorised into three types: Level 1 (convenience), Level 2 (primary), and Level 3 (fast).

References by Rahman et al. (2016) and Banguero et al. (2018) review more specific aspects of EV charging. Rahman et al. (2016) present a study on charging infrastructure optimisation methods. It focuses on optimisation approaches and solving various problems for charging infrastructure. The review by Banguero et al. (2018) discusses battery technology. They explain the control methods for battery charge and discharge processes, focusing on their impact on battery life. Some research articles address issues regarding the impact of EV charging on the electrical power grid. Goli and Shireen (2014) proposed a smart charging station with solar panels beside the power grid. Similarly, a study by Traube et al. (2012) suggests an optimal charging control for a solar-based charging station.

Previously, researchers have pointed out the importance of charging infrastructure for EV deployment (Coffman et al. 2016; Sun et al. 2019; Un-Noor et al. 2017). Furthermore, Fisher et al. (2014) argue that one of the infrastructure problems with conventional charging stations is that users have to plug in the EV manually. In line with their arguments, we predict that automatic charging stations (ACSs) will accelerate EV deployment and become necessary to promote AEV adoption. ACSs are significant as supporting facilities to reduce passenger interaction on the AEV for disabled passengers, people with limited mobility, and the older people. We illustrate the concept of an ACS for AEV in Fig. 1. This ACS has the primary elements: an electrical power grid as the main energy source and a charging unit with complete functional features, including a charging cable and plug. It also has individual features or combination features of autonomous docking (auto-docking), a robot manipulator for conductive charging, a robot for underbody wireless charging, and a robot for battery swapping. The ACS may use power derived from a renewable source such as photovoltaic.

We systematically searched for review papers regarding EVs, EV charging, AEV, and robotic EV charging and we only found two review papers concerning robotic EV charging (Zang and Wang 2022) and (Bi et al. 2020). Zang and Wang (2022) provide an overview of approaches and robotic techniques used in battery disassembly. They concluded that previous EV battery robotic disassembly was schedule-based and recommended to be made unscheduled through artificial intelligence (AI). Bi et al. (2020) review robot manipulators used in fuel dispenser systems. They describe the advantages and disadvantages of automatic robotic refuelling systems. They underline that crucial technologies in the system are sensing and mechanisms for opening and closing the filling

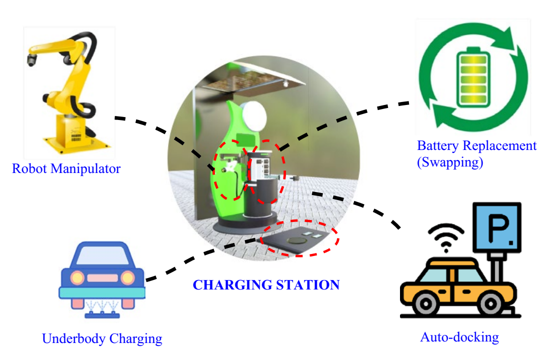

Fig. 1 An illustration of an ACS

cover, holder, and nozzle plug. This paper focuses on fossil fuel systems, not EVs. Fuel-based vehicles and EVs are significantly different from each other in terms of their propulsion system configurations.

We could not find any review papers published in recent years regarding EV charging equipped with robotic manipulators. To the best of our knowledge, this article is the first review article on charging stations with robotic manipulators. This study identified and analysed the research trends, methods, and challenges regarding the technical aspects of charging stations with robot manipulators. We used the Systematic Literature Review (SLR) method to collect and analyse 2912 articles published between 2012 and October 2022 and indexed by Web of Science, Scopus, Dimensions, and Lens.

Section I discusses the background and previous papers on several works of literature; Section II describes the research methodology; Section III presents the results and answers to the research questions; finally, the last section is the conclusion.

2 Methodology

This section uses the SLR method to describe the research questions, search strategies, article selection, and data extraction (Kitchenham et al. 2009; Wahono 2015). First, we formulated the research questions. Kitchenham et al. (2009) explain that Population, Intervention, Comparison, Outcomes, and Context (PICOC) criteria assist the literature review. The PICOC structure used in this study is shown in Table 1.

We defined the research questions (RQs) to maintain the focus of the review on specific targets. Table 2 shows the research questions addressed by this study.

RQ1 to RQ3 contain essential information that can help to evaluate the context of the main study. They provide trends, summaries, and synopsis of specific research areas in the charging station with a robot manipulator. RQ4 to RQ7 are the main research questions. To answer them, we extracted data regarding trends, methods, and challenges related to technical aspects of charging stations with robot manipulators in primary studies. We also designed a protocol to reduce bias and guide the review.

Table 1 Summary of PICOC

PICOC	Criteria
Population	Transportation technology, mechatronics, robotics
Intervention	Charging station, robot manipulator, methods, auto-docking, auto-parking, port detection, port recognition
Comparison	n/a
Outcomes	n/a
Context	Studies in industry and academia

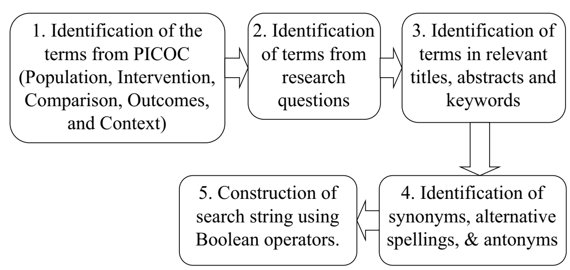

Fig. 2 Search string steps

Table 2 Research questions

ID	Research question	Motivation
RQ1	What is the research trendline in the charging stations with robot manipulators field?	Identify trendline research in charging stations with robot manipulators
RQ2	Which journal is the most significant for charging stations with robot manipulators?	Identify the most significant journals in the charging stations with robot manipulators
RQ3	Who are the most contributing and active authors in the charging stations with robot manipulators field?	Identify the most contributing and active authors by the number of documents in the field
RQ4	What are the key technologies in charging stations with robot manipulators?	Identify key technologies in charging stations with robot manipulators
RQ5	What methods/controllers are often used for charging stations with robot manipulators?	Identify the most used methods/controllers for charging stations with robot manipulators
RQ6	What sensors are used most often for charging stations with robot manipulators?	Identify the most used sensors for charging stations with robot manipulators
RQ7	Where might the research go next?	Identify the significant gaps in the research

Next, we established a search strategy by developing a search string and a search process flow chart. The search string stages were set with five steps (Fig. 2) (Wahono 2015). These steps helped the search so that the resulting string could obtain articles according to the needs of answering the research questions.

From the five steps, we formulated the following search strings based on logical expression: (Charging OR battery OR Recharging) AND (Manipulator OR Arm OR Robot) AND ((Autonomous OR driverless OR electric OR Automatic) AND (Vehicle OR Robot OR Car)).

We followed the flow chart of the search and selection process shown in Fig. 3. Each action was carried out sequentially. The number of articles obtained from each database was 345 from the Web of Science (WS), 1168 from Scopus (SC), 513 from Dimensions (DM), and 886 from Lens (LN). Therefore, the total number of articles for our review, based on the search result from four databases, was 2912 articles. We used Mendeley's software package to store and manage shortlisted articles.

We then selected articles based on our consideration of the inclusion and exclusion criteria, as shown in Table 3. The selection process of primary studies was conducted with the exclusion criteria based on the title, abstract, and full text. In addition to the inclusion and exclusion criteria, we also considered their relevance to the research questions. Similar articles by the same authors in various journals were removed. The final list included published papers from several journals and conference proceedings. Note that we set

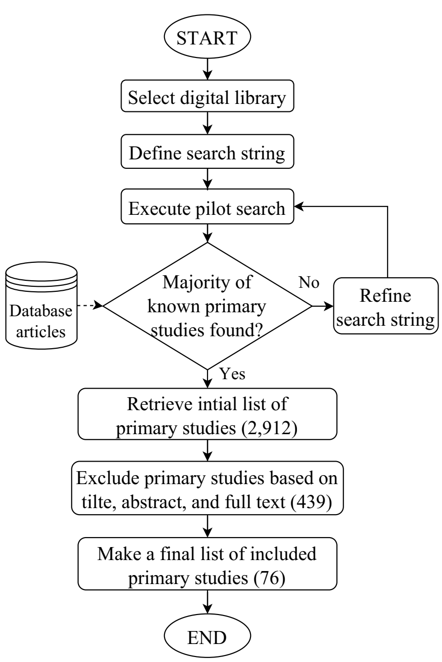

Fig. 3 Search and selection of primary studies

Table 3 Inclusion and exclusion criteria

Selection	Criteria
Inclusion	Peer reviewed
	Engineering field
	Only the most complete and newest one will be included for duplicate publications of the same study
	Publication of 2012 – October 2022
	Only the journal version will be included for studies with both the conference and journal versions
Exclusion	Studies overview (review articles)
	Studies not written in English

"review articles" as one of the exclusion criteria to focus on shortlisting "research articles" as the primary articles. However, prior to the exclusion, we used the "review articles" obtained through the SLR as references in the introduction of this paper.

Finally, we conducted data extraction iteratively on the selected primary articles to collect data that contributed to answering the research questions. The extraction form of a data table was made to facilitate data collection with a clustering system on several columns and rows. Table 4 shows the properties used to answer the research questions.

This study used the narrative synthesis method. We use bar charts, pie charts, tables, and other visualisation tools to facilitate the description in this paper. This review has analysed the study on technical aspects of charging stations with robot manipulators, including some statistical and machine-learning techniques.

3 Result and analysis

After selection, the number of primary articles obtained was 76 articles. They are listed in the table in Appendix A, where the reference numbers in the appendix can be used to trace the article's title in the list of references at the end of this paper. These primary articles' distribution based on the digital libraries is shown in Fig. 4.

In the next subsections, we present our review result and analysis of the primary articles in the following sequence: trend in the number of publications; significant publications and keywords; most active and contributing authors; key technologies, sensors, and methods; answer to the research questions and future challenges. The subsection of key technologies, sensors, and methods consumes the most space since we tried to identify and analyse in detail to get the comprehensive and thorough knowledge necessary to answer three research questions regarding key technologies, sensors, and methods.

Table 4 Data extraction properties mapped to research questions

Property	Research questions
Trendline research in charging station	RQ1
Publisher and Researchers	RQ2, RQ3
Charging station with robot manipulator key technology, methods/ controllers, and sensors	RQ4, RQ5, RQ6
Charging station with robot manipulator future research	RQ7

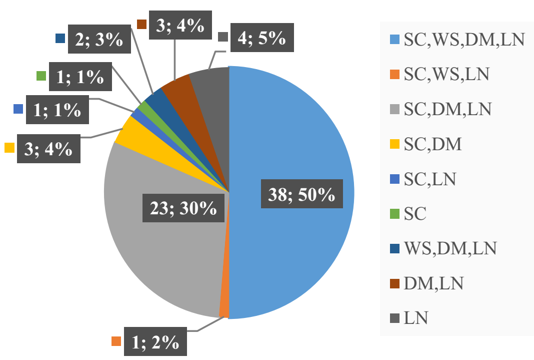

Fig. 4 Distribution of the primary articles based on digital libraries

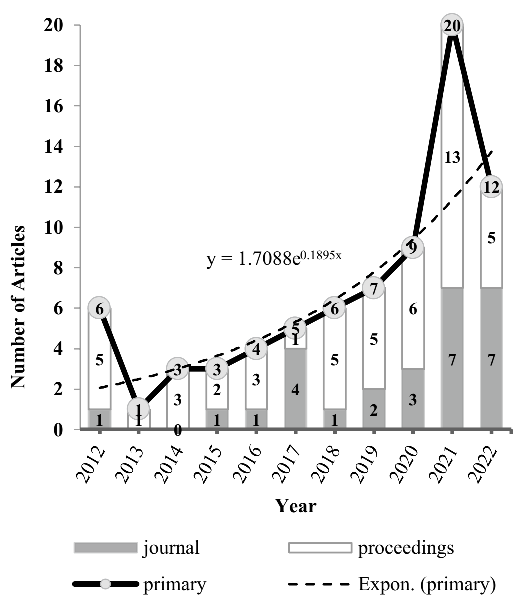

Fig. 5 The trend in the number of articles

3.1 Trend in the number of publications

The primary articles' distribution based on the year of publication is shown in Fig. 5. Recall that the articles were published from 2012 to 31st October 2022. The increase in the number of publications up to 2021 can be observed. A noticeable increase in 2021 shows that research interest is very high. The decrease in the number of publications in 2022 is not due to a decline in publications but rather because the retrieval from the article databases is still within the same year. The year 2022 has yet to end, so the data have yet to be fully recorded.

We can ascertain that the upward trend in the number of publications related to EV charging stations over the years is exponential growth. This trend is seen for the existing string combination, for example, "Charging Robot Electric Vehicle" and other string combinations we set in the previous section. One can expect that the number of publications will continue to rise in the next few years. It is in line with the development of EV technology in the future. Based on the data, the research area on charging stations is still relevant, especially concerning development in AEV.

3.2 Significant publications

According to the selected primary articles, the top 10 journals with the most citations are displayed in Fig. 6a. The top 10 proceedings with the highest number of citations are shown in Fig. 6b. Gray and white colours represent the number of documents and citations, respectively.

The total number of author keywords in 76 primary articles was 224. We then limited the keywords to those used by at least two papers and listed them in Table 5. In the table, there are 37 different author keywords that appear twice or more, with the total number of appearances of 112 (50%). It implies that keywords that appear only once count 112 (50%). From the table, we recognise that there is an explicit consistency between the top five author keywords and the search string: 13 articles (5.8%) mentioned "electric vehicle," 12 (5.4%) said "robotic," five (2.2%) cited "automatic charging," five (2.2%) said "pose estimation," and four (1.8%) mentioned "computer vision."

While we did not include "pose estimation" and "computer vision" in our search string, they came up in the top five of the author keywords. That is because they play an essential role in the automatic charging of EVs using robot manipulators. "Robot manipulator" appeared in three articles (1.3%). The other author keywords in the table may be implicitly linked to the search string. These keywords include, among others, autonomous, charging robot,

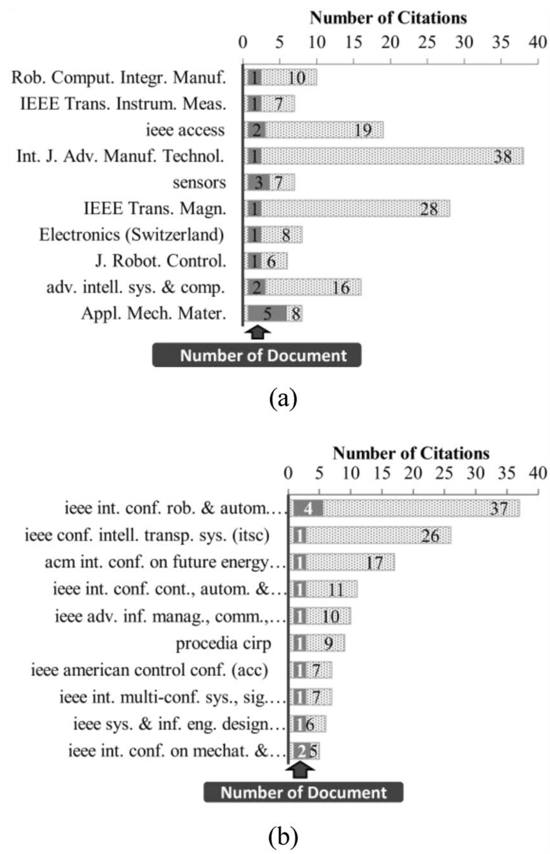

Fig. 6 Top sources: **a** journals; **b** proceedings

charging port recognition, deep learning methods, motion planning, and visual serving.

3.3 Most productive authors

Figure 7 shows the most productive and contributing authors. The authors were listed according to the number of articles included in the primary studies. Authors shown must have a minimum of three articles.

Xin Wang published five articles regarding robots for EV battery swapping (Shen et al. 2012; Wang and Wang 2014; Wang et al. 2015, 2012a, b) and one paper on a review of the technological development of EVs (Sun et al. 2019). H. Brunner, M. Hirz, and B. Walzel published five articles regarding vision-based robotic charging for EVs (Hirz et al. 2021; Miseikis et al. 2017; Walzel et al. 2019, 2021a, b). S. Di, Y. Lou, Z. Liang, H. Lin, and P. Quan published two articles concerning the recognition and localisation of EV charging ports (Quan et al. 2022a, b) and an article regarding collision localisation and classification on the end-effector of a cable-driven manipulator (CDM) for EV charging (2022) (Lin et al. 2022). S.Di and Y. Lou also published a paper on designing a CDM for EVs (2020) (Lou and Di 2020).

3.4 Key Technologies

Technology may be defined as the application of scientific knowledge for practical purposes. Let's consider an automatic charging scenario of an AEV or an autonomous mobile robot (AMR) at the ACS illustrated in Fig. 1:

Table 5 Most mentioned keywords

No	Keyword	Qty	No	Keyword	Qty
1	Electric vehicle	13	20	Ccs type 2	2
2	Robotic	12	21	Charging port recognition	2
3	Pose estimation	5	22	Charging robot	2
4	Automatic charging	5	23	Deep learning methods	2
5	Computer vision	4	24	Disassembly	2
6	Robot manipulator	3	25	Docking station	2
7	Autonomous mobile robot	3	26	Electric vehicle charging port	2
8	Battery swapping robot	3	27	F/t sensor	2
9	Charging	3	28	Factory automation	2
10	Ev charging	3	29	Image processing	2
11	Localization	3	30	Kinematic	2
12	Machine vision	3	31	Monocular vision	2
13	Mobile manipulator	3	32	Parallel robots	2
14	Mobile robot	3	33	Peg-in-hole	2
15	Autonomous	2	34	Ros	2
16	Autonomous driving	2	35	Sensor fusion	2
17	Battery swapping	2	36	Shape-based 3d-matching	2
18	Cable-driven manipulator	2	37	Vision	2
19	Cad shape models	2			

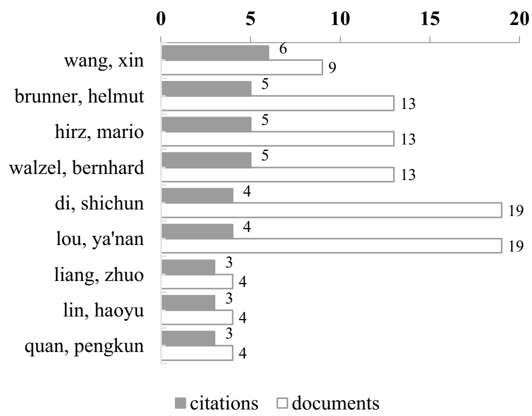

Fig. 7 Most active authors

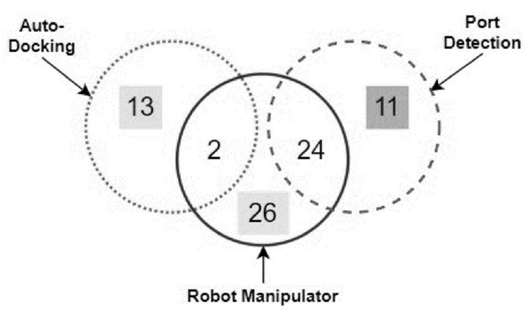

Fig. 8 Three clusters of the primary articles

(1) The AEV or AMR needs to identify the charging station's location autonomously and then dock to the proper pose at the station.
(2) The charging robot has to locate the pose of the charging port for conductive or inductive charging. In the case of battery swapping, the robot must be able to see and locate the posture of the battery that is to be replaced.
(3) The charging robot moves the charging plug from the charging unit to the correct position near the socket. It carries out the charging by a sequence of insertion, charging, and unplugging processes.

Therefore, we classified key technologies for automatic charging into three clusters: autonomous docking (auto-docking), port detection, and robot manipulator. Figure 8 illustrates the correlation of these critical technologies in the form of a Venn diagram. The robot manipulator may be installed at a stationary charging unit, a mobile charging unit, or at the AEV or AMR itself.

There are 15 articles related to auto-docking and robot manipulators, 35 articles related to port detection and robot manipulators, and 26 articles related to robot manipulators. Several documents discuss overlapping technologies with each other. This section identifies and analyses the primary articles from autonomous docking, port detection, and robot manipulator viewpoints.

We describe actual review results, including sensor type, autonomous docking method, methods for pose estimation of EV charging sockets, and robot mechanism and control for the charging plug insertion. Some articles experimented with their proposed designs and techniques and reported the success rate or accuracy. Appendix A summarises essential attributes of each article, including value proposition, the performance of the experiment, sensor types, number of degrees of freedom (DOF), compliance handling, digital processors and instruments, charging socket types, autonomous docking methods, socket detection and pose estimation algorithms, and plugging control methods.

3.4.1 Autonomous docking

Autonomous docking (auto-docking) is an AEV's first action to charge or replace its battery using a stationary charging unit. Autonomous docking requires two fundamental capabilities: charging location detection and autonomous motion control. We put the articles dealing with autonomous docking at the top part of Appendix A (1 to 15).

Although the SLR helped us in searching and selecting articles systematically, after reading the selected 76 primary papers, we found an article that is not suitable in the auto-docking cluster. Narvaez et al. (2021) developed an autonomous vertical take-off and landing (VTOL)—unmanned aerial vehicle (VTOL-UAV) docking system with a mobile manipulator. Hence, we did not make further review on it since our focus was on ground vehicles.

Most articles address automatic charging using stationary charging stations. However, only some articles reported using mobile robots for automatic battery charging/swapping. By considering the sensor type, the vehicle platform, and the operation mode of the charging station (stationary or mobile), we classified 15 articles in the auto-docking cluster into five categories:

1. Category 1: Small-size mobile robots that use cameras and predefined marks with four wheels drive (4WD) (Weng et al. 2016) or two wheels drive (2WD) (Cortes and Kim 2018; Du et al. 2021; Romanov and Tararin 2021);
2. Category 2: Small-size mobile robots that use non-cameras as the sensor, including light detecting and ranging (LIDAR) (Vongbunyong et al. 2021), laser range finder (Rocha et al. 2020), and infrared (IR) transmitter and receiver (Acosta Calderon et al. 2014; Chang et al. 2018; Rao and Shivakumar 2021);

3. Category 3: AEVs with front wheels steering systems that use laser scanner (Petrov et al. 2012) and IR camera (Klemm et al. 2016);
4. Category 4: Mobile robots for battery charging/swapping with 2WD (Behl et al. 2019; Fang et al. 2020) or with XYZ cartesian robot (Wang et al. 2012a, b);
5. Category 5; Not relevant to ground vehicle autonomous docking (Narvaez et al. 2021).

Figure 9 summarises several types of sensors used in the articles that belong to the autonomous docking cluster. In the followings, we analysed each article from the points of view of the sensor, the charging location identification algorithm, and the control method for autonomous docking.

Cameras are the most used sensor type for the autonomous docking of small-size mobile robots (Cortes and Kim 2018; Du et al. 2021; Romanov and Tararin 2021; Weng et al. 2016). The robots identify the charging locations by complex marker recognition (Weng et al. 2016), colour recognition (Cortes & Kim, 2018), and coloured simple marker recognition (Du et al. 2021; Romanov and Tararin 2021). Weng et al. (2016) used the covariance intersection (CI) algorithm to locate the predefined marker from an RGB-D camera and laser ranger. They did not disclose the motion control, and the experiment results did not describe docking accuracy. Cortes and Kim (2018) used the computer vision (CV) algorithm in OpenCV to track a red colour square with the camera. They used linear feedback controllers to move the robot's pose to the charging station. The robot used the CV to approach the target. Then it finished the docking process by detecting small misalignments using the misalignment-sensing coils. The robot could control its charging position within 5 mm. Du et al. (2021) used a red circle marker as the target and developed an algorithm based on the OpenCV library. They also used an IMU to measure the robot's orientation. They reported that the robot could not locate itself accurately, and further research is needed to improve the algorithm. Romanov and Tararin (2021) proposed a shape mark with a particular colour named ArIUco marker to locate its pose based on the geometric dimensions of the marker. The robot moved to the station using a simple procedure, relying on a rotation around its axis and a straight trajectory. They created the software using Robotic Operating System (ROS) and conducted experiments in the Gazebo simulator. In parallel, they check the presence of obstacles using a 2D LIDAR. From the simulation results, they achieved a docking accuracy of 5 cm.

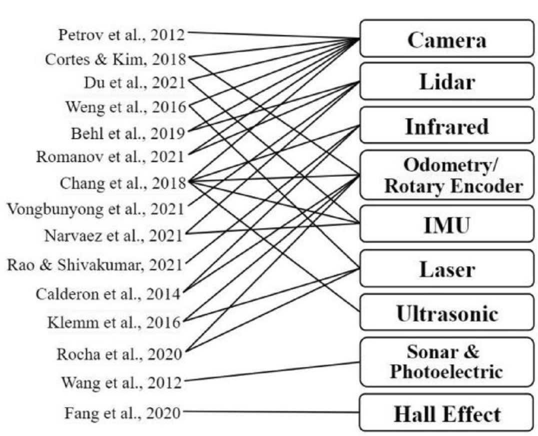

Fig. 9 Sensors used for autonomous docking

The other small-size mobile robots used LiDAR (Vongbunyong et al. 2021), laser range finder (Rocha et al. 2020), and IR (Acosta Calderon et al. 2014; Chang et al. 2018; Rao and Shivakumar 2021). Vongbunyong et al. (2021) used the RPLIDAR ROS package to process data points from the LiDAR to locate a geometrical marker on the station. Then, a state machine algorithm moved the robot to the station. From 20 times of experiments, they obtained the maximum position and orientation errors of 2.62 cm in the x direction, 1.91 cm in the y direction, and 0.015 rad in the heading. Rocha et al. (2020) resorted to a Beacon-based localisation algorithm using a laser range finder. However, they did not report docking accuracy. Acosta Calderon et al. (2014) used one IR emitter at the charging station and three IR receivers at the robot's back. The robot successfully docked at the station 23 times and failed twice because it turned entirely to one side. Chang et al. (2018) added three IR LEDs to the station to increase the existing IR signal range from 60 to 90 degrees. Since the existing IR sensor in the cleaning robot could not detect the added infrared LED signal, they installed an IR camera with the Raspberry Pi3. They concluded from the experiment results that the time spent by the sweeping robot to return to the station was reduced compared to the original sensor setup. Rao and Shivakumar (2021) used one IR transmitter at the docking station and one IR receiver in front of the robot. We did not evaluate it further because the robot's size is much smaller than mentioned above. The experiment scenario only used a fixed square path, lacking practical usage.

From the above review, we identified a research gap regarding the docking accuracy of small-size mobile robots, which includes sensing at the final docking step, a more accurate motion control method, and optimum charging connector mechanical design. When the robot has finished the target approach step and enters the final docking step, misalignment sensing is needed. A more accurate and robust control method will reduce the position and orientation errors along the trajectory.

We only obtained two articles from the SLR dealing with the autonomous docking of AEV for the charging process. Petrov et al. (2012) used an IR camera to estimate the vehicle's relative position to an IR LED pattern at the charging station through a coordinate transformation. They proposed a hybrid control method, a combination of time optimal and continuous control laws, to automatically dock the EV to the charging station. They obtained the precision for the docking manoeuvre 10 cm in the longitudinal and lateral directions around the docking point. Klemm et al. (2016) used laser scanners for localisation, mapping, and obstacle detection. The localisation process estimates the vehicle pose using an Extended Kalman Filter (EKF) to fuse information from odometry and 2D laser scanners. They used an incremental sampling-based motion planning algorithm to park the vehicle autonomously at the charging station. They reported a precision of 2 cm in the longitudinal position.

Autonomous docking is a subset of autonomous driving. We may get more abundant articles if we change the search string to autonomous driving or autonomous parking. To this end, the autonomous docking methods proposed in (Klemm et al. 2016; Petrov et al. 2012) are sufficient since a robot arm can perform the rest at the charging station.

Three articles presented conceptual designs of mobile charging robots without experimental results. Fang et al. (2020) proposed a 2WD mobile robot with an articulator. It charges EVs parking at specific locations in a parking lot by following a path preset on the parking lot. The authors used Hall effect sensors to track the fixed route on the ground. Behl et al. (2019) proposed a robot that can charge parked EVs in a parking lot at any location by navigating from the charging station to the EV location autonomously. It maps its surroundings and detects nearby objects with its LiDAR sensor. It distinguishes the parking lot boundary and the parking spot lines using its camera by the colour difference. Wang et al. (2012a, b) proposed a robot for EV battery replacement. It has a 4-DOF consisting of an XYZ cartesian robot with one rotational joint. They use sonar sensors to detect the distance between the robot and the platform.

3.4.2 Port detection and localisation

According to the automatic charging scenario at the ACS illustrated in Fig. 1, after the vehicle docking at the charging station, the charging robot has to recognise the charging socket and locate its pose. Then, the charging robot moves the charging plug near the socket and inserts the plug into the socket. Therefore, we need three essential tasks, i.e., socket recognition, socket localisation, and plug insertion.

There are several types of standardised charging plugs and sockets for conductive charging systems, i.e., Type-1, DC combined charging system (CCS) combo connector Type-1, Type-2, DC CCS combo connector Type-2, CHAdeMO Yazaki Connector, GB/T, and TESLA. Figure 10 summarises the primary papers that deal with each object type for battery charging and swapping.

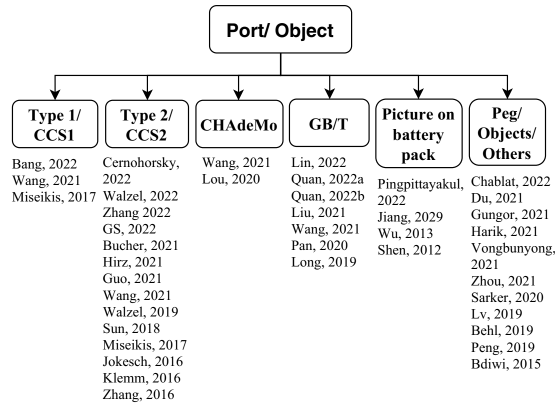

Fig. 10 Connector types for charging

Many articles use different sensor types to recognise and locate such standardised charging sockets without additional marks. Other papers use extra specific passive marks and active marks. On the other hand, limited articles described object detection and localisation for EVs' battery swapping.

As summarised in the middle rows of Appendix A, 35 articles in the port detection cluster propose values using several sensor types. We ranked the values according to the task levels. Based on the sensor types and the proposed values, we classified the primary articles in the port detection cluster into 11 categories as follows:

1. Category 1: Using cameras to recognise charging sockets (Bang et al. 2022; Cernohorsky and Jandura, 2019; Sun et al. 2018; Wang 2021).
2. Category 2: Using cameras to recognise and locate the socket position in the x–y plane (Zhang and Jin 2016).
3. Category 3: Using the camera and infrared-ultrasound (IR-US) range finder to recognise and locate the position in the x–y–z axes (Long et al. 2019).
4. Category 4: Using the camera to recognise and locate the socket position in the x–y-z axes and orientation Rx-Ry-Rz (Pengkun Quan et al. 2022a, b).
5. Category 5: Using cameras to recognise and locate the socket and insert the plug (Hirz et al. 2021; Miseikis et al. 2017; Pan et al. 2020; Pengkun Quan et al. 2022a, b; Walzel et al. 2019, 2021a, b; Zhou et al. 2021).
6. Category 6: Using cameras and Force/Torque (F/T) sensors to recognise and locate the sockets and insert the plugs (Guo et al. 2021; Liu et al. 2021; Lv et al. 2019).
7. Category 7: Using an endoscope camera with an IR-pass filter to recognise and locate the socket and insert the plug (Bucher et al. 2021).
8. Category 8: Focusing on force or impedance control for plug insertion using cameras and F/T sensors (Bdiwi et al. 2015; Jokesch et al. 2016; Zhang et al. 2022).

9. Category 9: Using cameras with the help of a marker or a QR code, but did not address specific charging socket localisation and plug insertion (Gungor and Kiyak 2021; Harik 2021; Park et al. 2021).
10. Category 10: Battery swapping (Jiang et al. 2019; Pingpittayakul and Mitsantisuk 2022; Shen et al. 2012; Wu et al. 2012).
11. Category 11: Not relevant to charging socket detection (Cernohorsky et al. 2022; Farhan et al. 2021; Luo and Shen 2020; Peng et al. 2019; Sarker et al. 2020; Xi et al. 2022).

All 15 articles in categories 1 to 5 use cameras to accomplish tasks with increasing levels, from only charging socket recognition to socket localisation and plug insertion. Three articles in Category 6 use cameras and F/T sensors to locate the socket and insert the plug. The article in Category 7 uses a specific camera that catches the infrared ray from infrared LEDs to find the socket and insert the plug. Although articles in Category 8 use cameras and F/T sensors, they only focus on force or impedance control for plug insertion. The articles in categories 9 to 11 are irrelevant to EV battery charging. In the followings, we analysed 22 articles that fall into categories 1 to 8 from the viewpoints of methods and performances. The performances may include socket recognition success rate, pose identification accuracy, insertion success rate, and insertion time.

Sun et al. (2018) and Wang (2021) used the convolutional neural network (CNN) models to recognise charging sockets. The model developed in (Sun et al. 2018) could identify the Type-2 socket with an accuracy of 99%. In (Wang 2021), they used a charging socket dataset from 40 different cars. They experimented with the recognition capability to divide the picture into two categories with, and without a socket. The results showed that the accuracy during the testing was 83.62%. Bang et al. (2022) proposed a novel image-to-image translation network, named the Environment Translation Generative Adversarial Network (EnT-GAN) that converts a given image into the environment described by the vector. They utilised contrast, brightness, and saturation to guide an environment. They obtained the average precision (AP) of the detection networks DetectoRS trained using the proposed EnT-GAN-augmented dataset 65.0, more significant than the ForkGAN-augmented dataset 63.6. Cernohorsky and Jandura (2019) only focused on the pattern matching of a CCS Type-2 socket using the Image Processing toolbox in MATLAB but did not describe the experiment result.

Zhang and Jin (2016) used the 2D image threshold segmentation based on the hue, saturation, intensity (HSI) colour model and the edge detection based on mathematical morphology, the Canny operator, and the Tukey weight function. They experimented using Halcon CV. From the results, the algorithm could locate the socket position in the x–y plane with an accuracy of 100%. Long et al. (2019) used the minimum distance iteration algorithm to estimate the x–y plane position. The split wide-angle range based on the IR-US range finder calculated the z-axis position. However, they did not report the evaluation results. Pengkun Quan et al. (2022a, b) adopted the Canny operator, the quadratic curve standardization (QCS), and the direct linear transform (DLT) to obtain the socket pose. Experiments reported the average socket posture accuracy for x, y, z, Rx, Ry, and Rz were 0.62 mm, 0.85 mm, 1.26 mm, 1.21 degrees, 1.00 degrees, and 0.52 degrees.

Miseikis et al. (2017) used the shape-based matching method to estimate the 3D socket location. It was performed using Halcon CV. They calculated perspective transformation to obtain the socket pose relative to the camera. They performed plug-in experiments for ten runs utilising a Type-2 connector when the socket cap opened. The experiment was successful three times, the plug was not fully inserted into the socket five times due to misalignment, and two times failed due to missed rotation. Walzel et al. (2019) define the sensor requirement of automated charging robots for EVs: an accuracy range from 0.1 to 1 mm and a maximum working distance of 10 m. Similar to (Miseikis et al. 2017), they used the shape-based matching method implemented in Halcon CV. They addressed the limitation of the detection accuracy (Miseikis et al. 2017) by improving the position and the field of view of the cameras. The method used the contours of known objects to determine the pose in a camera image. The 3D-shape model was obtained from a CAD model and comprised 2D projections of the 3D object from different views. They used the shape model to search for the object in an image and the 2D shape representations to find the best matching view in the matching process. They carried out 42 experiments with a CCS Combo 2 socket and reported 42 times of successful insertions. However, the article did not report experiment data during the insertion.

Walzel et al. (2021b) later define the socket pose detection requirement: the translational sensor demands are under 0.5 mm, and the rotational requirements are less than 1.4 degrees. The article presented the same system reported in (Walzel et al. 2019). Hirz et al. (2021) promoted that the system written in (Walzel et al. 2019) can be applied in industrial environments, e.g., logistics and warehouses. Walzel et al. (2021a) described the same system reported in (Walzel et al. 2019) with more detailed information regarding the edge detection quality with five different test vehicles. When the method was applied for vehicle classification and socket position detection experiments with five different test vehicles, the success rate was between 75 and 95%. The main difference was a curved surface compared to the standardised flat one.

Pan et al. (2020) described socket recognition based on CNN and its feature detection using image segmentation, edge detection, and ellipse fitting. The feature's centre coordinates and normal vector were obtained using the geometric method. They got an insertion success rate of 9/10 at the best illumination (1618–6151 lx). The maximum position error was − 2.1 mm at the y-axis, and the maximum orientation error was 2.6 degrees around the z-axis. Pengkun Quan et al. (2022a, b) used the experimental setup written in Pengkun Quan et al. (2022a, b). Similarly, they used the Canny operator and the DLT method. However, they proposed a cluster template matching algorithm (CTMA) replacing the QCS method for feature fitting. The test results concluded that the average positioning accuracy values in the directions of (x, y, z, R_x, R_y, and R_z) were 0.65 mm, 0.84 mm, 1.24 mm, 1.11 degrees, 0.95 degrees, and 0.55 degrees, respectively. The success rates of outdoor and indoor insertions were 93% and 99%, respectively. Zhou et al. (2021) adopted 3D point cloud technology to detect and locate the charging socket using the PointVoxel-Recursive CNN (PV-RCNN). Following the KITTI Vision Benchmark Suite, they established a real-time point cloud dataset from the 3D camera. From 50 experiments, the detection of the charging socket was 100%, and the plug-in success rate was 92%. However, they did not provide sufficient experiment data that support their claims.

Several articles used cameras and F/T sensors to locate charging sockets and to plug the charging connector into the socket (Guo et al. 2021; Liu et al. 2021; Lv et al. 2019). Lv et al. (2019) used Speeded Up Robust Features (SURF) algorithm to detect and match the socket feature. The Perspective-n-Point (PnP) algorithm was adopted to estimate the socket pose. Next, the force/torque data were analysed using a support vector machine (SVM). Based on the SVM results, they proposed an adjustment strategy for the plug-in-hole process. They concluded that the robotic plug-in-hole operation's force and torque values were within a reasonable range. Guo et al. (2021) used a visual servo to search the charging socket and roughly align the plug pose and the socket. It used the obtained image error for closed-loop feedback control. They used hue saturation value (HSV) to extract the charging socket features. Then, they used a reinforcement learning (RL) controller to control the planar (x–y) position and a PI force controller to obtain the displacement in the z-axis. They obtained an insertion accuracy of 97% and an insertion time of 9 s. Liu et al. (2021) used the template matching algorithm to identify, locate, and obtain the charging socket's pose. When the charging plug is in contact with the charging socket, the F/T sensor measures the force and torque data. They used SVM to classify the F/T sensor data into nine categories. They conducted 50 experiments and successfully inserted 47 times.

Bucher et al. (2021) used four infrared (IR)-LEDs and an endoscope camera with an attached IR-pass filter to locate the socket. This sensing arrangement reduced the necessity of image editing processes and increased the robustness against external light influences. Even at night, plugging is possible without an additional light source. They obtained a 97% success rate in insertion experiments.

Authors in (Bdiwi et al. 2015; Jokesch et al. 2016; Zhang et al. 2022) focused on force/impedance control by assuming the initial charging plug position is detected by a vision system with minor errors. The force/impedance control was used to compensate for the errors. Bdiwi et al. (2015) focused on force control to improve the socket plug-in using a six-component force/torque sensor mounted on the manipulator flange. The force control with spiral motion automatically corrected the error until the plug was completely inserted into the socket. The time required to complete the insertion task was around 80 s. They did not provide a success rate. Jokesch et al. (2016) proposed an algorithm of Cartesian impedance control for the peg-in-hole task during charging by a robot arm. The impedance control used torque sensors fixed at every robot arm joint. They obtained a 100% success rate in insertion experiments. Insertion was completed after 13 s since the first contact. Zhang et al. (2022) focused on plug insertion using impedance control and active remote center compliance (ARCC)-based strategy. They measured and plotted forces and torques on the x, y, and z axes. The success rate of insertion was 99%. The time required to complete the insertion task was about 6–8 s. The above three articles did not describe charging socket detection and localisation.

Park et al. (2021) derived formulas to calculate the relative position between the plug and the marker as well as the inclination and distortion angles using stereo images based on the calibration data from two cameras and the geometry of the marker. Harik (2021) presented the design and implementation of an autonomous charging station for a small agricultural electric tractor. He relied on a unique fiducial marker on the top of the charger socket. He implemented the USB Cam ROS package to obtain the RGB frames from the RGB camera and the Fiducial Markers ROS package to get the pose of the marker. Gungor and Kiyak (2021) used QR code technology and image processing methods by bringing the central point and width of the QR code to the specified value range. They wrote a conceptual design of the automatic charging system for EVs. The experimental results were not provided by them.

Some articles dealt with battery swapping (Jiang et al. 2019; Pingpittayakul and Mitsantisuk 2022; Shen et al. 2012; Wu et al. 2012). We did not review these articles thoroughly since battery swapping has the limitations of high cost and limited variability in view of servicing different vehicle types with varying battery sizes.

Moreover, we did not make an in-depth review of other articles due to specific reasons: Peng et al. (2019) focused on aviation charging; Sarker et al. (2020) used 2D LIDAR for obstacle avoidance of a small mobile robot; Luo and Shen

(2020) presented overall aspects of a conceptual design of automatic charging system; Farhan et al. (2021) described a robot arm for electronic components disassembly; Cernohorsky et al. (2022) only described the design of robotic plugging of CCS Type-2 connector, but the design concept was not firm, and the content was not complete; Xi et al. (2022) presented critical technologies for an underground inspection robot.

From the above review and observing Appendix A, we noted the following findings and research gaps:

1. Although the articles in Category 5 claim that they successfully inserted the charging plug into the socket, they did not provide sufficient experimental data to support the claim, such as insertion forces/torques from the first contact until the insertion end and insertion time (Hirz et al. 2021; Miseikis et al. 2017; Pan et al. 2020; Pengkun Quan et al. 2022a, b; Walzel et al. 2019, 2021a, b; Zhou et al. 2021). Moreover, the robustness against different charging socket shapes and light conditions needs improvement, as stated in (Pan et al. 2020; Walzel et al. 2021a).
2. The articles in Category 6 that use cameras and force/torque sensors to address charging socket pose estimation and plug insertion provide sufficient experimental data that prove successful insertion (Guo et al. 2021; Liu et al. 2021; Lv et al. 2019). However, the insertion success rate needs to be increased, and the insertion time may be shortened.
3. The article in Category 7 possesses strong robustness against external light influences, but this method requires charging socket modification in the vehicle (Bucher et al. 2021).
4. Although the articles in Category 8 use camera and force/torque sensors, they do not describe socket pose estimation. They focus on force or impedance control for inserting the plug into the socket by assuming that the initial pose of the charging plug is just near the charging socket and ready to move to the first contact with the socket (Bdiwi et al. 2015; Jokesch et al. 2016; Zhang et al. 2022).
5. Regarding charging plug insertion control, articles in Category 6 use machine learning algorithms, whereas articles in Category 8 use force or impedance control methods.

More details on the outcomes of insertion control methods are summarised in Table 6. We only listed the most relevant references that provide the success rate of insertion experiments. Instead of "success rate," the authors in (Guo et al. 2021) used "accuracy."

Table 6 shows that the model-based approach gives the best result regarding the success rate of plug insertion experiments and insertion time (Zhang et al. 2022). Since the initial insertion pose is significantly affected by the performance of charging socket pose estimation, in the followings, the charging socket pose estimation is further analysed.

Recall that among the four articles in Table 6, articles (Jokesch et al. 2016; Zhang et al. 2022) do not describe the socket pose estimation. Article (Guo et al. 2021) shortly describes the pose estimation method. They use conventional image processing algorithms, including HSV, circle identification, and the Hough transform. Article (Liu et al. 2021) does not describe the pose estimation. These articles only use one type of charging socket, i.e., GB/T 20234 charging socket.

Only four articles describe the socket pose estimation methods and reported their performances of experimental results (Pengkun Quan et al. 2022a, b; Pan et al. 2020; Miseikis et al. 2017). They used conventional image processing algorithms based on filtering, geometric method, ellipse lemmas, Canny operator, PNP algorithm, and DLT. Article (Pan et al. 2020) used the LeNet-5, a classic CNN, only to detect the charging plug, and the rest calculation was conducted using the conventional image processing algorithm.

Table 6 Plug insertion experiment outcomes

Approach	Ref.: Experiment Outcomes: Success rate or accuracy (%) Insertion time (s) Initial pose constraints
Machine learning	Guo et al. (2021) (1) 97%. (2) 9 s. (3) Initial position error is limited to 5 mm without orientation error
	Liu et al. (2021) (1)94%. (2) 8 s. (3) Initial position error is 1 cm with orientation error
Model-based	Jokesch et al. (2016) (1) 100%. (2) 13 s. (3) Initial position in front of the socket is 3 cm, initial orientation error is 5.1°
	Zhang et al. (2022) (1) 99%. (2) 6–8 s. (3) Initial position in front of the socket is 1 cm

It is worthwhile to underline that all these articles deal with only one type of charging socket.

Wang (2021) used a deeper conventional CNN with 19 weight layers, known as VGG, to detect various types of charging sockets. Bang et al. (2022) used the DetectoRS object detection network to detect two types of charging sockets. The network relies on ResNet-50 as the Backbone, having 48 convolution layers, one MaxPool layer, and one Average Pool layer. However, these two articles only describe socket detection and do not deal with its pose estimation.

Zhou et al. (2021) adopted 3D point cloud technology to detect and locate the charging socket using the PointVoxel-Recursive CNN (PV-RCNN) based on a dataset measured by a 3D camera. The raw 3D point clouds are labeled by cuboid annotation, and the PV-RCNN produces the classification, position, orientation, and dimension of cuboid boxes. However, they did not report the socket position and orientation errors from experimental results.

Robotic charging requires fast processing time. However, all the above charging socket pose estimation methods do not discuss processing time. In searching for image segmentation and classification algorithms using CNN that provide fast processing time, we found two articles outside our searching string in the SLR process. Ranjbarzadeh et al. (2021, 2022) developed swallow CNN models with multi-route feature extraction layers that provide satisfactory object segmentation performances and fast processing time. Their methods rely on multi-route feature extraction layers, multi-modalities, and powerful image pre-processing algorithms.

3.4.3 Robot manipulator

Recall the charging scenario at the ACS illustrated in Fig. 1. After the vehicle docking at the station, the charging robot moves the charging plug from the standby pose to an appropriate approaching pose near the charging socket and inserts the plug into the socket. Several robot mechanisms have been developed to accomplish this task.

Figure 11 shows a timeline of robot manipulator prototyping for EV charging from 2013 to 2022. Several robot mechanisms, including snake-like manipulators, cartesian robots, serial mechanical manipulators, parallel links manipulators, serial-parallel links manipulators, delta-parallel links manipulators, and flexible arms can be observed. Some robotic charging system prototypes use commercialised industrial robot manipulators, while others use their dedicated designs.

A few robot manipulator types in Fig. 11 were published online for public audiences, such as Powerhydrant robot, TU-Dortmund, VW eSmart connect, Metal Snake (Tesla), and EVAR Samsung electronics. The others were published in scientific publications. We only analysed these scientific articles, neglecting non-scientific publications.

Besides accuracy, the robot's degrees of freedom (DOF) determine its capability to insert the plug into the socket. We classified robot mechanisms based on DOF, as shown in Fig. 12.

A closer review found that the robot manipulators listed in Fig. 12 were for ground EV charging and other purposes. Moreover, we have reviewed, in the previous subsections, the performances of robotic charging systems in several articles overlapping with the robot manipulator (RM) cluster and the other clusters (see Appendix A), i.e., the primary articles in the PD cluster that overlap with the RM cluster (Bdiwi et al. 2015; Bucher et al. 2021; Cernohorsky et al. 2019, 2022; Guo et al. 2021; Harik 2021; Hirz et al. 2021; Jokesch et al. 2016; Liu et al. 2021; Long et al. 2019; Lv et al. 2019; Miseikis et al. 2017; Pan et al. 2020; Pengkun Quan et al. 2022a, b; Walzel et al. 2019, 2021a, b; Zhang et al. 2022; Zhou et al. 2021), and the primary articles in the AD cluster that overlap with the RM cluster (Behl et al. 2019; Wang et al. 2012a, b). Therefore, for the subsequent in-depth review, we classified the primary articles that only belong to the RM cluster into nine categories (see Appendix A):

1. Category 1: Conductive charging for ground EVs with a 6-DOF robot manipulator (Yuan et al. 2020);
2. Category 2: Conductive charging for ground EVs with a 4-DOF cable-driven automatic charging robot (CDACR) (Lin et al. 2022; Lou and Di 2020);
3. Category 3: Conductive charging for ground EVs with 3-DOF parallel links (Chablat et al. 2022);
4. Category 4: Conductive charging for mobile robots with 3-DOF parallel links (Okunevich et al. 2021a, b);
5. Category 5: Conductive charging for ground EVs with a rigid-flexible manipulator (GS & PS 2022);
6. Category 6: A compliant mechanism (Hu et al. 2020);
7. Category 7: Inductive charging for ground EVs with a 3-DOF manipulator (Barzegaran et al. 2017);
8. Category 8: Robot mechanisms for battery swapping of EVs (Sun et al. 2014; Wang et al. 2012a, b; Wang and Wang 2014), electric buses (Lin et al. 2012; Wang et al. 2015), small mobile robots (Dandan et al. 2012), or small UAVs (Barrett et al. 2018; Dong et al. 2018);
9. Category 9: Robot manipulators that are irrelevant to battery charging or swapping of ground EVs.

Table 7 lists the selected articles that use robot manipulators for the conductive charging of ground EVs. From 2015 to 2022, the most widely used robot manipulators have 6-DOF, and all those serial mechanical articulated robots are commercial robots. They have a payload range from 3 to 10

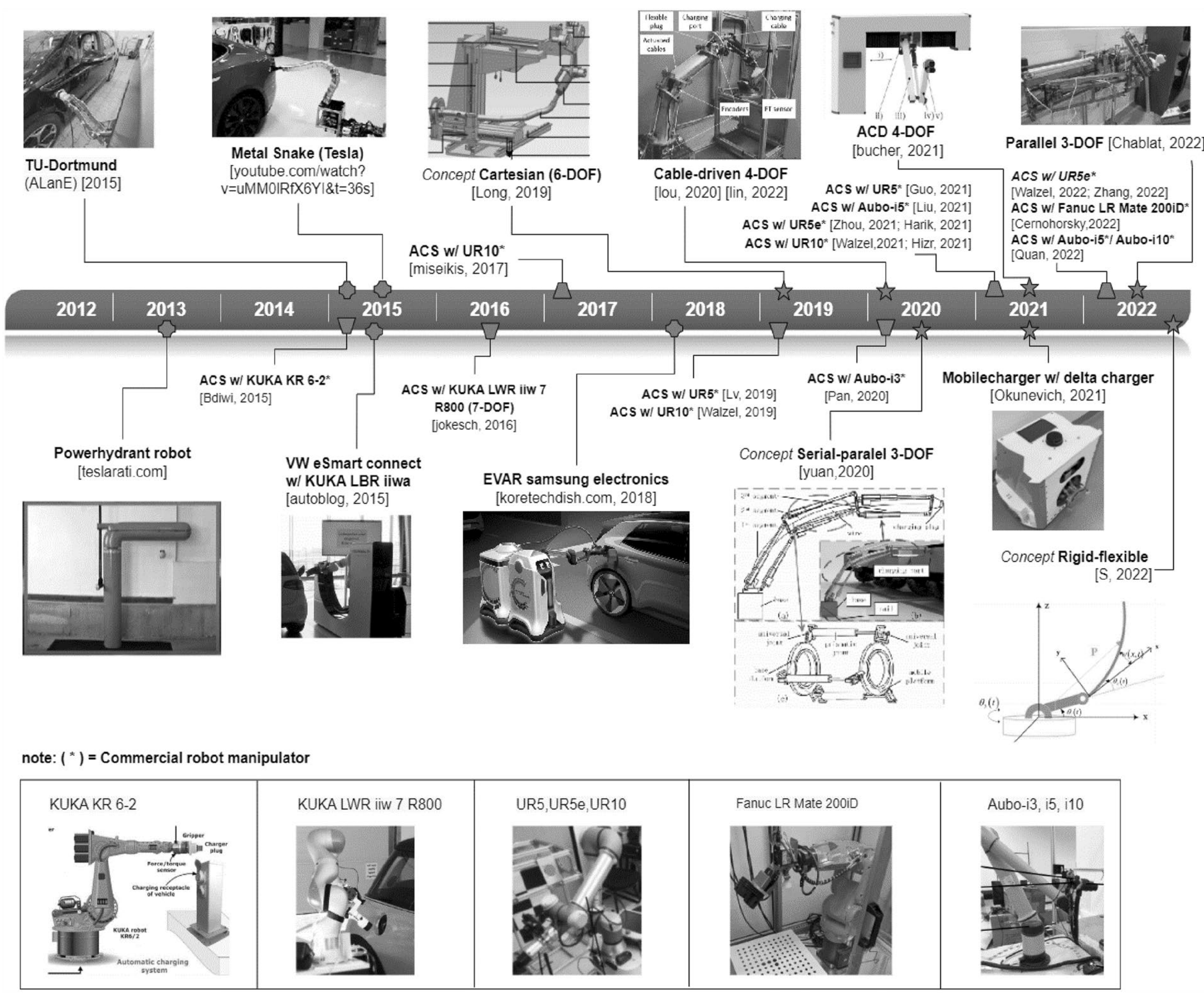

Fig. 11 Timeline of robot manipulators prototyping for EV charging

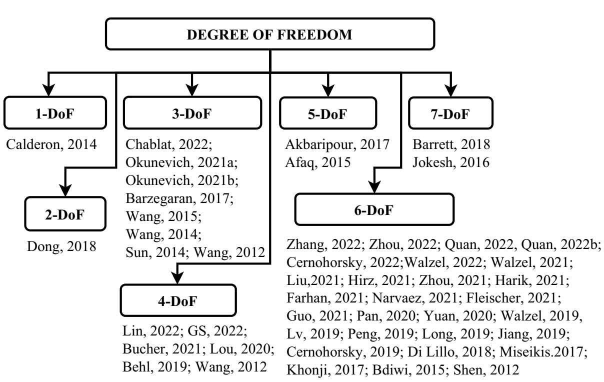

Fig. 12 Robot's DOF in the primary articles

kg and repeatability from ± 0.01 to ± 0.1 mm. Most of them have been implemented in experiments by researchers to evaluate the performance of charging plug insertion into the charging socket. Cernohorsky et al. (2019), in Fig. 12, only focused on image processing. Therefore, it was excluded from Table 7. In the followings, we review articles that belong to the RM cluster.

To provide a larger payload, more cable arrangement convenience, and dexterity, Yuan et al. (2020) proposed the design of a hybrid serial-parallel robot. It comprises three 3 universal-prismatic-universal parallel mechanisms arranged in serial and has nine actuating DOFs to realize six DOFs movements. The article focuses on addressing kinematics and static models and optimising the configuration, the unit length, the unit diameter, and the actuating force. Long et al. (2019) proposed a design concept of 6-DOF robots by combining 3-DOF translational and 3-DOF rotational motions to accommodate higher power that necessitates a larger payload. But their design is still preliminary, and they did not report experimental results.

Lou and Di (2020) developed a 4-DOF cable-driven automatic charging robot (CDACR) with a 3-DOF cable-driven manipulator and a moving platform. The robot could control

Table 7 Robot manipulators for conductive charging of ground EVs

#Arm types (Ref.)	DOF	Payload (kg) & Repeatability (mm)	Remarks
#KUKA LWR iiwa 7 R800 (Jokesch et al. 2016)	7	7 & ± 0.1	Commercial robot manipulator with serial mechanical articulators
#KUKA KR 6–2 (Bdiwi et al. 2015)	6	6 & ± 0.05	
#UR10 (Hirz et al. 2021; Miseikis et al. 2017; Walzel et al. 2021b, 2019)		10 & ± 0.1	
#UR5 (Guo et al. 2021; Lv et al. 2019)		5 & ± 0.1	
#AUBO-i3 (Pan et al. 2020)		3 & ± 0.03	
#UR5e (Harik 2021; Walzel et al. 2021a; Zhang et al. 2022; Zhou et al. 2021)		5 & ± 0.03	
#AUBO-i5 (Liu et al. 2021; Pengkun Quan et al. 2022a, b)		5 & ± 0.02	
#AUBO-i10 (Pengkun Quan et al. 2022a, b)		10 & ± 0.05	
#LR Mate 200iD (Cernohorsky et al. 2022)		7 & ± 0.01	
(Yuan et al. 2020)	6	N/A	Concept
(Long et al. 2019)	6	N/A	Concept
(Bucher et al. 2021; Lin et al. 2022; Lou & Di 2020)	4	N/A	1-DOF translational and 3-DOF rotational
Parallel links (Chablat et al. 2022)	3	N/A	Charging EV at home
#Parallel links: #MobileCharger #DeltaCharger (Okunevich et al. 2021a, b)	3	N/A	Charging small mobile robots

the position and pitch angle of the end-effector. They fixed a flexible plug at the end-effector to accommodate small rotational elastic deformation due to angular errors of the end-effector relative to the charging socket. They conducted preliminary experiments by varying translational displacement along the x-axis from − 78 to 123 mm and a yaw angle from − 5 to 5 degrees. They reported that the plugging-unplugging interaction forces could satisfy the requirement while all cable tension kept positive. However, they did not count the success rate. Lin et al. (2022) used IMU to locate and classify collision at the end-effector of the CDACR previously developed by Lou and Di (2020). They proposed a collision and localisation method based on machine learning algorithms (CNN and SVM). From the simulation, they claimed the technique could provide localisation classification simultaneously.

Bucher et al. (2021) developed an articulating arm with a reverse configuration called the 4-DOF automatic connection device (ACD). It comprises a 3-DOF articulator, a translational moving platform, and a flexible compensation unit. They examined in which area the flexible compensation unit works successfully through experiments. They varied the yaw and roll angles. Three experiment sets were conducted with different pitch angles, and from 27 tests, twice failed under the following two inlet orientations (pitch = − 7.5°, yaw = − 7.5°, roll = − 6°) and (pitch = − 7.5°, yaw = 7.5°, roll = − 6°). The connector entered the inlet but was canted and could not be fully inserted.

Chablat et al. (2022) developed a 3-DOF robot for charging an EV with the charging socket on its front side, especially for charging at home. They presented a detailed kinematics analysis and an experiment video showing that the charging plug was successfully inserted into the socket. Okunevich et al. (2021a) developed a DeltaCharger mechanism with a parallel link structure for charging small mobile robots. It comprises a setup ring with three servomotors, a moving platform as the end-effector with two electrodes, and three parallel links that connect the setup ring with the end-effector. Okunevich et al. (2021b) installed the DeltaCharger (Okunevich et al. 2021a) on a mobile robot for charging other mobile robots. They named it MobileCharger. This design uses two electrodes attached to the charging and main mobile robots. The charging is carried out by contacting both sides of the electrodes.

GS and PS (2022) derived a dynamic model of the rigid-flexible manipulator based on the Euler–Bernoulli beam theory. They designed a joint angle controller using Adaptive Fault-tolerant control (AFTC). They did not elaborate on charging port recognition and localisation using the You Only Look Once (YOLO) model. They only provided preliminary simulation results of the joint angle tracking and the end effector x–y trajectory. Hu et al. (2020) developed a compliant mechanism for the automatic charging robot end-effector. It is based on Stewart parallel mechanism. Experimental results showed that the maximum position deviation adaptabilities were 5 mm in the x-axis direction and 9 mm in the z-axis. The maximum rotational deviation adaptabilities were 7 degrees around the x-axis and 6 degrees around the z-axis. It could insert the plug with a maximum insertion force of less than 100 N.

Only one article describes inductive charging using a robot manipulator Barzegaran et al. (2017). They designed a 3-DOF manipulator attached to the vehicle's undercarriage carrying the receiving coil that places it right on top of the transmitting coil. Since 2017, limited articles have reported inductive charging for vehicles using robot manipulators.

From 2012 to 2019, researchers had proposed robots for several battery-swapping systems. However, no scientific publications have been on battery-swapping robots since 2020 until the end of 2022. Articles in AD and RM cluster (Behl et al. 2019; Wang et al. 2012a, b); PD and RM cluster (Jiang et al. 2019; Shen et al. 2012); and RM cluster (Sun et al. 2014; Wang et al. 2012a, b; Wang and Wang 2014) proposed robots for battery swapping of ground electric vehicles. Lin et al. (2012) and Wang et al. (2015) designed robots for electric bus battery swapping. A robot for small mobile robot battery swapping was designed by Dandan et al. (2012). Dong et al. (2018) and Barrett et al. (2018) proposed robots for small UAV battery-swapping systems. Note that the robot manipulator used by Barrett et al. (2018) has 7-DOF.

Other articles in Fig. 12 do not focus on robot manipulators for battery charging or swapping of ground EVs. See the articles at the bottom of Appendix A to find out the values proposed by those articles. For example, Jiang et al. (2017) developed a robot manipulator for the maintenance of high-voltage (HV) transmission lines, Di Lillo et al. (2018) built an underwater vehicle manipulator system, and Fleischer et al. (2021) designed a flexible disassembly system for drive train components of EVs. We did not review further articles in this category.

After reviewing thoroughly on all the articles that proposed new designs or developed new robot mechanisms for ground EV battery charging, we found some research gaps as follows:

1. The hybrid serial-parallel robot proposed by Yuan et al. (2020) requires nine actuating DOFs to achieve six DOFs movements, increasing complexity and risk of failure.
2. The 4-DOF CDACR developed by Lou and Di (2020) requires at least seven actuators. The speed and range of motion of this robot are limited. Moreover, the unidirectional constraints may substantially reduce the power efficiency of the actuators and require further investigation.
3. The 4-DOF ACD developed by Bucher et al. (2021) could insert the charging plug with a success rate of 97%. The remaining 3% was due to the connector entering the socket, which was canted and could not be fully inserted.
4. The 3-DOF parallel links manipulator developed by Chablat et al. (2022) will mostly fail to insert the charging plug into the socket when the socket height and tilt angle differ from the initial setting. The tilt angle needs to be readjusted manually.

3.5 Answers to the research questions and research challenges

This paper delivers a comprehensive review of autonomous robotic manipulation approaches in the field of charging stations for electric vehicles. Seventy-six recent papers have been selected through the SLR and thoroughly reviewed. All these papers were analysed by prioritizing three key technologies: autonomous docking, charging port detection, and robot manipulators. Figure 13 highlights the answers to all research questions implemented in this study, including research trendline, significant journal publication, most active authors, key technologies, sensors, methods, and challenges. See Appendix A for the details of key technologies, sensors, and methods.

In general, the followings are the research challenges that we identified:

1. The success rate of charging plug insertion is affected by several factors, including the vision system accuracy and robustness, the components' tolerances, mechanical deviation, temperature extension, vibration, and motion control.
2. Two critical factors rooted in CV that lead to failed charger plug insertion are calibration errors, including camera and hand-eye calibration errors, and feature detection errors, mainly from the pixel extraction error in the threshold segmentation, edge detection, and fitting process.
3. The edge detection quality in CV is negatively affected by light intensity variation, shadow, and camera angles.
4. A slight misalignment can lead to excessive plugging contact force, yielding jamming or damage. Under complex, varying lighting conditions in the actual scene, it is more challenging to increase the accuracy further.
5. Optimum design of a compliant element at the end-effector of the robot manipulator capable of compensating for the pose error is due to the limitation of the sens-

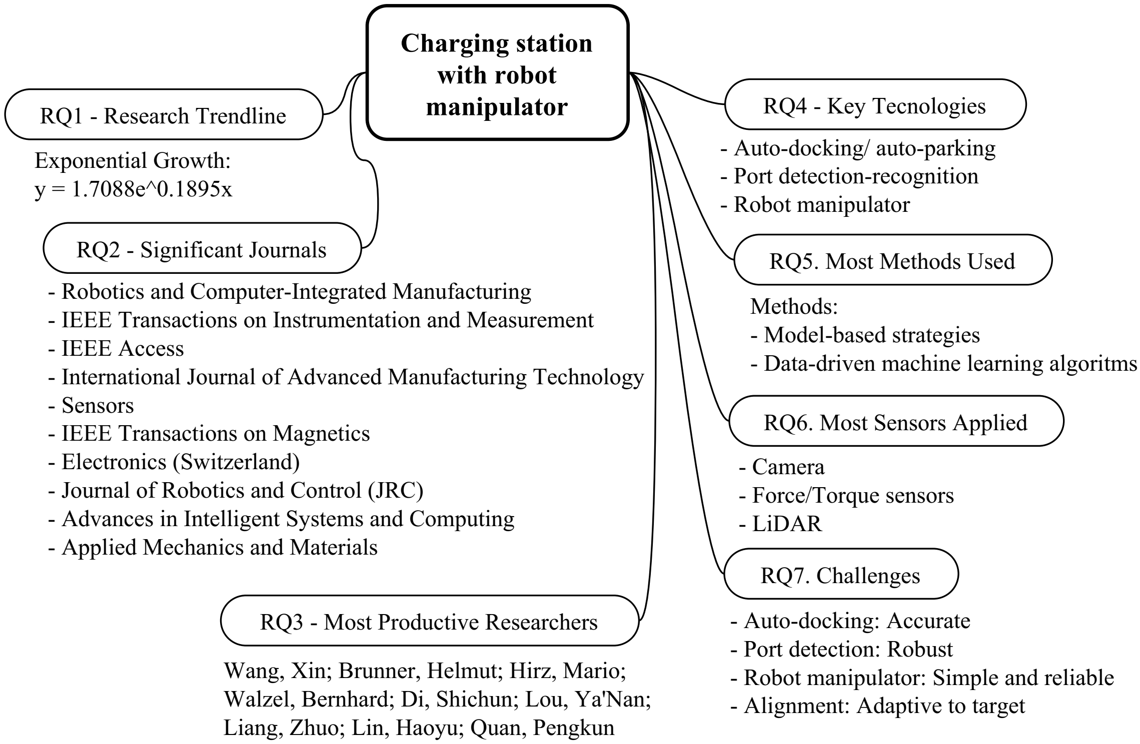

Fig. 13 Answers to the Research Questions

ing system and control system under varying complex environments.

6. Several EVs from different manufacturers have different locations where their charging socket is located, as listed by Wang (2021). The charging socket may be located on the left side, the back, the right side, or the front side of the EV. These location differences put additional challenges in designing a low-cost, high-fidelity robot manipulator for charging EVs.

In particular, we are challenged by a requirement to design a robot manipulator, as simple as possible yet reliable for EV automatic charging. To this end, a 4-DOF robot manipulator with a compliant device can fulfil this requirement. However, such a 4-DOF manipulator should be optimised by taking into account the following factors:

1. Payload limitation. We must design the structure of a robot manipulator that can handle the charging plug with its cable that may be assumed to have a mass of 3 kg/m.
2. Boundaries of the robot manipulator workspace. We must determine the robot manipulator's range of motion and the end-effector's pose to be compatible with vast EV classes.
3. Boundaries of the sensor system, e.g., the camera position, limits the field of view.
4. Accuracy and robustness of the charging socket's pose estimation method using the sensing system for different EVs under varying light conditions.
5. Accuracy and robustness of the charging socket's pose control from the initial standby pose to the insertion start position.
6. Accuracy and speed of the charging plug insertion control from the insertion start position to the first contact and finally to the insertion end.

The most significant open question is: how to design a more accurate and robust charging socket pose estimation system for various socket types under varying light conditions. See the deep analysis in the last part of Sect. 3.4.2.

We identified the main problems which are socket pose estimation and plug insertion. To solve the problems, we suggest developing a more accurate and robust socket pose estimation system based on CV by controlling an illuminator to regulate lighting conditions and exploring alternatives of neural-network structures, model parameters, and hyperparameters. We suggest information fusion using CV and force/torque sensor for plug insertion.

There are 45 international standards for electric vehicle charging stations, as reported by Rajendran et al. (2021). Most are related to electrical aspects such as plugs, sockets, connectors, converters, controllers, power quality, and others. To the best of our knowledge, there are no standards and regulations for robotic charging systems yet. This review will impact standards development, particularly regarding the robotic aspect and location of charging sockets in the EVs to make them safer and more efficient.

4 Conclusion

Our statistical analysis reveals that the number of publications related to EV automatic charging stations, indexed by Web of Science, Scopus, Dimensions, and Lens, has increased exponentially since 2013. The top five author keywords are electric vehicle, robotic, automatic charging, pose estimation, and CV. The three author groups each published the most articles respectively on EV battery swapping, vision-based robotic charging for EVs using commercial 6-DOF manipulators, and the development of a 4-DOF cable-actuated manipulator for EV charging.

Regarding autonomous docking, researchers relied on a camera, Lidar, Laser, or Infrared as the primary sensor to locate the charging station, but most used a camera based on CV. Some researchers used a combination of the primary sensors, while others combined one of those main sensors with an IMU or encoder. Several motion control methods have been developed, such as an incremental sampling-based motion planning algorithm and a hybrid control that combine time optimal and continuous control laws for autonomous docking. However, no article that used a camera, Lidar, or Laser as the sensor reported successful autonomous docking without significant position error. Position error remained persistent. One way to overcome this problem is to develop a more precise and robust control method, which is quite challenging due to non-holonomic constraints. Another way is to borrow the ability of a robot manipulator to complete automatic charging.

Most articles detected the charging socket, estimated its pose, and inserted the charging plug into it using only a camera based on CV (algorithm-based approach). However, we identified two problems: low robustness against different charging socket shapes due to vehicle variation and light conditions due to a time-varying complex environment; inability to monitor and avoid excessive plugging contact force that could yield jamming or damage. On the other hand, an article used infrared LEDs combined with an endoscope camera with an IR-pass filter to locate the socket (hardware-based approach), which made it robust against external light influences. Nevertheless, the risk of excessive contact force remains. Moreover, this approach requires modification of the charging socket on the vehicle. A few articles used a camera to detect and locate the charging socket pose and force/torque sensors to monitor and control the plug insertion into the socket, which is a preferable option for us. The challenges are to increase the insertion success rate and shorten the insertion time.

Regarding the control method of the charging plug into the socket, some researchers adopted model-based force/impedance control. In contrast, others applied data-driven machine learning, such as SVM and reinforcement learning. We are interested in comparing these two approaches' performances and then combining them to get better performance compared to the individual ones.

Most researchers used 6-DOF robot manipulators for ground EV battery charging because they can control the position in the x–y–z axes and orientation in roll-pitch-yaw angles of the charging plug. They used commercial robot manipulators instead of self-built robots since they only focused on developing methods for charging socket identification-localisation and plug insertion into the socket. However, a few researchers studied designing the lower DOF robot manipulators to solve different locations of the charging socket on EVs. Further research is needed concerning the optimisation of the 4-DOF robot manipulator design for charging EVs to compromise performance and cost. Some design factors to be considered are the payload of the charging plug, boundaries of the robot workspace, robustness of the socket detection and its pose estimation, accuracy of the pose control from the standby pose to the socket approaching pose, and the performance of the plug insertion control from the first contact to the insertion end. An optimum design of an end effector having 2-DOF with compliance is very challenging to ensure a 100% success rate of plug insertion by compensating for the plug pose error.

We limited sources to the four databases, limiting our review scope. On the other hand, when manually reviewing key technologies, we realised articles exist regarding underwater and aerial vehicles. It would have better tightened our exclusion criteria to include "water OR aerial."

Appendix A: Summary of the primary articles

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
Primary articles belong\ing to the autonomous docking (AD) cluster									
1	AD	Weng et al. (2016)	Category 1: Auto-docking of small-size mobile robots that use cameras and predefined marks. They have the platforms of four wheels drive (4WD) or two wheels drive (2WD)	CI method improves target estimation performance	RGB-D camera,Laser ranger	N/A	4WD mecanum wheel, 2D SICK laser ranger, Bluetooth Low Energy (BLE)	N/A	Kinematic model, covariance union (CU), covariance intersection (CI), SIFT pattern
2	AD	Cortes and Kim (2018)		Effective power transfer of receiver position: ± 5 mm	Camera, rotary encoder	N/A	Differential-Drive Mobile Robot, Arduino mega, Raspberry Pi B	N/A	Llinear quadratic regulator (LQR), computer vision (OpenCV ver 3)
3	AD	Du et al. (2021)		Circle Hough Transform (CHT) accuracy is 50%, while Circle detection accuracy is 20% higher than CHT	Camera, IMU (BNO05 Absolute orientation)	N/A	Tracked robot, NVIDIA Jetson Nano (OpenCV), Arduino Uno, Adafuit motorshield	Conductive metal pads (circle pattern)	Pre-Contour-Gradient (Color), color-based contour, Def-circle, PID control loop, Line detection: PHT, LSD, FPE
4	AD	Romanov and Tararin (2021)		Accuracy: 5 cm, Min. distance: 58 cm	Camera, LiDAR	N/A	Wheeled mobile robots, ArUco markers	N/A	Differential kinematics, ROS implementations (Gazebo Simulator)

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
5	AD	Vongbunyong et al. (2021)	Category 2: Auto-docking of small-size mobile robots that use non-cameras as the sensor, including light detecting and ranging (LIDAR), laser range finder, and infrared (IR) transmitter and receiver	< ± 20 mm position error & < 0.05 rad orientation error	LiDAR	Mechanical	AMR "CARVER", RP- LiDAR A1, Sick LiDAR Tim-781 s, intel-NUC (ROS), BLDC motor	Connector (2P)	Geometrical marker (position & localisation)
6	AD	Rocha et al. (2020)		N/A	Odometry, laser-range finder,	N/A	Hospital car model, LRF SICK S300, Arduino mega, ROS	N/A	TEA, Perfect Match, Beacon-based Localisation, Kalman filter,
7	AD	Acosta Calderon et al. (2014)		The connector moves freely at 30° to reduce misalignment	Infrared, odometry	N/A	Mobile robot	N/A	Mechanism methods; 1-DOF
8	AD	Chang et al. (2018)		The infrared signal range is widened from 60° to 90°	Camera, infrared, encoder, ultrasonic	N/A	IRobot Create2, Arduino Uno, Rasberry pi 3, MPU-6050	N/A	Neural network linear regression, Opcode (Open Interface control instruction)
9	AD	Rao and Shivakumar (2021)		95% success rate; stop charging > 12 V	IR Transceiver, Voltage	N/A	Arduino UNO, Bluetooth HC 05, ALCD Display, L293 Drivers	N/A	Locomotion Control and Docking Method
10	AD	Petrov et al. (2012)	Category 3: Auto-docking of AEV with front wheels steering systems that use laser scanners and IR cameras	The precision is 10 cm in the longitudinal and lateral direction around the docking point	Infrared camera	N/A	Car	N/A	Kinematics-based control (lateral-longitudinal & path tracking), POSIT algorithm
11	AD	Klemm et al. (2016)		The precision is 2 cm in the longitudinal position	Laser scanners, Odometry	N/A	Car	Type-2	SLAM, RRT-based approach, TOSDF, OSD, EKF

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
12	AD	Fang et al. (2020)	Category 4: Battery charging/swapping of mobile robots with 2WD or with XYZ cartesian robot	N/A	Hall sensor	N/A	5-wheel tracking car with manipulator, CPU	N/A	Unified deployment of charging socket, tracking positioning, trolley bus sliding
13	AD, RM	Behl et al. (2019)		N/A	Camera, LiDAR	N/A	TurtleBot 3 WafflePi, Raspberry Pi 3, ROS	Connector (3P)	Hough Transform, Template Matching, SLAM, PID, 4-DOF
14	AD, RM	Wang et al. (2012a, b)		N/A	Sonar, Photoelectric	N/A	Mobile robot, PLC, CPU, AC motor, DMP position	N/A	4-DOF
15	AD	Narvaez et al. (2021)	Category 5: Not relevant to ground vehicle autonomous docking	NDR	NDR	NDR	NDR	NDR	NDR
Primary articles belonging to the port detection (PD) cluster									
1	PD	Sun et al. (2018)	Category 1: Using the camera to recognise the charging socket of EV	99% accuracy of the socket recognition experiment	3D Camera	N/A	Dataset, CPU Intel i7 7800, GPU nvidia, Camera	Type-2	Convolutional Neural Network (CNN)
2	PD	Wang (2021)		83.62% accuracy of the socket recognition experiment	RGBD Camera	N/A	N/A	All type	Very Deep CNN
3	PD	Bang et al. (2022)		From experimental results, the EnT-GAN gave an Average Precision (AP) of 66.5, which is better than the state-of-the-art 63.6	Intel RealSense Depth Camera D435i	N/A	Connector EV dataset (Chevrolet Bolt & Kia Niro)	Type-1 Combo (Chevrolet Bolt, Kia Niro)	DetectoRS: Detecting objects with recursive feature pyramid and switchable atrous convolution; Generative Adversarial Network (GAN); EnT-GAN; ForkGAN

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
4	PD	Cernohorsky et al. (2019)		N/A	RGBD Camera with IR lens	N/A	UR3 robot, Intel Realsense D435i camera	Type-2 CCS (CCS2)	The Image Processing Toolbox in MATLAB; 6-DOF
5	PD	Zhang and Jin (2016)	Category 2: Using the camera to detect and locate the socket position in the x–y plane	100% accuracy of the charging port localisation	CCD Camera	N/A	Halcon CV; CCD Camera, TOSHIBA PORTEGE M909 computer	Type-2	HSI (hue, saturation, intensity) color model; Mathematical morphology, Canny operator, Tukey weight function
6	PD, RM	Long et al. (2019)	Category 3: Using a camera and IR-US range finder to detect and locate the socket position in the x–y-z	Only conceptual design; No experiment result	2D monocular Camera, IR-US range finder, UV light source	N/A	Ring ultraviolet light	GB/T	The minimum distance iteration algorithm; The split wide-angle range based on IR-US range finder technology; 6-DOF
7	PD, RM	Pengkun Quan et al. (2022a, b)	Category 4: Using the camera to detect and locate the socket position in the x–y-z & orientation Rx-Ry-Rz	94.80% success rate of the socket pose estimation experiment	3D Camera, Light source	N/A	GBT 20234.3–2011 DC, AUBO-i5 6-DOF, MER-125-30GM/C-P Mercury Gig PoE, M0814-MP2	GB/T (DC)	Hough circle and Hough line detection; Canny operator; Quadratic Curve Standardization (QCS); Perspective-n-point (PNP) algorithm; Direct Linear Transform (DLT); 6-DOF
8	PD, RM	Miseikis et al. (2017)	Category 5: Using only cameras as the sensor to detect and locate the charging socket and insert the charging plug into the charging socket	8/10 success rate of the plug-in experiment	Stereo Camera	N/A	Halcon CV	Type-1, Type-2	Shaped-based template matching (SBTM) method; Perspective transformation based on the least squares (LS) fit method; 6-DOF

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
9	PD, RM	Walzel et al. (2019)		42/42 success rate of the insertion experiment	Stereo Camera	N/A	Halcon CV	Type-2 CCS (CCS2)	SBTM method; Perspective transformation based on the LS fit method; 6-DOF
10	PD, RM	Walzel et al. (2021b)		Not available	Stereo Camera	N/A	Halcon CV	Type-2 CCS (CCS2)	SBTM method; Perspective transformation based on the LS fit method; 6-DOF
11	PD, RM	Hirz et al. (2021)		Not available	Stereo Camera	N/A	Halcon CV	Type-2 CCS (CCS2)	SBTM; Perspective transformation based on the least squares fit method; 6-DOF
12	PD, RM	Walzel et al. (2021a)		42/42 success rate of the plug-in experiments using the same vehicle; 75% to 95% success rates of socket position detection with five different EVs	Stereo Camera	N/A	Halcon CV	Type-2 CCS (CCS2)	SBTM method; Perspective transformation based on the LS fit method; 6-DOF
13	PD, RM	Pan et al. (2020)		9/10 success rate of insertion experiment at the best illumination (1618–6151 lx)	Monocular Camera	N/A	MER-125-30UM camera, M0814-MP2 camera lens, LED	GB/T (AC)	CNN; HSI color model, Otshu method; Canny operator; Hough transform ellipse detection; geometric method; 6-DOF
14	PD, RM	Pengkun Quan et al. (2022a, b)		Insertion experiment success rates: indoor 99%, outdoor 93%	Camera	N/A	GBT 20234.3–2011 DC, MER-125-30GM, Camera lens M0814-MP2	GB/T (DC)	Canny operator; cluster template matching algorithm (CTMA); EPnP algorithm; Direct Linear Transform (DLT); 6-DOF

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
15	PD, RM	Zhou et al. (2021)		100% success rate of the socket detection experiment; 92% success rate of the plug-in experiment	3D Camera with ToF technique	N/A	MiR 200 mobile platform, PMD 3D camera, Robotiq 85-F two finger gripper	Plug charger	The Point-Voxel-Recursive Convolutional Neural Network (PV-RCNN); KITTI Vision Benchmark Suite; 6-DOF
16	PD, RM	Lv et al. (2019)	Category 6: Using the camera and F/T sensor to detect and locate the charging socket and insert the charging plug into the charging socket	92% success rate of socket pose estimation experiments;	2D Camera, F/T sensor	N/A	UR5 robot arm, type-2 charging plug, monocular camera	Template picture	Speeded Up Robust Features (SURF) algorithm, Perspective-n-point (PnP) algorithm, SVM; 6-DOF
17	PD, RM	Guo et al. (2021)		Insertion accuracy 97%; Insertion time 9 s; Initial position error is limited to 5 mm with no orientation error	RGB-D Camera, ft300 F/T sensor	N/A	UR5 robot arm, robotiq ft300 F/T Sensor, Intel D435i RGB-D camera	Type-2	Visual servo control; Hue saturation value (HSV); Reinforcement Learning (RL) position control; Proportional Integral (PI) force control; PyBullet simulation; 6-DOF
18	PD, RM	Liu et al. (2021)		94% success rate of insertion experiments;Insertion time since the first contact: 8 s; Time from the initial position to the first contact: 15 s; Insertion initial position error is 1 cm with orientation error. Accuracy of classifier is 92.59%	3D Camera, F/T sensor	N/A	AUBO robot, AT-S1000-06C camera, Axia80-M8 F/T sensor	GB/T	Point-cloud template matching algorithm; Space Vector Machine (SVM); 6-DOF

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other objectives	Method/algorithm; DOF
19	PD, RM	Bucher et al. (2021)	Category 7: Using an endoscope camera with an IR-pass filter to detect and locate the socket and insert the charging plug	97% success rate of insertion experiment	Endoscope camera with IR-pass filter; 4 IR-LEDs as active markers	Elastic compensator	Endoscope camera: CMOS 1/6-inch camera sensor, ROS (Ver. Melodic Morenia on Ubuntu 18.04), IR-LED pattern	Type-2 CCS (CCS2)	Four infrared (IR)-LEDs marker and an endoscope camera with an IR-pass filter; A 4-DOF ACD consists of a 3-DOF articulator, a translational platform, and an elastic compensation unit
20	PD, RM	Bdiwi et al. (2015)	Category 8: Using camera and F/T sensor but focus on force or impidance control for charging plug insertion into the socket	Success rate: NA; Insertion time: 80 s; Initial position error is limited to 1 cm without orientation error	Camera; F/T sensor	N/A	KUKA KR6/2 robot, FT Delta SI-660–60 force sensor	IEC 60309 splug-socket	Integral force control with the force error as the input and position correction as the output; Parallel position/force control using a spiral motion; 6-DOF
21	PD, RM	Jokesch et al. (2016)		100% success rate of insertion experiments; Insertion time: 13 s; Initial position in front of the socket 30 mm with a maximum error of 7.35 mm; Insertion initial orientation error is 5.1°	3D Camera; F/T sensor	Torque sensor in every joint	KUKA LWR iiwa 7 R800	Type-2	Impedance control; Compliant blind-search strategy; Phase shifted Lissajous path; 7-DOF
22	PD, RM	Zhang et al. (2022)		99% success rate of insertion experiments; Insertion time: 6–8 s. Insertion initial position in front of the socket: 10 mm	Camera, F/T sensor	Impedance control	UR5e robot, L515 camera	Type-2	D-H coordinate system; Impedance control; Active Remote Centre Compliance (ARCC)-based insertion strategy; 6-DOF

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
23	PD	Park et al. (2021)	Category 9: Using a camera with the help of a squared unique marker or QR code. Do not explicitly address charging socket localisation and plug insertion	N/A	Stereo Camera	N/A	NA	N/A	Geometry
24	PD, RM	Harik (2021)		N/A	RGB-Camera	NA	Superdroid mecanum robot, UR5e robot, two fingered Robotiq 2F-85 gripper, NVDIA Jetson TX2 (ROS), Logitech C920 web-camera	Connector (2P)	The high-level computer runs Ubuntu with ROS as the middleware. The main node subsribes and publishes from/to different nodes: usb-cam ROS package, aruco-ros ROS package, and rosserial_python ROS package; 6-DOF
25	PD	Gungor and Kiyak (2021)		N/A	Camera	N/A	N/A	QR code	Calculate the difference between the center of the QR code and the center of the camera in the x–y plane; calculate the QR code's width to control the plug-in z direction
26	PD, RM	Shen et al. (2012)	Category 10: Battery swapping for EVs	NDR	NDR	NDR	NDR	NDR	NDR
27	PD	Wu et al. (2012)		NDR	NDR	NDR	NDR	NDR	NDR
28	PD	Jiang et al. (2019)		NDR	NDR	NDR	NDR	NDR	NDR

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/ additional/other tools	Port type/ other object	Method/algorithm; DOF
29	PD	Pingpittayakul and Mitsantisuk (2022)		NDR	NDR	NDR	NDR	NDR	NDR
30	PD, RM	Peng et al. (2019)	Category 11: Aviation charging-peng (Peng et al. 2019); Obstacle avoidance of a small mobile robot (Sarker et al. 2020); A design concept of ACS (Luo and Shen 2020); Robot arm for electronic components disassembly (Farhan et al. 2021); Concept of robotic plugging (Cernohorsky et al. 2022); Underground inspection robot (Xi et al. 2022)	NDR	NDR	NDR	NDR	NDR	NDR
31	PD	Sarker et al. (2020)		NDR	NDR	NDR	NDR	NDR	NDR
32	PD, RM	Luo and Shen (2020)		NDR	NDR	NDR	NDR	NDR	NDR
33	PD, RM	Farhan et al. (2021)		NDR	NDR	NDR	NDR	NDR	NDR
34	PD, RM	Cernohorsky et al. (2022)		NDR	NDR	NDR	NDR	NDR	NDR
35	PD, RM	Xi et al. (2022)		NDR	NDR	NDR	NDR	NDR	NDR

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
Primary articles belonging to the robot manipulator (RM) cluster									
1	RM	Yuan et al. (2020)	Category 1: A design of a hybrid serial-parallel robot with 6-DOF movements to provide a larger payload and cable arrangement convenience	N/A	N/A	N/A	N/A	N/A	The charging robot has nine actuating DOFs and achieves six DOFs movements –kinematic and static models; optimization of the manipulator configuration
2	RM	Lou and Di (2020)	Category 2: A 4-DOF cable-driven automatic charging robot (CDACR) with a 3-DOF cable-driven manipulator and a moving platform. The robot can control the position and pitch angle of the end-effector (Lou & Di 2020); A collision localisation and classification method based on machine learning for the CDACR (Lin et al. 2022)	Insertion success rate: NA; From experiments by varying displacement along the x-axis from -78 to 123 mm and a yaw angle from -5 to 5 degrees, the forces could satisfy the requirement while all cable tension kept positive	Camera, ATI F/T sensor, Encoders	Flexible plug with elastic element	Cable-driven auto-charging robot (CDACR)	CHAdeMO	A flexible plug at the end-effector to accommodate small rotational elastic deformation due to angular errors of the end-effector relative to the charging socket; Machine vision; PI Controller; 4-DOF

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other objectives	Method/algorithm; DOF
3	RM	Lin et al. (2022)		From simulated experiments, they claimed the method could simultaneously provide collision localisation and classificattion	Camera, ATI F/T sensor, Encoders, IMU	Elastic compensator	CPU: Intel Core i7-10700 K @ 3.80 GHz, GPU: NVIDIA GeForce RTX 3080	GB/T (DC)	Machine learning, CLC, DCNN–SVM, CNN and LSTM; PI Controller; 4-DOF
4	RM	Chablat et al. (2022)	Category 3: A 3-DOF robot for charging EVs at home with the socket on its front side	Insertion success rate: NA. The insertion experiment can be seen at: https://youtu.be/P5wCgRqSyDQ	Camera, QR code	N/A	Planar parallel robot, Rasberry Pi 4, Arduino board, 42BYG Geared Stepper Motor, OpenCV	DC connector	The robot comprised parallel links that move the reference point in the x–y plane and a linear actuator that moves the charging plug in a line constrained in the y–z plane; 3-DOF
5	RM	Okunevich et al. (2021a)	Category 4: A parallel link structure is installed on a 2WD mobile robot for charging small mobile robots. It uses CCN to perceive tactile that predicts misalignment	The system could predict the angle, vertical, and horizontal values of end effector misalignment with an accuracy of 95.46%, 98.2%, and 86.9%, respectively	Tactile sensor	Tactile perception system	Inverted Delta Mechanism, Three Dynamixel MX64, Intel NUC comp. + OpenCM 9.04 Dynamixel Contr	Delta mechanism	CCN-based tactile perception; The electrode's misalignment in 3 directions can be compensated by controlling the angle of each link using the corresponding motor; Machine Learning, deep learning; 3-DOF
6	RM	Okunevich et al. (2021b)		Electrode localisation success rate: 83 out of 10; execution time: 60 s	Tactile, RGB-D camera, LiDAR	Tactile sensor	Mobile robot, Intel NUC7i5BNK, OpenCM 9.04, RPLiDAR A3, RealSense D435 camera	Delta mechanism	CNN, OpenCM 9.04 Dynamixel; 3-DOF; The contact force is controlled by the motor current

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
7	RM	GS and PS (2022)	Category 5: A concept of a rigid-flexible manipulator for conductive charging	Insertion success rate: NA; Only provided joint angle tracking and the end effector 2D trajectory;	Camera	Rigid-flexible arms	Rigid- flexible manipulator,	Type-2	Euler–Bernoulli beam theory; Adaptive Fault-tolerant control (AFTC); PD controller; 4-DOF
8	RM	Hu et al. (2020)	Category 6: A passive, compliant mechanism for the automatic charging robot end-effector	Insertion success rate: NA; It could insert the plug reliably with a maximum insertion force of less than 100 N	Binocular camera, F/T sensor	N/A	UR5 robot arm, F/T sensor	N/A	The passive complaint mechanism was developed based on Stewart parallel mechanism
9	RM	Barzegaran et al. (2017)	Category 7: Adaptive robot for inductive charging of EV	N/A	Camera, ultrasonic	N/A	N/A	N/A	Inverse kinematics, mathematical adaptive: extremum seeking; 3-DOF
10	RM	Wang et al. (2012a, b)	Category 8: Robot mechanisms for EV battery swapping (Sun et al. 2014; J. Wang et al. 2012a, b; Wang and Wang 2014); Battery swapping for electric buses (Lin et al. 2012; Wang et al. 2015); A robot for small mobile robot battery swapping (Dandan et al. 2012); Robots for small UAV battery-swapping systems (Barrett et al. 2018; Dong et al. 2018)	NDR	NDR	NDR	NDR	NDR	NDR

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
11	RM	Sun et al. (2014)		NDR	NDR	NDR	NDR	NDR	NDR
12	RM	Wang and Wang (2014)		NDR	NDR	NDR	NDR	NDR	NDR
13	RM	Lin et al. (2012)		NDR	NDR	NDR	NDR	NDR	NDR
14	RM	Wang et al. (2015)		NDR	NDR	NDR	NDR	NDR	NDR
15	RM	Dandan et al. (2012)		NDR	NDR	NDR	NDR	NDR	NDR
16	RM	Dong et al. (2018)		NDR	NDR	NDR	NDR	NDR	NDR
17	RM	Barrett et al. (2018)		NDR	NDR	NDR	NDR	NDR	NDR
Primary articles belonging to the robot manipulator (RM) cluster Category 9:									
18	RM	Jiang et al. (2017)	A manipulator for the maintenance of HV transmission lines	NDR	NDR	NDR	NDR	NDR	NDR
19	RM	Akbaripour and Masehian (2016)	Semi-lazy probabilistic roadmap (SLPRM) for motion planning of industrial manipulators	NDR	NDR	NDR	NDR	NDR	NDR
20	RM	Zhou et al. (2022)	A 3D point-cloud technology is adopted to measure the shapes and depth of targeted objects in SME production	NDR	NDR	NDR	NDR	NDR	NDR

No	CODE	Articles	Value proposition	Performance: Success rate/accuracy/time	Sensor	ConnectorAlignment	Platform type/processor/microcontroller/additional/other tools	Port type/other object	Method/algorithm; DOF
21	RM	Di Lillo et al. (2018)	An underwater vehicle manipulator system	NDR	NDR	NDR	NDR	NDR	NDR
22	RM	Fleischer et al. (2021)	A flexible disassembly system for drive train components of EVs	NDR	NDR	NDR	NDR	NDR	NDR
23	RM	Afaq et al. (2015)	A customizable system for implementing the control algorithm of 5 DOF manipulator	NDR	NDR	NDR	NDR	NDR	NDR
24	RM	Khonji et al. (2017)	A robotic rover with a 2D lidar to localize a drone and a robotic arm with an inductive charging pad	NDR	NDR	NDR	NDR	NDR	NDR
25	RM	Zhang and Huang (2020)	A control strategy for multiple unmanned ground vehicle-manipulator systems	NDR	NDR	NDR	NDR	NDR	NDR
26	RM	Sujati et al. (2021)	A charging system is installed on a mobile manipulator	NDR	NDR	NDR	NDR	NDR	NDR

AD auto-docking/auto parking, *PD* port detection-recognition, *RM* robot manipulator, *N/A* not available, *NDR* no deep review. AD = 13; PD = 11; RM = 26; AD & RM = 2; PD & RM = 24

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Declarations

Conflict of interest The authors declare no conflict of interest.

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