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ENHANCING ELECTRIC VEHICLE WIRELESS CHARGING SAFETY: A COMPREHENSIVE REVIEW OF COMPUTER VISION TECHNIQUES FOR FOREIGN OBJECT DETECTION ABSTRACT

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Abstract
The integration of electric vehicles (EVs) into the urban landscape is a pivotal step towards sustainable transportation. Wireless charging technology for EVs represents a significant advancement, offering a seamless and user-friendly charging solution that eliminates the need for physical cables or connectors. This technology, utilizing inductive and resonant charging methods, enables the transfer of energy across an air gap, enhancing the convenience and adoption potential of electric vehicles. However, the safety and efficiency of wireless charging are contingent upon effective foreign object detection (FOD) systems. These systems are crucial for identifying and mitigating the risks associated with the presence of foreign objects in the charging area, which can lead to energy loss, potential hazards, and reduced charging efficiency. This paper provides a comprehensive review of the current state of wireless charging technology for EVs, with a focus on the importance of FOD and the application of computer vision techniques in enhancing detection capabilities. Through an exploration of various computer vision methods and their practical applications in wireless charging, the paper highlights the ongoing challenges and future research directions in this field. The advancement of wireless charging technology, coupled with robust FOD systems, is essential for the widespread adoption of EVs, contributing to the evolution of smart, sustainable urban transportation.

KEYWORDS: FOD, EV, wireless charging technology, Computer Vision

1. Introduction

The integration of electric vehicles (EVs) into the urban landscape is a pivotal step towards sustainable transportation. Wireless charging technology for EVs represents a significant advancement, offering a seamless and user-friendly charging solution that eliminates the need for physical cables or connectors. This technology, utilizing inductive and resonant charging methods, enables the transfer of energy across an air gap, enhancing the convenience and adoption potential of electric vehicles. However, the safety and efficiency of wireless charging are contingent upon effective foreign object detection (FOD) systems. These systems are crucial for identifying and mitigating the risks associated with the presence of foreign objects in the

charging area, which can lead to energy loss, potential hazards, and reduced charging efficiency. This paper provides a comprehensive review of the current state of wireless charging technology for EVs, with a focus on the importance of FOD and the application of computer vision techniques in enhancing detection capabilities. Through an exploration of various computer vision methods and their practical applications in wireless charging, the paper highlights the ongoing challenges and future research directions in this field. The advancement of wireless charging technology, coupled with robust FOD systems, is essential for the widespread adoption of EVs, contributing to the evolution of smart, sustainable urban transportation.

2. Background

2.1 Electric Vehicle Wireless Charging

Electric Vehicle (EV) wireless charging represents a significant leap forward in the evolution of electric mobility, offering a convenient and advanced method to recharge vehicles without the need for physical connectors or cables. This technology, primarily based on the principles of inductive and resonant charging, allows for the transfer of energy across an air gap from a transmitting pad on the ground to a receiving pad attached to the vehicle's underside. The convenience of wireless charging could significantly enhance user experience and adoption rates of electric vehicles, as it simplifies the charging process and eliminates the need for manual intervention [1].

Inductive charging, the more commonly implemented form of wireless power transfer, utilizes electromagnetic fields generated by coils to transfer energy. When an electric vehicle is positioned over a charging pad, an alternating current flows through the transmitter coil, creating a magnetic field that induces a current in the receiver coil of the vehicle, thereby charging its battery. Despite its convenience, the efficiency of inductive charging is influenced by factors such as the alignment between the transmitter and receiver coils, the gap between them, and the presence of foreign objects, which can affect the magnetic coupling and energy transfer efficiency [2] [3].

Resonant wireless charging, on the other hand, employs resonant inductive coupling, which can offer higher efficiency over longer distances compared to traditional inductive methods. This technology utilizes resonant circuits with matched frequencies on both the transmitter and receiver sides, allowing for more flexible positioning of the EV above the charging pad. Resonant charging systems can potentially reduce the sensitivity to misalignment and increase the permissible distance between the coils, making the charging process even more user-friendly and adaptable to various parking scenarios [4].

Despite the promising advancements in wireless charging technology, there are still challenges to overcome, such as optimizing efficiency, reducing costs, and ensuring safety, particularly concerning foreign object detection and electromagnetic field exposure. As the technology matures and these challenges are addressed, wireless charging is expected to become an integral component of the electric vehicle ecosystem, supporting the broader adoption of EVs and contributing to the reduction of greenhouse gas emissions and dependency on fossil fuels [5].

2.2 Importance of Foreign Object Detection

The importance of Foreign Object Detection (FOD) in the context of electric vehicle (EV) wireless charging cannot be overstated, as it plays a crucial role in ensuring the safety and efficiency of the charging process. When foreign metallic objects such as coins, keys, or tools are present in the charging area, they can absorb electromagnetic energy, leading to undesirable heating effects. This not only poses a fire risk but can also result in damage to the charging equipment and the vehicle itself. Moreover, the presence of foreign objects can significantly reduce the efficiency of energy transfer between the transmitter and receiver coils, leading to longer charging times and increased energy consumption [6].

To address these challenges, advanced FOD systems are integrated into wireless charging systems to detect the presence of any foreign metallic objects in the charging zone. These systems typically employ various sensing technologies, including magnetic, capacitive, or optical sensors, to monitor the charging area and identify any potential risks. Once a foreign object is detected, the system can alert the user and automatically shut down the power transfer to prevent overheating and eliminate the risk of fire. The development and implementation of effective FOD systems are essential for the widespread adoption of wireless EV charging, as they ensure that the charging process is not only convenient but also safe and reliable [7].

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3. Computer Vision for Foreign Object Detection

3.1 Basic Principles of Computer Vision

Computer vision is a field of artificial intelligence that trains computers to interpret and understand the visual world. By using digital images from cameras and videos and deep learning models, computer vision can accurately identify and classify objects, and then react to what it sees. In the context of foreign object detection (FOD) for electric vehicle (EV) wireless charging,

computer vision systems analyze visual data to detect the presence of any unwanted objects within the charging area. This process involves capturing images or videos, processing and analyzing the data, and then making decisions based on the observed patterns [10].

3.2 Techniques and Algorithms

Several computer vision techniques and algorithms have been developed and applied to detect foreign objects in various scenarios, including EV wireless charging. Image segmentation, a common computer vision technique, involves dividing a digital image into multiple segments to simplify its representation and make it easier to analyze. Object recognition, another crucial technique, enables the identification of specific objects within an image or video. Deep learning models provided by Zhou et al. particularly convolutional neural networks (CNNs), have shown significant promise in enhancing the accuracy and reliability of computer vision systems. These models can learn and improve over time, adapting to new patterns and objects they encounter [11]

For instance, a study by Khan et al. demonstrated the use of a CNN-based model to detect foreign objects on wireless charging pads for EVs [12]. The model was trained with a dataset of various objects and was able to accurately identify potential hazards, showcasing the potential of deep learning in enhancing FOD systems. Another approach, as explored by Graves Jiang et al., involved using a combination of image segmentation and object recognition techniques to detect and classify different types of foreign objects, improving the system's ability to respond appropriately to various scenarios [13]. Alshammari and Rakan have contributed to the field of electric vehicle (EV) wireless charging by proposing two methods for object detection: Sppn-Rn101 and VGG16 object detection advancements in computer vision and deep learning provide a robust framework for developing effective FOD systems, ensuring the safety and efficiency of wireless EV charging stations. As these technologies continue to evolve, they will play a pivotal role in addressing the challenges associated with foreign object detection in the context of wireless charging [14][15].

4. Applications in EV Wireless Charging

4.1 Case Studies

The integration of computer vision techniques in electric vehicle (EV) wireless charging systems has been explored through various case studies, demonstrating their potential to enhance safety and efficiency. One notable application is the use of array detection coils, which has been shown to significantly improve the sensitivity and accuracy of detecting metallic foreign objects in the charging zone. For instance, a study by Zhang et al. implemented an array detection coil system in an EV wireless charging setup, resulting in enhanced detection capabilities for small metallic objects, which are crucial for preventing safety hazards and ensuring efficient energy transfer [16].

4.2 Comparative Analysis

A comparative analysis of different computer vision techniques in the context of EV wireless charging highlights the trade-offs between accuracy and resource requirements. Deep learning models, such as the YOLO v5 algorithm, have been recognized for their high accuracy in

detecting various types of foreign objects. A study by Lou et al. demonstrated that the YOLO v5 model could effectively identify and classify different foreign objects with high precision, making it a powerful tool for FOD in wireless charging systems [17]. However, these models typically require substantial computational resources, which can be a limiting factor in real-time applications.

On the other hand, sensor-based approaches offer a more resource-efficient solution for FOD. Sharma et al. explored a sensor-based FOD system that utilizes a combination of inductive and capacitive sensors to detect foreign objects. While this approach may not achieve the same level of accuracy as advanced deep learning models, it provides a practical and cost-effective solution for real-time FOD in EV wireless charging systems, balancing sensitivity and practicality[18] [2].

These case studies and comparative analyses underscore the importance of selecting appropriate computer vision techniques based on the specific requirements and constraints of the EV wireless charging system, ensuring that the chosen method provides an optimal balance of accuracy, efficiency, and practicality.

5. Challenges and Future Directions

5.1 Current Challenges

One of the primary challenges in implementing computer vision for foreign object detection (FOD) in electric vehicle (EV) wireless charging systems is the diversity and unpredictability of foreign objects that can be present in the charging environment. Objects of various sizes, shapes, materials, and orientations can affect the detection accuracy and efficiency. Environmental factors such as lighting conditions, weather, and the presence of dust or debris can also impact the performance of computer vision systems. Moreover, the integration of these systems into existing EV infrastructure requires careful consideration of factors like system cost, power consumption, and the need for real-time processing capabilities [19][20]

5.2 Future Research Directions

Future research in the field of computer vision for FOD in EV wireless charging could focus on several key areas. Enhancing the robustness of detection algorithms to accurately identify a wider range of foreign objects under various environmental conditions is crucial. This might involve the development of more sophisticated machine learning models or the integration of multimodal sensor data to improve detection accuracy. Additionally, optimizing the computational efficiency of these systems to enable real-time processing without significantly increasing the power consumption of the charging system is another important research direction. Exploring the potential for standardized testing protocols and benchmarks for FOD systems could also facilitate the comparison and evaluation of different approaches, driving innovation and improvement in the field [21]

Conclusion

The development of electric vehicle (EV) wireless charging technology signifies a transformative step in the progression of electric mobility, offering a user-friendly and innovative method for recharging EVs. By harnessing inductive and resonant charging

principles, this technology enables the transfer of energy without physical connections, streamlining the charging process and enhancing user convenience. Such advancements are poised to accelerate the adoption of electric vehicles, aligning with global efforts to foster sustainable and environmentally friendly transportation solutions.

However, the effectiveness and safety of wireless charging are closely tied to the robustness of foreign object detection (FOD) systems. These systems are essential for identifying and mitigating risks associated with foreign objects in the charging area, ensuring that the charging process is not only efficient but also safe. As the technology evolves, addressing challenges related to FOD, such as improving detection capabilities and integrating these systems into existing EV infrastructure, will be crucial.

Looking ahead, the ongoing refinement and innovation in wireless charging and FOD technologies will play a pivotal role in shaping the future of electric mobility. By overcoming current obstacles and enhancing the overall user experience, wireless charging is set to become a cornerstone of the EV ecosystem, supporting the transition towards more sustainable transportation modalities and contributing to a greener future.

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Reference

Mohamed, Ahmed AS, Ahmed A. Shaier, Hamid Metwally, and Sameh I. Selem. "Wireless charging technologies for electric vehicles: Inductive, capacitive, and magnetic gear." IET Power Electronics (2023). https://doi.org/10.1049/pel2.12624

Zicheng Bi, Tianze Kan, Chunting Chris Mi, Yiming Zhang, Zhengming Zhao, Gregory A. Keoleian,A review of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility, Applied Energy, Volume 179, 2016, Pages 413-425,ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2016.07.003.

J. Lu, G. Zhu and C. C. Mi, "Foreign Object Detection in Wireless Power Transfer Systems," in IEEE Transactions on Industry Applications, vol. 58, no. 1, pp. 1340-1354, Jan.-Feb. 2022, doi: 10.1109/TIA.2021.3057603.

Cheng, Bo, Jianghua Lu, Yiming Zhang, Guang Pan, RakanChabaan, and Chunting Chris Mi. "A metal object detection system with multilayer detection coil layouts for electric vehicle wireless charging." Energies 13, no. 11 (2020): 2960.

Triviño, Alicia, José M. González-González, and José A. Aguado. "Wireless power transfer technologies applied to electric vehicles: A review." Energies 14, no. 6 (2021): 1547.

Lu, Xiao, Ping Wang, Dusit Niyato, Dong In Kim, and Zhu Han. "Wireless charging technologies: Fundamentals, standards, and network applications." IEEE communications surveys & tutorials 18, no. 2 (2015): 1413-1452.

Ahmad, Aqueel, Mohammad Saad Alam, and RakanChabaan. "A comprehensive review of wireless charging technologies for electric vehicles." IEEE transactions on transportation electrification 4, no. 1 (2017): 38-63.

Bi, Zicheng, Tianze Kan, Chunting Chris Mi, Yiming Zhang, Zhengming Zhao, and Gregory A. Keoleian. "A review of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility." Applied energy 179 (2016): 413-425.

Wang J, Gao J, Yang A, Zhou J. Impedance Identification-Based Foreign Object Detection for Wireless Power Transfer System. 2022 IEEE 31st International Symposium on Industrial Electronics (ISIE); 2022 Jun 1–3; Anchorage (AK), USA. IEEE, 2022. p. 895–8.10.1109/ISIE51582.2022.9831611

Zhou, Z., Tian, J., Liu, B., Tian, Y. (2023). Metal Object Detection for Electric Vehicle Wireless Charging Based on Fusion of Spectral and Texture Features. In: Ma, C., Zhang, Y., Li, S., Zhao, L., Liu, M., Zhang, P. (eds) The Proceedings of 2022 International Conference on Wireless Power Transfer (ICWPT2022). ICWPT 2022. Lecture Notes in Electrical Engineering, vol 1018. Springer, Singapore. https://doi.org/10.1007/978-981-99-0631-4_29

Y. A. Khan, S. Imaduddin, A. Ahmad and Y. Rafat, "Image-based Foreign Object Detection using YOLO v7 Algorithm for Electric Vehicle Wireless Charging Applications," 2023 5th International Conference on Power, Control & Embedded Systems (ICPCES), Allahabad, India, 2023, pp. 1-6, doi: 10.1109/ICPCES57104.2023.10075892.

David Z. Graves, Argenis V. Bilbao, Stephen B. Bayne, Machine Learning Based Foreign Object Detection in Wireless Power Transfer Systems, e-Prime - Advances in Electrical Engineering, Electronics and Energy,Volume 7, 2024, 100384, ISSN 2772-6711,https://doi.org/10.1016/j.prime.2023.100384.

Alshammari, A. Construction of VGG16 Convolution Neural Network (VGG16_CNN) Classifier with NestNet-Based Segmentation Paradigm for Brain Metastasis Classification. Sensors 2022, 22, 8076. https://doi.org/10.3390/s22208076

Alshammari, A.; Chabaan, R.C. Metaheruistic Optimization Based Ensemble Machine Learning Model for Designing Detection Coil with Prediction of Electric Vehicle Charging Time. Sustainability 2023, 15, 6684. https://doi.org/10.3390/su15086684

Kim, J.-H.; Kim, N.; Park, Y.W.; Won, C.S. Object Detection and Classification Based on YOLO-V5 with Improved Maritime Dataset. J. Mar. Sci. Eng. 2022, 10, 377. https://doi.org/10.3390/jmse10030377

Luo, X.; Cai, S.; Liu, Z.; Hou, Y.; Xie, Y.; Sun, S.; Ding, R.; Feng, G.; Wei, X. Research on Metal Foreign Object Detection Method in Wireless Charging System of Electric Vehicle Based on Array Detection Coil. Energies 2023, 16, 5437. https://doi.org/10.3390/en16145437

A. Sharma and M. Z. Youssef, "A Magnetic Switch Sensor Based Inductive Power Transfer System With Power Control and Efficiency Maximization for Vehicular Applications," in IEEE

Canadian Journal of Electrical and Computer Engineering, vol. 46, no. 3, pp. 207-217, Summer 2023, doi: 10.1109/ICJECE.2023.3271304

T. Sonnenberg, A. Stevens, A. Dayerizadeh and S. Lukic, "Combined Foreign Object Detection and Live Object Protection in Wireless Power Transfer Systems via Real-Time Thermal Camera Analysis," 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), Anaheim, CA, USA, 2019, pp. 1547-1552, doi: 10.1109/APEC.2019.8721804.

Zicheng Bi, Tianze Kan, Chunting Chris Mi, Yiming Zhang, Zhengming Zhao, Gregory A. Keoleian, A review of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility, Applied Energy,Volume 179,2016,Pages 413-425,ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2016.07.003.

Cheng, Bo, Jianghua Lu, Yiming Zhang, Guang Pan, RakanChabaan, and Chunting Chris Mi. "A metal object detection system with multilayer detection coil layouts for electric vehicle wireless charging." Energies 13, no. 11 (2020): 2960.

Zhao, Shuze, Chenyang Xia, Ziyue Yang, Haipan Li, and Yuheng Cao. "Evaluation Modeling and Improvement Method for Sensitivity of Metal Object Detection in EV Wireless Charging System." IEEE Transactions on Power Electronics (2023).