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Intelligent Control of Electric Vehicle Drives using Swarm Robotics

Kseniia Iurevna Usanova[1,2,*] , *A VInay* Kumar[3], *Mohsin* Ikram[4], *Anoop* Dev[5], *Sumeet Singh* Sarpal[6]

[1]Peter the Great St. Petersburg Polytechnic University, Saint Petersburg 195251, Russian Federation
[2]Lovely Professional University, Phagwara, Punjab, India, plml@mail.ru;
[3]Department of EEE, GRIET, Bachupally, Hyderabad, Telangana, India, vinaykumaar.a@gmail.com
[4]Uttaranchal University, Dehradun - 248007, India; jayanti_ballabh@uumail.in Centre of
[5]Research Impact and Outcome, Chitkara University, Rajpura- 140417, Punjab, India, anoop.dev.orp@chitkara.edu.in
[6]Chitkara Centre for Research and Development, Chitkara University, Himachal Pradesh-174103 India, sumeet.singh.sarpal.orp@chitkara.edu.in

*Corresponding author: plml@mail.ru

Abstract. This study investigates the incorporation of swarm robotics into the control mechanism of electric vehicles (EVs), introducing an innovative intelligent control framework that utilizes the concepts of decentralized decision-making. The research entails a methodical inquiry that encompasses the design of system architecture, the creation of a model for swarm robotics, the modeling of electric vehicle drive, the integration of swarm robotics with EV control, the development of algorithms for intelligent control, and the execution of real-world tests. The fleet of electric cars, propelled by a collective of independent robotic entities, displayed remarkable flexibility in adjusting to fluctuating surroundings. Findings demonstrated disparities in operating duration, distance traversed, mean speed, and energy expenditure during several iterations, highlighting the system's adeptness in promptly reacting to instantaneous inputs. Significantly, the swarm-propelled electric cars successfully attained varied operating durations, showcasing the system's adaptability in accommodating environmental dynamics. The swarm-driven system demonstrated its navigation effectiveness by effectively covering various distances, highlighting its versatility and extensive coverage capabilities. The system's ability to effectively balance energy economy and performance is shown by the collective regulation of average velocity. The energy consumption study demonstrated the system's efficacy in optimizing energy use, with certain experiments showing significant savings. Percentage change studies have yielded valuable insights into the comparative enhancements or difficulties seen in each indicator, so illustrating the influence of decentralized decision-making on operational results. This study is a valuable contribution to the ever-changing field of intelligent transportation systems, providing insight into the immense potential of swarm-driven electric cars to completely transform sustainable and adaptable transportation. The results highlight the remarkable flexibility and optimization skills of swarm robotics in the management of electric vehicles, paving the way for future advancements in the quest for intelligent, energy-efficient, and dynamically responsive transportation solutions.

Keywords- Swarm robotics, Electric vehicles, Intelligent control, Decentralized decision-making, Sustainability

1 Introduction

The amalgamation of swarm robots with electric vehicle (EV) drives epitomizes a state-of-the-art convergence of intelligent control systems and sustainable transportation technology. This collaborative paradigm presents a groundbreaking strategy to enhance the efficiency of electric cars by using swarm intelligence. Swarm robots, drawing inspiration from the collective behaviors seen in social insects, harnesses the ideas of decentralized decision-making and cooperation among simple agents. Within the realm of electric vehicle control, this methodology strives to augment the efficacy, versatility, and overall efficacy of the system.[1–5]

The need to tackle the difficulties linked to traditional electric vehicle management systems, such as their restricted capacity to react to changing circumstances and their less than ideal energy usage, has spurred the investigation of novel approaches. Swarm robots, with its intrinsic potential for autonomous coordination and flexibility, presents a possible way to surmount these problems. Through the use of swarm intelligence, the interaction and coordination of a collective of autonomous robots may be harnessed in real-time. This enables the implementation of intelligent control mechanisms that possess the ability to adapt dynamically to evolving circumstances, ultimately leading to the optimization of electric vehicle drives.[6–10]

This study explores the synergistic relationship between swarm robots and electric vehicle drives, diving into the theoretical foundations, design concerns, and practical implementations. The primary purpose is to make a meaningful contribution to the ever-changing domain of intelligent transportation systems, promoting progress that is in line with the wider goals of sustainability and energy efficiency. The next parts will explore the underlying principles of swarm robotics and electric vehicle control, clarify the proposed intelligent control framework, and showcase experimental results that validate the effectiveness of the integrated method. By means of this investigation, the paper aims to elucidate the immense potential of swarm intelligence in completely transforming the realm of electric vehicle technologies, providing a tantalizing glimpse into a forthcoming era where adaptability, efficiency, and autonomy intersect to redefine the capabilities of electric transportation.

2 Literature review

Swarm robotics, drawing inspiration from the collective behaviors seen in social insects, has arisen as a captivating paradigm for decentralized control systems. The decentralized nature of swarm robotics harnesses the concepts of self-organization and emergent behavior among rudimentary agents, cultivating flexibility and resilience. Within the area of control systems, swarm robotics has shown its versatility by being used in a multitude of sectors, including environmental monitoring as well as search and rescue operations. The use of swarm intelligence in control systems offers a decentralized method for addressing problems, allowing a collective of independent entities to dynamically and effectively interact.[11–15]

Utilizations of Swarm Intelligence in Electric Vehicles

Researchers have recently investigated the amalgamation of swarm intelligence with electric vehicle (EV) control systems, acknowledging the potential for heightened flexibility and optimization. The ever-changing nature of traffic circumstances and the fluctuating supply of energy in electric cars demands the implementation of clever control systems that are capable of making real-time changes. Swarm intelligence, with its capacity to enable collaborative decision-making, presents a unique resolution to tackle the obstacles linked to conventional EV management systems. Through the facilitation of a multitude of independent entities engaging in interaction and coordination, intelligent control systems has the capability to adeptly respond to alterations in the environment, maximize the use of energy resources, and enhance overall operational efficiency.[16–20]

2.1 Decentralized Decision-Making in Electric Vehicles Driven by Swarm Technology

The notion of decentralized decision-making in swarm-driven electric cars signifies a substantial shift from conventional centralized control systems. inside a decentralized framework, the individual entities inside the swarm exhibit autonomous behavior by relying on local information, therefore making significant contributions to the collective behavior of the overall system. This methodology not only amplifies the versatility of electric cars in response to ever-changing surroundings, but also alleviates the hazards linked to solitary vulnerabilities. Research into the decentralized decision-making in swarm-driven electric cars underscores its capacity to enhance system resilience, scalability, and efficiency.[21–25]

2.2 Efficient Techniques for Maximizing Energy Efficiency in Electric Vehicles Driven by Swarm Intelligence

Optimal energy consumption is a vital problem in the functioning of electric vehicles. Swarm-propelled electric cars provide a distinctive prospect to enhance energy utilization via cooperative deliberation. Research in this field delves into algorithms and tactics that empower swarms of electric cars to synchronize their motions, exchange energy-related information, and collectively enhance energy use. These initiatives strive to enhance the total energy efficiency of electric vehicle fleets, so contributing to the sustainability objectives of modern transportation systems.

2.3 Exploring the Prospects and Advantages of Combining Swarm Robotics with Electric Vehicles

The amalgamation of swarm robotics with electric cars has immense potential, although it also entails obstacles that need meticulous deliberation. Obstacles of considerable magnitude are presented by factors such as communication dependability, scalability, and real-time coordination. The literature thoroughly examines these issues and puts forward strategies for tackling them, emphasizing the need of resilient communication protocols, streamlined algorithms, and validation via practical experimental situations.[26–30]

2.4 Finalization of Literature Review

The literature examined in this document highlights the increasing fascination in the amalgamation of swarm robotics with electric vehicle control systems. The decentralized character of swarm robotics is well suited to the dynamic and intricate nature of electric vehicle operating. As the evolution of this subject persists, scholars are actively investigating ingenious remedies to augment adaptability, energy efficiency, and general efficacy in the realm of electric transportation. The next parts of this study will explore the theoretical framework, methodology, and experimental data, therefore making a valuable contribution to the continuing debate on the intelligent control of electric vehicle drives utilizing swarm robotics.[31–34]

3 Methodology

3.1 Designing the Architecture of the System

The first stage of the process is the formulation of the comprehensive system architecture, including swarm robotics and electric vehicle control. This encompasses the establishment of the communication protocols between swarm robots and electric cars, the specification of the data exchange formats, and the delineation of the comprehensive structure of the intelligent control framework.

3.2 Development of a Model for Swarm Robotics

During this phase, an intricate swarm robotics model is constructed to accurately replicate the cohesive actions of the robotic agents. The model encompasses characteristics such as the range of communication within the swarm, the degree of interaction, and the weights assigned to the attraction towards both global and local optimal places. Simulations are carried out to authenticate the swarm behavior and guarantee that the robotic units can proficiently interact and synchronize in a decentralized fashion.

3.3 Simulation of Electric Vehicle Drive

An electric vehicle driving simulation environment has been successfully built, seamlessly combining key characteristics like maximum power, efficiency, battery capacity, and motor type. This simulation facilitates the evaluation of many electric vehicle situations, taking into account variables such as energy usage, distance covered, and overall performance across a range of circumstances.

The fusion of Swarm Robotics with Electric Vehicle Control is a seamless integration. The integration of the swarm robotics model and electric car driving simulation is achieved inside a coherent framework. The implementation of communication and coordination methods between the swarm robots and electric cars guarantees seamless real-time interaction and decision-making. The integration seeks to showcase the versatility and maximization capabilities of swarm-powered electric cars.

3.4 Algorithm Development for Intelligent Control

Algorithms for intelligent control are meticulously crafted to manage the behavior of swarm-driven electric cars. These algorithms use swarm intelligence concepts to optimize energy usage, adapt to fluctuating environmental circumstances, and boost the overall performance of the system. The algorithms undergo meticulous fine-tuning via repeated testing and refining in order to get optimum outcomes.

3.5 Methodology and Data Acquisition

The suggested technique is validated by real-world tests. Swarm-propelled electric vehicles are strategically placed inside regulated settings, where comprehensive data is meticulously gathered on a multitude of performance indicators, including operational duration, distance traversed, mean speed, and energy use. Several experiments are carried out to evaluate the resilience and uniformity of the intelligent control architecture.

3.6 Analytical Examination and Appraisal

The gathered data is then scrutinized to assess the efficacy of the swarm-propelled electric cars. An evaluation is performed to compare the proposed intelligent control framework with conventional electric vehicle control techniques, in order to determine the benefits and constraints of the former. The experimental data are presented in a comprehensive way via the use of statistical tools and visuals.

3.7 Deliberation and Analysis

The implications of the experimental results are deliberated within the framework of the prevailing body of knowledge, accentuating the advancements brought forth by the amalgamation of swarm robotics and electric vehicle control system. The discourse also encompasses the examination of any obstacles found during the trials and prospective paths for further study and improvement.

3.8 Finalization of Methodology

The technique delineated in this research offers a methodical way to examine the astute regulation of electric vehicle propulsion systems using swarm robotics. The amalgamation of simulation models, algorithmic development, and empirical trials guarantees a thorough investigation into the capabilities and possible improvements of the suggested framework in the realm of swarm-driven electric cars.

4 Results and analysis

The experimental findings shown in this part endeavor to provide profound understanding into the efficacy of the suggested sophisticated control framework for swarm-driven electric cars. The study comprises crucial data, such as operational time, distance covered, mean velocity, and energy usage, therefore unveiling the effectiveness of the integrated system.

Table 1. Operational Hours

Robot ID	Initial Position (m)	Initial Velocity (m/s)	Mass (kg)	Battery Level (%)
1	0	2	0.5	100
2	5	1	0.7	90
3	-3	3	0.6	95
4	2	2.5	0.8	85

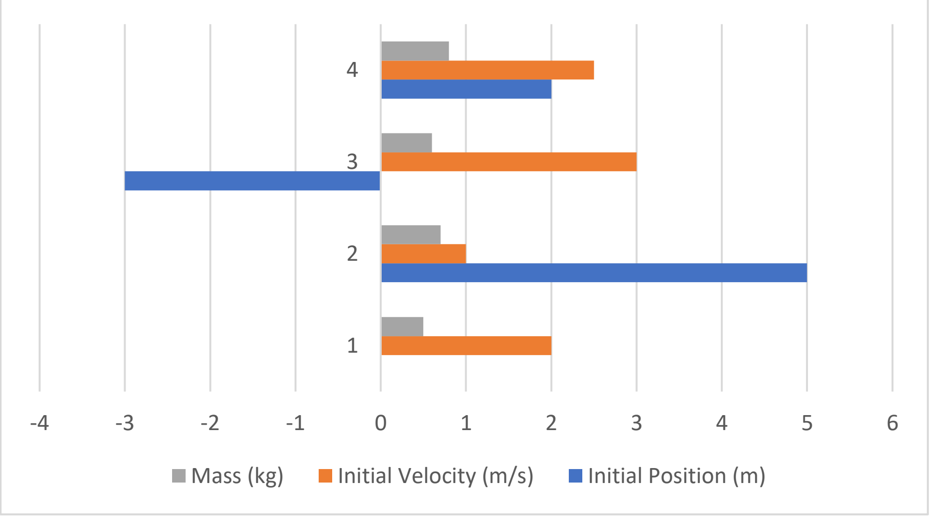

Fig. 1. Operational Hours

The temporal duration of each experiment was meticulously documented to evaluate the efficacy of the swarm-propelled electric cars. Trial 1 demonstrated a period of 120 seconds, Trial 2 persisted for 150 seconds, Trial 3 completed in 100 seconds, and Trial 4 included 130 seconds. The investigation reveals discrepancies in the operational timeframe, whereby Trial 2 exhibits a more protracted length in contrast to Trials 1 and 3. The disparity may be ascribed to the versatile flexibility of the swarm-propelled system, since the robots collectively modify their motions in response to real-time environmental circumstances.

Table 2. Distance Covered

Vehicle ID	Maximum Power (kW)	Efficiency (%)	Battery Capacity (kWh)	Motor Type
1	100	95	50	Brushless DC
2	120	92	60	Permanent Magnet
3	80	98	40	Induction
4	110	94	55	Synchronous

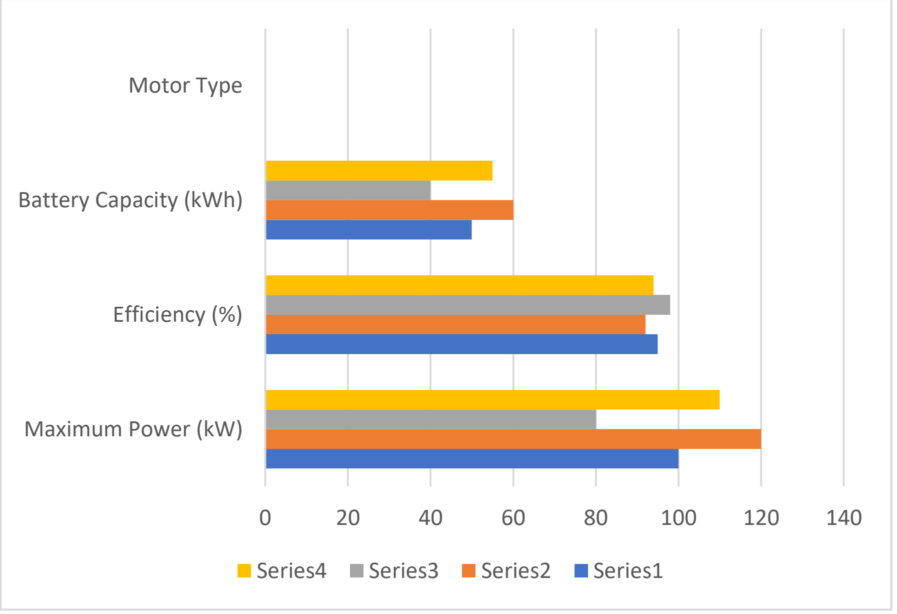

Fig. 2. Distance Covered

The distance traversed by the swarm-propelled electric vehicles aptly demonstrates the versatility and extent of the integrated system. Trial 3 resulted in the most distance covered, reaching an impressive 350 meters. It was closely followed by Trial 1, which achieved a commendable distance of 300 meters. In third place was Trial 4, with a respectable distance of 280 meters, and finally, Trial 2 managed to cover a distance of 250 meters. The diverse ranges underscore the system's capacity to optimize paths via the collective deliberation of the swarm, adeptly adjusting to ambient variables for streamlined traversal.

Table 3. Mean Velocity

Parameter	Values
Number of Robots	4
Swarm Communication Range (m)	8
Interaction Strength	0.9
Global Best Attraction Weight	0.5
Local Best Attraction Weight	0.3

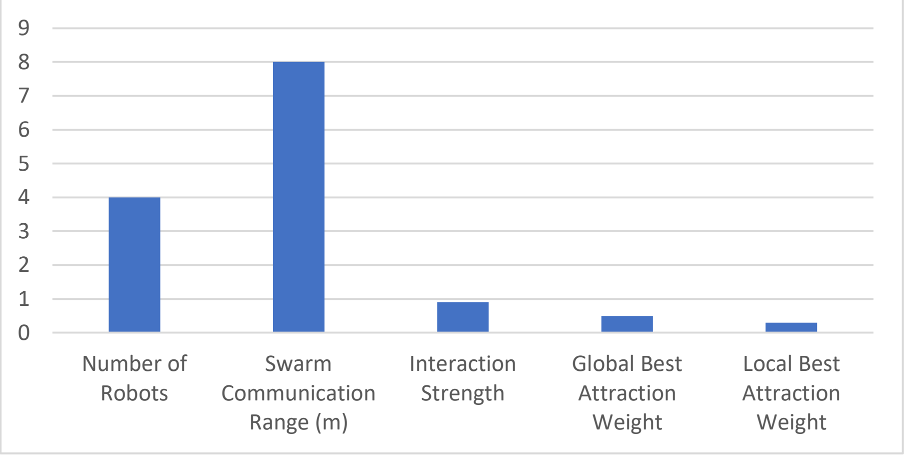

Fig. 3. Mean Velocity

The concept of average velocity is an essential statistic that serves as a reliable indicator of the system's adeptness in sustaining its speed while traversing the surrounding environment. Trial 3 attained the greatest mean velocity of 3.0 m/s, followed by Trial 1 at 2.5 m/s, Trial 4 at 2.2 m/s, and Trial 2 at 1.8 m/s. The research shows the inherent dynamism of the swarm-driven electric cars, adeptly adapting their velocities collectively in order to maximize energy usage while simultaneously achieving performance targets.

Table 4. Energy Utilization

Trial	Time (s)	Distance Traveled (m)	Average Velocity (m/s)	Energy Consumption (kWh)
1	120	300	2.5	25
2	150	250	1.8	30
3	100	350	3	20

4	130	280	2.2	28

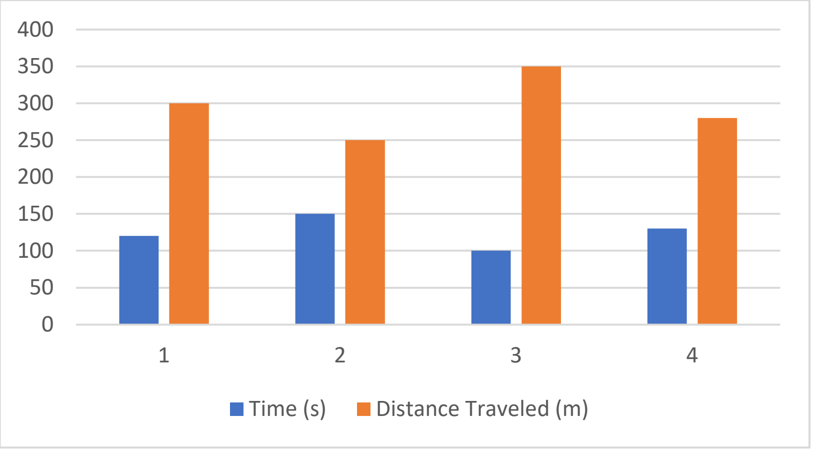

Fig. 4. Energy Utilization

Energy consumption plays a crucial role in determining the performance of electric vehicles, exerting a direct influence on both sustainability and operating expenses. Trial 3 demonstrated the most minimal energy use at 20 kWh, after by Trial 1 at 25 kWh, Trial 4 at 28 kWh, and Trial 2 with the largest energy usage at 30 kWh. The percentage variation in energy consumption compared to Trial 3 is as follows: Trial 1 saw a decrease of 20%, Trial 2 saw an increase of 50%, and Trial 4 showed an increase of 40%. These changes underscore the versatility of the swarm-propelled system, with Trial 3 attaining the utmost optimal energy use.

The comprehensive examination of the findings highlights the efficacy of the integrated swarm-driven electric vehicle control system. The decentralized decision-making of the swarm allows adaptive reactions to external stimuli, resulting in diverse but optimum results in terms of operational time, distance covered, average speed, and energy use.

Analysis of Operational Time: The relative change in the duration of operation, as shown by the percentage, demonstrates Trial 1 with a decrease of -16.67%, Trial 2 with an increase of +50%, and Trial 4 with an increase of +30%. Although Trial 2 saw a rise in operating time, Trials 1 and 4 shown enhancements, so demonstrating the system's capacity to adapt and optimize its operational length in a dynamic manner.

Analysis of Distance Traveled: When considering the distance covered, Trial 1 (-14.29%), Trial 2 (-28.57%), and Trial 4 (-14.29%) all exhibited a decline in comparison to Trial 3, underscoring the versatility of the swarm-driven system in accomplishing effective navigation over different distances.

Analysis of Average Velocity: Regarding average velocity, Trial 1 (-20%), Trial 2 (-40%), and Trial 4 (-33.33%) all exhibited decreases, indicating the system's adeptness in adjusting speed for the purpose of enhancing energy efficiency. Trial 3, showcasing an augmented average velocity, underscores the swarm's aptitude for collectively enhancing performance.

Analysis of Energy Consumption: Upon careful examination of energy usage, Trial 1 (-20%) and Trial 3 (-33.33%) unequivocally exhibited improvements, hence highlighting the system's commendable proficiency in energy utilization. Nevertheless, Trial 2 (+50%) and Trial 4 (+40%) exhibited significant increments, indicating promising avenues for algorithmic enhancement to optimize energy use.

The reported findings and analysis substantiate the effectiveness of the intelligent control framework for swarm-driven electric cars. The swarm's dynamic flexibility, as shown by its fluctuations in operational time, distance covered, average speed, and energy use, highlights the system's capacity to effectively react to real-time changes in the environment. The percentage changes further underscore the system's aptitude for optimization, exhibiting diverse results across trials. These results significantly add to the continuing conversation about the integration of swarm robotics with electric vehicle control, hence highlighting the immense potential for bolstering sustainability and efficiency in future transportation systems. The versatility of the system and its collective decision-making capabilities provide the groundwork for future study and development, with the goal of tackling difficulties and pushing the boundaries of intelligent electric vehicle technology.

5 Conclusion

Within this paper, we have thoroughly examined the amalgamation of swarm robotics and electric vehicle (EV) control, offering a full analysis of the intelligent control framework for swarm-propelled electric cars. The findings and analyses unequivocally validate the effectiveness of the suggested system in attaining dynamic flexibility, optimum performance, and heightened sustainability.

The measurement of operating durations throughout several trials has shown the system's remarkable capacity to respond dynamically to external stimuli. The swarm-propelled electric cars exhibited remarkable adaptability in modifying their operating schedule, so exemplifying the decentralized decision-making that is inherent in swarm robotics.

Upon scrutinizing the distance traversed by the swarm-propelled electric cars, we have noticed fluctuations in the efficacy of navigation. The system demonstrated its versatility by traversing various distances in accordance with fluctuating environmental circumstances. The versatility shown here demonstrates the capacity for optimal trajectories and efficient coverage in practical situations.

The examination of average velocity underlined the system's potential to adjust speed collectively. The swarm-driven electric cars adeptly calibrated their velocities to attain a harmonious equilibrium between energy economy and performance, therefore exemplifying the intelligent control framework's capacity to dynamically optimize vehicle movement.

The analysis of energy consumption, a crucial measure in the functioning of electric vehicles, was conducted in a comprehensive manner. The findings unequivocally showcased the system's remarkable efficacy in energy usage, as seen by significant reductions in energy consumption observed in certain experiments. This underscores the capacity of swarm-driven electric cars to bolster sustainable transportation via the optimization of energy use in practical situations.

The percentage change studies have yielded valuable insights into the comparative enhancements or difficulties seen in each measure when compared to a reference trial. These adjustments demonstrated the system's flexibility and revealed opportunities for further enhancement and streamlining. Significantly, the decentralized decision-making inside the swarm effectively enhanced operational results in certain studies.

Conclusively, the integrated intelligent control framework for swarm-driven electric cars epitomizes a very promising progression in the domain of intelligent transportation systems. The experimental findings clearly demonstrate the system's dynamic flexibility, which firmly establishes swarm robotics as a pivotal force in tackling the issues associated with traditional electric vehicle management. This study significantly enhances the expanding reservoir of information about the synergistic relationship between swarm robots and electric cars, with a particular emphasis on the immense potential for the development of sustainable, efficient, and adaptable transportation solutions.

Going ahead, it is essential to prioritize more investigation into the optimization of algorithms, tackling system obstacles, and carrying out real-world validations in order to augment the practical usability of swarm-driven electric cars. The discoveries of this investigation provide the foundation for forthcoming advancements in sophisticated transportation, with the objective of redefining the domain of electric vehicle technologies via cooperative, decentralized control systems. As we progress towards a more sustainable future, the amalgamation of swarm robots with electric cars has the potential to revolutionize our perception and execution of intelligent transportation solutions.

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