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Research Progress on Robotic Arm-Based Automatic Charging Systems for Electric Vehicles

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Abstract. With the increasing adoption of electric vehicles (EVs), conventional human-operated charging methods face limitations under challenging conditions, including low illumination, adverse weather, and accessibility constraints for users with limited mobility. Meanwhile, advances in robotic perception, multi-sensor fusion, and autonomous control technologies provide new possibilities for automated charging systems. This paper reviews recent developments in automatic EV charging technologies and proposes a design framework based on vision-based perception, sensor-fusion, and robotic manipulation. The proposed system integrates cameras and radar sensors for charging interface detection, position estimation, and robotic connector operation, aiming to improve charging efficiency and operational safety. The research focuses on several key challenges including accurate charging inlet localization, environmental adaptability, mechanical positioning accuracy, and safety control during charging operations. Existing studies indicate that automatic charging systems are technically feasible, however, practical deployment remains constrained by high equipment costs, variations in charging interface configurations, and robustness requirements under complex environments. This paper further analyzes potential optimization directions, including low-cost sensing solutions, intelligent perception algorithms, and improved cross-model compatibility. The study provides a comprehensive reference for the future development of automated EV charging systems.

Keywords: Electric Vehicles, Automatic Charging System, Sensor Fusion, Robotic Arm Control

1. Introduction

Electric vehicles (EVs) are experiencing increasing adoption in private transportation due to their environmental benefits and lower operating costs. However, EV charging still largely relies on human-operated procedures. Under low-illumination conditions or adverse weather conditions such as rain and snow, manually connecting and disconnecting the charging connector can be inconvenient and may pose safety hazards. Such operations can be particularly difficult for elderly users and individuals with mobility limitations. Therefore, the development of automatic charging system that minimize human intervention has the potential to improve charging convenience and user experience. Motivated by these challenges, this paper explores an automatic EV charging system designed for residential smart garage environments. This system utilizes a robotic arm to

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perform automated connector insertion and removal, while integrating sensor technologies to perceive vehicle position and support accurate operation. Compared with alternative solutions, robotic-arm-based charging systems offes flexible positioning capabilities and can potentially be integrated with existing charging interfaces without requiring major modifications. However, existing research on robotic arms has primarily focuses on industrial manufacturing applications, while feasibility analyses for residential parking and charging scenarios remain relatively limited.

To evaluate the practical applicability of this system, this paper adopts a literature analysis method and review existing studies on robotic arm control, sensor technologies, automated parking systems, and EV charging standards. The feasibility of the proposed system is examined from three perspectives: technical performance, safety considerations, and economic factors. The technical analysis focuses on whether sensing and robotic control technologies can satisfy the requirements of automated charging operations. The safety analysis considers mechanisms for preventing vehicle damage and electric safety risks. The economic analysis evaluates potential hardware and maintenance costs. The study provides an initial assessment of the feasibility of applying industrial robotic arm technologies to residential EV charging scenarios.

2. Background and related work

2.1. Development background of automatic charging technology

In recent years, energy vehicles (EVs) have experienced rapid growth and have become a key direction in the transformation of the automotive industry. According to data from the China Association of Automobile Manufacturers, EV ownership continues to increase as more households adopt them for daily transportation [1]. Concurrently, data from the National Energy Administration indicate continuous expansion of public and private charging infrastructure, further supporting the development of EV ecosystems [2]. These changes suggest that as EVs adoption increases, charging convenience and operational efficiency have become increasingly critical factors affecting user experience. Automatic charging technology has emerged from advances in industrial robotics, computer vision, and automatic control. Universities such as Jilin University and Tongji University have conducted research on robotic arm-based automatic charging systems by integrating visual recognition and robot control technologies to achieve functions such as charging interface detection, position localization, and automated connector connection and disconnection [3, 4]. Although existing studies adopt different technical approaches, their fundamental concept is similar: sensors are used to acquire vehicle position information, and robotic systems execute precise charging operations based on perception results.

Overall, key technologies including vehicle localization, robotic arm control, and charging management have achieved significant progress, providing important technical support for the further development of automatic EV charging systems.

2.2. Limitations of conventional manual charging and requirements for automation

Manual connection and disconnection remain the dominant charging operations for EV users. This approach offers advantages like simple equipment structure, low cost, and convenient maintenance, making it widely used in residential and public charging scenarios. However, with the increasing adoption of EVs, limitations associated with conventional manual charging have become increasingly apparent.

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Firstly, manual charging operations are highly affected by environmental conditions. Under low-illumination conditions, underground garage environments, or adverse weather such as rain and snow, users may experience difficulties in locating the charging interface and performing connector connection and disconnectionoperations. Moreover, when the vehicle parking position deviates from the optimal charging location or the cable length is insufficient, users may need to reposition the vehicle, reducing charging convenience.

Second, manual operation poses difficulties for certain user groups. Fast-charging connectors are generally heavy and connected with thick cables, requiring considerable physical effort during operation. This may result in difficulties for the elderly, disabled, or those with limited mobility. With the advancement of autonomous driving technologies, automated parking and charging are becoming important components of future intelligent transportation systems. Even when vehicles are capable of autonomous operation, manual charging procedures may remain a limitarion in achieving fully automated mobility. Furthermore, improper connector insertion, delayed disconnection after charging completion, and other operational errors may introduces safety risks and accelerate equipment wear. Therefore, automated charging systems can reduce human intervention, minimize operational errors, and improve charging reliability.

In summary, while conventional manual charging provides advantages like low cost and mature technology, the proliferation of EVs and the demand for intelligent transportation solutions highlight the strong need for automated charging systems.

2.3. Existing automatic charging technologies

To evaluate the technical feasibility of automatic charging systems, academic institutions and research organizations have investigated key technologies including vehicle localization, charging interface recognition, robotic arm control, and safety protection mechanisms. Vehicle localization is fundamental to automatic charging system operation. Existing systems typically employ cameras, ultrasonic sensors, or LiDAR to obtain vehicle position and orientation information, combined with image processing algorithms to estimate the relative position between the vehicle and the charging interface. With the development of artificial intelligence, some studies have introduced deep learning-based methods to recognize vehicle features and charging interface locations, improving localization accuracy under complex conditions [3]. Charging interface recognition is equally crucial. Since charging interface locations vary among different EV models, the system must identify and localize the charging interface according to vehicle characteristics and environmental conditions. Previous studies ndicates that vision-based recognition methods can achieve accurate interface localization under controlled lighting conditions, providing positioning information for robotic connector insertion [3, 4]. Robotic arm control technology originates primarily from industrial robotics. Industrial robots have been widely used in manufacturing due to their high repeatability and positioning accuracy. Compared with complex industrial operations such as welding and assembly, automated connection and disconnection of charging connectors represent a relatively manipulation task, making robotic arms a promising solution for automatic EV charging applications. Additionally, the system must ensure operational safety. Current research commonly employs mechanisms such as electrical leakage detection, abnormal condition alarms, and emergency stop controls to terminate operations promptly when equipment anomalies occur, thereby improving system reliability.

Overall, many individual technologies involved in automatic charging have achieved significant progress. However, differences in charging interface configurations among vehicle models, high equipment costs, and environmental adaptability requirements remain major challenges. Therefore,

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automatic charging technology is still largely at the stage of pilot deployment and further optimization.

2.4. Design and research of automatic charging systems

Although existing automatic charging systems utilize different hardware configurations, their overall architectures are relatively similar, typically consisting of four functional modules: perception, control, robotic manipulation, and charging interfaces.

After the vehicle enters the designated parking area, the system first uses cameras and other sensing devices to estimate vehicle position and locate the charging interface. Based on the perception results, the control system plans the robotic arm trajectory and guides the end-effector to grasp and connect the charging connector. During charging, the system continuously monitors parameters such as current, voltage, and temperature. Upon completion, the robotic arm automatically disconnects the charging connector and returns to its initial position.

In recent years, academic institutions and enterprises have conducted research on different aspects of automatic charging systems. Some studies focus on optimizing visual recognition algorithms to enhance adaptability to variations in vehicle parking position and environmental conditions. Others investigate robotic end-effector designs to enhance connection stability, while some explore the integration of AI algorithms to enhance compatibility across different EV models. Some automatic charging systems have progressed from laboratory prototypes toward pilot demonstrations and field testing, with applications in public charging stations and smart parking environments evaluating functions like automatic interface localization and automated connector connection and disconnection.

However, automatic charging systems still face several challenges. Differences in charging interface location and geometry among different EV models increase perception and localization difficulties. The relatively high cost of robotic manipulators and sensing equipment limits large-scale deployment. Moreover, changes in illumination, dust, and complex weather conditions mat affect recognition accuracy and system reliability.

3. Feasibility analysis of key technologies for automatic charging systems

3.1. Operational workflow and coordinated control of automatic charging systems

The practical feasibility of an automatic charging system depends on the establishment of a stable operational workflow and effective coordination among functional modules. According to existing research, an automatic charging systems generally follows a sequential workflow involving vehicle parking, vehicle status confirmation, charging interface localization, robotic connector connection, charging process monitoring, and post-charging connector removal [5].

When an EV enters the designated charging area, the perception module first obtains environmental information and determines whether the vehicle is positioned appropriately for charging operations. Based on the acquired information, the control system coordinates the robotic arm movement and adjusts to the operation path to achieve accurate alignment between the charging connector and the vehicle charging interface. After successful connection, the charging management module initiates and monitors the charging process by collecting parameters such as current, voltage, and battery temperature. Once the predefined charging condition is reached, the system controls the robotic arm to disconnect the charging connector and complete the charging procedure.

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The coordination between the automatic charging system and the vehicle's Battery Management System (BMS) further improves operational reliability. The BMS can provide real-time informationregarding battery status and charging conditions, enabling the external charging system to perform safer and more adaptive control. In addition, publicly reported testing results indicate that automatic charging systems can achieve reliable connector connection and disconnection under appropriate parking conditions [5].

Overall, the existing automatic charging systems demonstrate the feasibility of integrating perception, robotic control, and charging management technologies into a coordinated workflow.

3.2. Analysis of charging port recognition and vehicle localization technologies

Charging interface recognition is pivotal affecting the performance of the entire system. Accurate identification of the charging interface is necessary for enabling the robotic arm to complete subsequent connector connection operations. Currently, most studies employ machine vision technologies, in which image processing algorithm are applied to estimate the location of the charging interface [6]. Research from Tsinghua University indicates that vision-based recognition methods can achieve relatively accurate interface localization under controlled lighting conditions, providing essential positioning information for automatic charging operations [6]. To improve adaptability under challenging environments, some studies further introduce auxiliary lighting systems or infrared imaging technologies to enhance recognition performance under low-illumination conditions.

In conclusion, existing visual recognition technologies provide technical support for automatic charging, but further optimization is needed for complex environments and multi-vehicle compatibility.

3.3. Analysis of robotic arm positioning and plug/unplug control

The robotic arm serves as the primary execution component in automatic charging systems, performing operations including grasping, connecting, and disconnecting the charging connector. Due to the relatively structured and repetitive nature of automatic charging tasks, existing industrial robotic technologies provide sufficient positioning accuracy and motion control capablility for such applications [7].

To improve operational safety during connector connection, some studies incorporate force sensors into the robotic end-effector to monitor contact forces and dynamically adjust motion parameters. When abnormal resistance or excessive contact force is detected, the system can halt operations promptly, enhancing safety.

Currently, the primary challenge in applying robotic arms to automatic charging is positional variation among different vehicle models. Hence, improving vehicle recognition capability and path adaptation flexibility is key for future large-scale deployment.

3.4. Analysis of automatic charging safety assurance

Safety performance is crucial for evaluating the practical value of automatic charging systems. Compared with manual charging, automated systems reduce direct human involvement but introduce additional risks associated with robotic motion, perception errors, and automated control. Therefore, effective safety mechanisms are essential to ensure reliable system operation.

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Current NEV charging equipment is developed according to relevant national and industry safety safety standards, which specify requirements for leakage protection, insulation performance, emergency stop controls [8]. Automatic charging systems build upon these existing charging safety frameworks while introducing additional protection mechanisms for robotic arm operation. For instance, vision-based safety monitoring can detect the presence of people within the operating area and suspend robotic arm motion when necessary. Force sensing technologies can interrupt connector connection operations when abnormal resistance or excessive contact force is detected. During charging, electrical monitoring mechanisms can respond to conditions such as leakage, overcurrent, or abnormal temperature to reduce potential safety risks. These approaches, which have been widely used in industrial robotics and automated manufacturing, offer important references for automated charging safety design.

Overall, automatic charging systems currently have fairly comprehensive safety assurance mechanisms, although long-term operational stability in complex environments requires further validation.

4. Feasibility analysis of automatic charging system applications

4.1. Foundation of industrial robotics technology and application maturity

The realization of automatic charging systems relies on the maturity of robotic manipulation and motion control technologies. Industrial robots have been widely used in manufacturing fields, such as automotive production, electronics assembly, and logistics, with their reliability and control capabilities demonstrated through extensive engineering practices [9]. Therefore, developing automatic charging systems does not require creating entirely new robotic equipment but rather extending existing mature technology.

According to the *China Robotics Industry Development Report* and related research, industrial robots currently perform high-precision tasks like welding, painting, and assembly [9]. Compared with these complex applications, automatic charging mainly involves structured and repetitive connector manipulation tasks, resulting in relatively moderate requirements for robotic motion accuracy and load capacity. However, industrial robots typically operate in structured production environments, whereas home garages and public parking lots present more complex conditions, including potential vehicle positioning deviations and varying lighting. Therefore, practical deployment requires further enhancing robotic adaptability to complex environments.

4.2. Safety feasibility analysis

China has established comprehensive safety standards for EV charging equipment, such as "Electric Vehicle Conductive Charging System" (GB/T 18487), specifying requirements for insulation, leakage prevention, short-circuit protection, and emergency power-off [10]. Since automatic charging systems utilize nationally standardized charging equipment, their baseline safety performance aligns with conventional charging piles.

A major additional concern is the safety of robotic operation in public or residential environments. During automatic charging, unexpected human or object intrusion may affect system operation. To address this issue, automatic charging robots are typically equipped with cameras, ultrasonic sensors, or LiDAR for real-time environmental monitoring. The system can pause operation immediately upon detecting someone approaching the work area, resuming after the person leaves. This safety approach, widely applied in industrial robotics, offers high reliability.

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Environmental conditions such as rainfall may also influence charging safety. In fact, current EV charging interfaces incorporate waterproof and insulation designs. As long as equipment meets national standards, it can operate safely in normal rainfall.

4.3. Economic feasibility analysis

Beyond technology and safety considerations, cost remains a significant factor influencing the promotion of automatic charging systems. Current systems primarily consist of robotic arms, cameras, sensors, control systems, and charging equipment, among which robotic hardware and perception systems represent major cost drivers. For average households, the current installation cost remains relatively high, making near-term widespread adoption comparable to standard home charging piles unlikely. However, as the robotics industry develops and localization improves, costs of industrial robots and related sensors are gradually decreasing [9]. Concurrently, improvements in system reliability and maintenance efficiency may further enhance economic feasibility. Regarding application scenarios, automatic charging systems are better suited for initial deployment in public parking lots, large shopping malls, airports, and logistics parks. These high-vehicle-traffic areas offer higher equipment utilization, better showcasing efficiency gains from automation and enabling unit cost reduction through economies of scale.

In summary, while automatic charging systems currently face high initial costs, economic feasibility will gradually improve with robotic technology maturation and cost reduction, indicating future potential for broader application.

5. Conclusion

This paper has evaluated the feasibility of automatic EV charging systems for civilian smart garage applications. By reviewing existing research on EV charging requirements, robotic technologies, sensing methods, and charging safety mechanisms, this study analyzes the potential of integrating perception, robotic control, and charging management technologies into an automated charging workflow.

The literature analysis indicates that perception and control technologies in industrial robotics and autonomous driving are maturing, yet existing applications largely focus on industrial manufacturing, with limited comprehensive solutions for civilian parking charging. This paper therefore demonstrates system feasibility from technical, safety, and economic perspectives. Technically, current sensor precision and robotic arm control technologies basically meet automatic plugging/unplugging requirements. Notably, deep learning-based charging interface recognition and positioning methods have established research foundations. Regarding safety, appropriate force control strategies and fault detection mechanisms can manage risks of vehicle damage or leakage during plugging within acceptable limits. Economically, the high cost of required sensors and robotic arms, coupled with variations in charging port locations across models, presents realistic challenges for large-scale promotion.

In conclusion, automatic charging technology is feasible in core perception and control aspects. However, to achieve widespread application in civilian smart garages, further breakthroughs are needed in cost reduction and interface standardization.

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