User-Friendly Wireless Charging with Capacitive Coupling in Electric Mobilities

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ABSTRACT: This comprehensive study introduces an innovative capacitive coupling-based wireless charging system specifically engineered for electric mobility applications. The system, which was initially conceptualized and developed for deployment in shared e-scooter fleets, represents a significant advancement in charging technology by completely eliminating the need for manual charging operations, substantially reducing operational costs associated with fleet management, and dramatically enhancing the overall user experience through automated charging capabilities. The system's sophisticated design incorporates several groundbreaking technical features, including remarkable tolerance to positioning variations during charging operations, an ultra-compact charging port with an exceptionally low 35 mm profile for seamless environmental integration, and an advanced non-invasive receiver unit that can be mounted on vehicles without requiring structural modifications. Through careful engineering and sophisticated design principles, the system demonstrates excellent scalability potential, enabling successful implementation across a diverse range of applications from personal electric vehicles (EVs) to automated guided vehicles (AGVs), thereby contributing significantly to the broader adoption of sustainable electric transportation solutions in urban environments.

KEYWORDS: Wireless Charging, Capacitive Coupling, Electric Mobility, Alignment Tolerance, Shared E-Scooters, Electric Vehicles (EVs), Automated Guided Vehicles (AGVs), Non-Invasive Retrofit, User-Friendly Charging, Sustainable Transportation

1. INTRODUCTION

The remarkable and transformative expansion of shared electric mobility services, characterized by the widespread deployment of extensive fleets comprising electric scooters and various small electric vehicles operating throughout urban environments, has fundamentally revolutionized the landscape of contemporary urban transportation.(1) These groundbreaking mobility solutions have achieved unprecedented popularity by effectively addressing crucial transportation challenges, particularly in terms of first- and last-mile connectivity, while simultaneously contributing to the significant reduction of urban traffic congestion and advancing critical environmental sustainability objectives through the substantial reduction of carbon emissions and environmental impact. Nevertheless, as the implementation and utilization of electric mobility solutions continue to experience exponential growth across metropolitan areas worldwide, the intricate and multifaceted challenge of efficiently managing charging infrastructure and associated operations has emerged as a paramount consideration that profoundly impacts both the operational efficiency of service providers and the overall experience of end-users in the ecosystem.

Service providers face increasingly complex and resource-intensive logistical and operational challenges in their daily operations, particularly concerning the demanding tasks of vehicle retrieval, strategic redistribution, and comprehensive management of charging operations for their extensive vehicle fleets through conventional charging methodologies or sophisticated battery swapping systems. According to detailed and comprehensive industry research analyzing operational costs across multiple markets and service models, the substantial expenses associated with charging operations constitute an increasingly significant and rapidly growing portion of the total operational costs in shared electric mobility services.(2) In response to these escalating operational expenses and logistical complexities, service providers have implemented various innovative strategic measures designed to redistribute charging responsibilities more effectively to users, such as developing sophisticated user-based manual charging protocols or establishing comprehensive incentive structures that actively encourage and reward vehicle returns to strategically positioned charging stations. While these carefully considered operational strategies may successfully mitigate certain administrative and logistical complexities within the system, they inadvertently introduce new and potentially significant friction points in the user experience, such as the considerable inconvenience associated with manually connecting charging cables or the added complexity and potential frustration of locating and navigating to designated charging locations within the service area. This fundamental and persistent tension between optimizing operational efficiency for service providers and maintaining a seamless, frictionless user experience represents a critical challenge in the development and implementation of sustainable mobility solutions that can effectively serve the diverse needs of both service providers and end-users in the evolving mobility landscape.

To comprehensively address these multifaceted challenges and establish a new paradigm in electric mobility charging, an innovative and highly sophisticated wireless charging system utilizing advanced capacitive coupling technology has been meticulously developed and extensively refined through rigorous testing and optimization.(3) This cutting-edge charging system, initially conceptualized and engineered specifically for small electric mobility devices such as shared e-scooters, represents a significant technological breakthrough in charging technology and offers an exceptionally promising pathway toward truly user-friendly charging solutions with broad applications across the entire spectrum of electric mobility. Through the sophisticated implementation of state-of-the-art capacitive coupling technology and advanced power management systems, the charging process becomes entirely contactless and fully automated, effectively eliminating any requirement for manual intervention while consistently maintaining optimal battery levels across the entire vehicle fleet through intelligent charging algorithms. Through careful engineering refinements, extensive testing protocols, and the implementation of scalable design principles, this revolutionary capacitive coupling technology demonstrates remarkable adaptability and versatility, enabling its successful application across an incredibly diverse range of vehicles, from personal electric vehicles (EVs) and light-duty transport vehicles to sophisticated automated guided vehicles (AGVs) utilized in complex industrial logistics operations.(4)-(8) By completely eliminating the traditional requirements for manual cable connections or complex battery swapping procedures, this groundbreaking solution delivers substantial and measurable benefits in both operational cost reduction and significantly enhanced user convenience and satisfaction metrics. The strategic implementation of advanced capacitive coupling technology ultimately represents a truly transformative and user-centric approach to wireless charging in the rapidly evolving electric mobility sector, enabling seamless integration and highly efficient operation across both shared mobility services and personal vehicle applications, while simultaneously establishing new industry standards for charging convenience, operational efficiency, and user satisfaction.

Fig. 1 A capacitive coupling-based wireless charging system, showing the 35 mm low-profile charging port on the ground and the vehicle-mounted receiver under the scooter.

2. TECHNICAL FEATURES

The innovative charging system comprises a sophisticated ground-level charging port working in seamless coordination with an advanced vehicle-mounted receiving unit, representing a significant advancement in wireless charging technology. These carefully engineered components incorporate precisely designed and optimized conductive plates that are strategically arranged according to sophisticated electromagnetic principles to form highly efficient capacitive couplers when an electric vehicle is positioned within the charging zone above the charging port. Through the carefully controlled application of optimized high-frequency voltage patterns and advanced power management algorithms, energy is transferred with exceptional efficiency through the established electric field, completely eliminating the traditional requirement for direct electrical contact between system components. In marked contrast to conventional inductive charging systems that rely heavily on magnetic field interactions and demand extremely precise alignment between charging coils, this advanced capacitive method demonstrates superior tolerance to positioning variations while maintaining optimal charging efficiency.

The challenging and dynamic nature of real-world operating conditions in urban environments necessitates the implementation of a highly robust charging system capable of functioning effectively without requiring precise positioning by users during standard parking maneuvers. Extensive laboratory testing and comprehensive field trials have conclusively demonstrated that the current system prototype maintains impressive charging efficiency even under significant misalignment conditions, successfully tolerating positioning variations of up to ±80 mm in the longitudinal direction and ±135 mm laterally without experiencing substantial degradation in power transfer efficiency or charging performance. This remarkable positioning flexibility and operational robustness ensures that standard parking maneuvers performed by users are entirely sufficient to initiate and maintain effective charging operations without requiring specialized training or precise positioning instructions. The innovative charging port's ultra-low-profile design, measuring approximately 35 mm in thickness, facilitates seamless integration into various surface types and installation environments, ranging from public sidewalks and parking areas to dedicated charging zones, while incorporating all necessary power management components and safety features in a convenient and reliable plug-and-play configuration optimized for rapid deployment.

The groundbreaking vehicle-mounted receiver component has been meticulously engineered to enable straightforward installation and system integration without requiring any permanent modifications or structurally invasive alterations to the vehicle's frame or existing electrical systems. This carefully considered non-invasive integration approach successfully preserves existing vehicle warranties and ensures continued compliance with original manufacturer specifications while maintaining optimal charging performance. While the initial demonstration and comprehensive validation of this innovative technology has been primarily focused on shared electric scooters in urban mobility applications, the fundamental concept demonstrates excellent scalability and adaptability for implementation in larger electric vehicles through strategic adjustments to plate area dimensions, power handling capabilities, and operating parameters optimized for specific vehicle requirements. Similarly, the core technology principles can be effectively adapted and optimized to meet the specialized requirements of automated guided vehicles (AGVs) in sophisticated industrial applications, where reliable automated, contactless charging capabilities could significantly streamline operational efficiency and reduce maintenance requirements in warehouse environments, manufacturing facilities, and other industrial settings requiring continuous vehicle operation.

3. CONCLUSIONS

T This comprehensive research study introduces an advanced and highly innovative capacitive coupling-based wireless charging system that fundamentally revolutionizes the charging process for diverse electric mobility applications across multiple sectors. Initially validated through successful implementation and extensive testing with shared electric scooters in urban environments, the system's remarkable flexibility, innovative compact design, and seamless integration capabilities position it as an ideal solution for an exceptionally diverse range of applications, encompassing both personal electric vehicles and sophisticated industrial AGV systems. The system's demonstrated exceptional tolerance to alignment variations, revolutionary ultra-compact form factor, and non-invasive retrofit capability create compelling opportunities for scalability and broader implementation across an expanding range of electric vehicles, including specialized industrial applications requiring continuous operation. Through the comprehensive automation of charging operations and sophisticated power management, the system delivers substantial and measurable improvements in user experience while simultaneously reducing operational complexity and associated costs, thereby supporting and accelerating the widespread adoption of clean transportation solutions in urban environments worldwide.

Future development efforts and ongoing research initiatives will concentrate on conducting extensive and rigorous real-world testing through strategically designed pilot programs in diverse operating environments, engineering sophisticated solutions for scaling the technology to accommodate larger vehicle platforms and higher power requirements, and continuously optimizing energy transfer efficiency across a wide range of operating conditions and environmental factors. These systematic development steps and careful optimization processes represent critical milestones in achieving widespread commercial adoption and establishing robust, sustainable, and highly efficient EV charging infrastructure on a global scale, supporting the continued growth and evolution of electric mobility solutions.

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