Postprint: Trajectory Tracking Method for Multi-Robot Agricultural Machinery Formation Driving Based on MPC Delay Compensator

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Abstract

[Purpose/Significance] The characteristics of agricultural machinery, such as large dimensions and low travel speeds, can easily cause severe road congestion during road operations. Consequently, formation driving is regarded as the primary mode of future on-road travel in multi-machine cooperative processes. However, current autonomous driving technology for agricultural machinery remains at the single-machine stage, and coordination among multiple machines constitutes the main bottleneck restricting large-scale autonomous production in Chinese agriculture. To address communication delay issues and their compensation strategies in multi-vehicle formation cooperative control, this study proposes a trajectory tracking method for multi-machine formation driving of agricultural machinery based on a Model Predictive Control (MPC) delay compensator.

[Method] Grounded in vehicle networking technology and focusing on the domain of multi-machine formation cooperative control, this study addresses the poor lateral control accuracy arising from communication delays in Controller Area Network (CAN) bus. A delay-compensated model predictive controller is designed based on Linear Quadratic Regulator (LQR) and MPC algorithms to compensate for communication delays. Finally, co-simulation of the proposed algorithm is conducted using Carsim and Simulink software.

[Results and Discussion] Carsim and MATLAB/Simulink can be effectively interfaced to achieve co-simulation between software and external solvers. When the delay step d=5, the application of delay compensation results in faster MPC response and smoother performance; the speed error curve responds more rapidly and gradually stabilizes to zero error without oscillation; Vehicle 1 effectively executes lane changes within a short duration and maintains alignment with the lead vehicle in the same lane. Under the longer delay step d=10, the controller without delay compensation exhibits more pronounced performance degradation. Even under high-delay conditions, the MPC with delay compensation still enables rapid response and gradual stabilization of speed error and longitudinal acceleration to zero error, avoiding oscillation. The trajectory of Vehicle 1 indicates that the effectiveness of the delay compensation mechanism diminishes under extreme delay conditions.

[Conclusion] The formation algorithm designed in this study enables multiple vehicles to complete multi-vehicle lane changes to form a queue while maintaining a certain distance and speed. The communication delay compensation control algorithm allows vehicles subject to communication delays to satisfactorily complete formation tasks, achieving stable lateral and longitudinal control, thereby validating the feasibility of the delay-compensated model predictive controller proposed in this study.

Full Text

Trajectory Tracking Method for Multi-Robot Agricultural Machinery Formation Based on MPC Delay Compensator

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Abstract

Objective: Agricultural machinery exhibits characteristics such as large size and slow operating speeds, which can cause significant road congestion during return-to-depot operations. Formation driving is therefore considered the primary mode of future road operation in multi-machine collaborative scenarios. However, current autonomous driving technology for agricultural machinery remains at the single-machine stage, with multi-machine coordination representing a major bottleneck restricting large-scale autonomous production in Chinese agriculture. To address communication delay issues and compensation strategies in multi-vehicle formation cooperative control, this study proposes a trajectory tracking method for multi-robot agricultural machinery formation based on a Model Predictive Control (MPC) delay compensator.

Methods: Grounded in vehicle-to-everything (V2X) technology and focusing on multi-machine formation cooperative control, this study addresses the poor lateral control accuracy caused by communication delays in Controller Area Network (CAN) bus systems. Based on the Linear Quadratic Regulator (LQR) algorithm, a model predictive controller with delay compensation was designed to mitigate communication delay effects. The effectiveness of the proposed algorithm was validated through co-simulation using CarSim and Simulink.

Results and Discussion: CarSim and MATLAB/Simulink proved effectively compatible, enabling joint simulation between software and external solvers. When the delay step size d = 5, the MPC with delay compensation demonstrated faster response and smoother performance. The speed error curve responded more rapidly and gradually stabilized to zero error without oscillation. Vehicle 1 effectively changed lanes within a short time, maintaining the same lane as the lead vehicle. Under longer delay step size d = 10, controllers without delay compensation exhibited more significant performance degradation. Even under high delay conditions, the MPC with delay compensation maintained rapid response, with speed error and longitudinal acceleration gradually stabilizing to zero error while avoiding oscillations. The trajectory of Vehicle 1 indicated that the effectiveness of the delay compensation mechanism decreased under extreme delay conditions.

Conclusion: The formation control algorithm designed in this study enables multiple vehicles to complete lane changes, form convoys, and maintain specific distances and speeds. The communication delay compensation control algorithm allows vehicles with induced delay to effectively accomplish formation tasks, achieving stable longitudinal and lateral control. This validates the feasibility of the proposed MPC controller with delay compensation.

Keywords: vehicle-to-everything; intelligent agricultural machinery; multi-machine collaboration; formation driving; trajectory tracking

1. Design of Multi-Machine Formation Cooperative Control Strategy

1.1 Multi-Machine Formation Cooperative Scenario Description

This study considers a scenario where four agricultural machinery units travel on three lanes. Based on multi-machine coordination, four machines with different initial speeds combine into a single formation to travel at a uniform speed, ultimately achieving consistent inter-vehicle distances and speeds within the formation. The initial and final states are illustrated in [Figure 1: see original paper] and [Figure 2: see original paper], respectively. This approach saves road resources while improving traffic efficiency and reducing energy consumption. In the road coordinate system, the initial centroid coordinates and speeds of the four agricultural machinery units are shown in .

1.2 Architecture Design

1.2.1 Vehicle-to-Everything Technology V2X represents a comprehensive communication technology that integrates four communication modes: Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Network (V2N), and Vehicle-to-Pedestrian (V2P). It enables communication between vehicles and surrounding network information environments, with the goal of constructing an information interaction network among all entities in the transportation environment through fusion technologies. This facilitates data exchange and sharing between vehicles and other traffic participants or infrastructure while establishing a real-time, reliable communication network for effective mutual transmission of data among vehicles, roads, and cloud structures.

1.2.2 System Architecture Design Since single-machine perception technology suffers from errors due to environmental and lighting influences, formation vehicles must transmit sensor information via V2X communication to Road Side Units (RSU) to enhance multi-machine coordination safety. The RSU then distributes position, speed, and acceleration information for each vehicle in the formation.

As shown in [Figure 3: see original paper], this study employs a V2X communication-based system to centrally process sensor data from each vehicle in the convoy, including position, speed, and acceleration information. This data is first transmitted to the RSU for comprehensive processing. The processed data, including desired speed and pose for each vehicle, is then sent back to every vehicle in the convoy. Subsequently, each vehicle transmits this information via CAN bus to its controller and actuators, enabling precise tracking control of the predetermined trajectory and pose.

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2. Agricultural Machinery Modeling

2.1 Kinematic Model

This study constructs an agricultural machinery model based on a two-degree-of-freedom vehicle kinematic model. The model ignores the difference in side slip angles between left and right front tires during turning. During operation, the front wheel steering angle remains within a predetermined range, while the lateral force generated during turning is proportional to the side slip angle. Based on these assumptions, the agricultural machinery model is simplified to a bicycle model, as shown in [Figure 4: see original paper].

In the road coordinate system, where (x, y) represents the front axle center coordinates and v_f represents front axle velocity, the vehicle kinematic equations in matrix form are given by equation (1). The vehicle model differential equations derived from Newton’ s laws are given by equation (2), where m is vehicle mass (kg), I_z is vehicle moment of inertia, F_{yf} and F_{yr} are lateral forces on front and rear wheels (N), and F_{xf} and F_{xr} are longitudinal forces on front and rear wheels (N).

Under steady-state steering conditions, this study derives the front wheel feedforward steering angle δ_{ff} based on the bicycle model. Assuming a fixed steering angle and constant speed, the steady-state steering equation is derived using geometric relationships, as illustrated in [Figure 5: see original paper], where c.g. represents the vehicle centroid and $l = l_f + l_r$ represents the wheelbase.

According to Ackermann steering geometry, shown in [Figure 6: see original paper], the vehicle kinematic model is formulated as equation (5).

2.2 Dynamic Model

Based on the relationship between motion and mechanics, a dynamic model of agricultural machinery was established to achieve high-precision trajectory tracking and robust control stability. Building upon the kinematic model, constraints such as lateral forces during machinery operation were incorporated to establish the dynamic model shown in [Figure 7: see original paper].

The following assumptions were made: (1) vehicle weight remains constant and always acts at the center of gravity; (2) front and rear wheel lateral forces are proportional to their respective side slip angles; and (3) aerodynamic resistance is neglected.

In the road coordinate system, F_{xf} and F_{xr} represent longitudinal forces on front and rear wheels (N); F_{yf} and F_{yr} represent lateral forces on front and rear wheels (N); $\dot{x}$ is longitudinal velocity (m/s); $\dot{y}$ is lateral velocity (m/s); l_f and l_r are front and rear wheelbases (m); ϕ is vehicle heading angle in the global coordinate system (rad); $\dot{\phi}$ is yaw rate (rad/s); m is vehicle weight (kg); and I_z is moment of inertia ($kg \cdot m^2$).

As shown in [Figure 7: see original paper], the dynamic characteristics of the i-th vehicle can be expressed as equation (6), where $i \ \{1, 2, 3, 4\}$. The transformation between vehicle coordinate system and road coordinate system is given by equation (7).

According to the Pacejka magic tire model, tire forces can be approximated using linear functions when side slip angles and slip ratios are small. When lateral acceleration $a_y \leq 0.4g$ and tire side slip angle α is small, the fitting accuracy for tires is high. The lateral force expression is given by equation (8), where c_f and c_r are front and rear tire cornering stiffness (N/rad), and β_f and β_r are front and rear tire side slip angles (rad).

Finally, the vehicle dynamics can be expressed as equation (9), with the state vector defined by equation (10), where $\dot{y}_i$ is lateral velocity in road coordinates (m/s), $\dot{x}_i$ is longitudinal velocity in road coordinates (m/s), ϕ_i is heading angle (rad), ϕ_i is yaw rate (rad/s), Y_i is lateral position (m), and X_i is longitudinal position (m).

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3. Controller Design

3.1 Linear Quadratic Regulator Tracker Design

This section focuses on tracking control during lane changes in the return-to-depot process. A tracking error state-space model was established based on the Linear Quadratic Regulator (LQR). Using input and system state variables as the objective function, and based on parameters Q and R, the optimal state feedback matrix K was designed to minimize the objective function.

Matrices A and B are defined by equations (11) and (12), where c_f and c_r are front and rear tire cornering stiffness (N/rad), l_f and l_r are front and rear wheelbases (m), and I_z is the moment of inertia about the Z-axis (kg · m^2). The optimal state feedback matrix K is given by equation (13).

The objective function is defined by equation (14). Minimizing this function yields the optimal state feedback matrix given by equation (15), where P is the solution to the Riccati equation or cost function, measuring system performance and control cost, as expressed by equation (16).

3.2 Delay Compensation Controller Design

Model Predictive Control (MPC) encompasses various methods including adaptive control and internal model control. Its advantages in handling variable interactions and constraints have led to increasing adoption in industry. With the development of mechanical intelligence, MPC has been widely applied in control systems for unmanned aerial vehicles and robots. In 1986, Kuntze et al. proposed the fundamental principles of predictive control algorithms centered on internal models, trajectory references, and control algorithms. Today, the three main components of MPC have evolved into model prediction, rolling optimization, and feedback correction.

As shown in [Figure 8: see original paper], the MPC controller continuously maintains a reference trajectory throughout the process. By fusing current values with a predictive model, system outputs are predicted over the prediction horizon [k, k+N_p]. Based on solving the objective function and through constrained optimization, a control sequence is obtained over the control horizon [k, k+N_c]. The actual control input at time k is applied, and rolling optimization is continuously performed for the k+1 moment to achieve robust control of the controlled object.

3.2.1 Linearization and Discretization Agricultural machinery dynamic and kinematic models are nonlinear systems. To achieve high-precision real-time control, the models must be linearized. Linearizing the dynamic equations at time t and ignoring higher-order terms in the Taylor expansion at [_i(t), _i(t)] yields equation (17). Linearization and discretization produce equation (18), which can be rearranged as equation (19).

3.2.2 Prediction Model Considering communication delays between the CAN bus and actuators in autonomous driving, an MPC controller with intentional delay compensation was designed. Using control increments as input yields a new state equation, given by equation (20). Using prediction errors between predicted outputs and trajectory planning references over the prediction horizon as the objective function, the agricultural machinery state vector is defined by equation (21), which can be rearranged as equation (22).

In these equations, N_c represents the control horizon, N_p represents the prediction horizon (N_c ≤ N_p), k denotes the system prediction model at time k, ˆ_i(k+1|k) represents the augmented matrix state predicted at time k for time k+1, ˆ_i(k) is the state vector of subsystem i at time k, B̄_i(k) is the control input matrix of subsystem i at time k, ΔU_i(k) is the control input increment of subsystem i at time k, đ_i(k) is the disturbance or bias term of subsystem i at time k, y_i(k) is the output vector of subsystem i at time k, and Ĉ_i(k) is the output matrix of subsystem i at time k.

3.2.3 Objective Function To achieve robust trajectory tracking control for agricultural machinery, the objective function for the robust trajectory tracking controller is obtained by optimizing state variables, state increments, and reference deviations, as expressed by equation (23). In this equation, J(k) evaluates the control strategy at time k, j is the future prediction time step index, Q is the state weight matrix, and R is the control weight matrix.

3.2.4 Constraint Functions Due to physical constraints on vehicle actuators, corresponding constraints on control inputs and control increments are designed as equations (24) and (25). In equation (24), U_{min}i(k+t) and U_{max}i(k+t) represent the minimum and maximum constraint values for control input at time (k+t), while U_i(k+t) is the actual control input. In equation (25), ΔU_{min}i(k+t) and ΔU_{max}i(k+t) represent the minimum and maximum constraint values for control input increment at time (k+t), where ΔU_i(k+t) = U_i(k+t) - U_i(k+t-1).

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4. Joint Simulation Platform

4.1 Platform Setup

CarSim is professional software developed by MSC that can analyze handling stability, braking performance, and fuel economy for vehicles including SUVs, light trucks, and passenger cars. It can simulate the influence of external factors such as road conditions and aerodynamic resistance, featuring a user-friendly interface.

Testing and optimization of autonomous driving algorithms based on real vehicles requires significant time and economic investment, and faces difficulties related to laws and regulations, scenario reproduction, and safety. Simulation platform testing effectively addresses these challenges. presents the relevant vehicle dynamics parameter settings used in the CarSim simulation.

CarSim and MATLAB/Simulink can be effectively compatible, enabling joint simulation between software and external solvers. The multi-vehicle formation cooperation structure flowchart is shown in [Figure 9: see original paper]. In Simulink, sensor-monitored speed, position, and yaw angle are fed back to adjust actuator parameters for following vehicles, including throttle opening, acceleration, braking, and steering angle. Based on trajectory tracking algorithms, control signals are output as input signals to CarSim vehicle models, enabling the control system to manage collision avoidance, lane changing, and following for robust safe following control.

4.2 Controller Parameters

4.2.1 Discrete Driving Controller The speed controller is the most critical component of the vehicle control system, adjusting engine output traction based on the difference between actual and set speeds. The mathematical expression for a traditional PID controller is given by equations (27), (28), and (29), where u(t) is system input, y(t) is system output, x(t) is vehicle state, and K_p, K_i, and K_d are the proportional, integral, and derivative control parameters, respectively.

4.2.2 Vehicle Powertrain The vehicle engine provides driving power, outputting corresponding traction under the control of the vehicle control system to change vehicle speed and reach the set value. This relationship is expressed by equation (30), where v is vehicle speed (m/s), F is traction force (N), m is vehicle weight (1465 kg), and the resistance factor b is set to 20.

4.2.3 Single-Vehicle Controller Settings Communication between the vehicle control unit and low-level actuators occurs via CAN bus, which introduces communication delays. This study addresses constant time-invariant delays between single-vehicle execution units and low-level actuators, without exploring time-varying delays. When the maximum delay is τ_{in} and sampling time is T, the delay step size in the discrete system is represented by equation (31). [Figure 10: see original paper] illustrates the system with fixed delay in control input.

This section describes the maximum delay discrete linear system using equation (32) to represent the motion state of a single agricultural machine. The prediction horizon for the trajectory tracking controller is N_p = 40, control horizon is $N\_c = 20$, and sampling period is $T = 0.01$ s. The weight matrices Q (state) and R (control) and relaxation factor   require tuning. The corresponding delay step size d is calculated using equation (33).

When $d = 5$, experimental results shown in [Figure 11: see original paper] demonstrate that MPC with delay compensation responds faster and performs more smoothly, while MPC without delay compensation exhibits significant overshoot, slow response, and oscillatory non-convergence.

[Figure 12: see original paper] presents the speed error and longitudinal acceleration comparison for $d = 5$. The delay-compensated MPC responds faster and gradually stabilizes to zero error without oscillation, whereas the uncompensated MPC responds slowly with oscillatory non-convergence, causing abrupt acceleration or deceleration.

The trajectory performance of Vehicle 1 at $d = 5$ is shown in [Figure 13: see original paper]. Without delay compensation, Vehicle 1 responds slowly with obvious trajectory oscillations. With delay compensation applied, [Figure 14: see original paper] shows that Vehicle 1 can effectively change lanes within a short time, maintaining the same lane as the lead vehicle.

5. Experimental Results

5.1 Delay Step Size d = 5

With a maximum artificially set delay $\tau\_\{in\} = 0.05$ s, the delay step size d is calculated as 5. The results demonstrate that delay-compensated MPC exhibits faster response and smoother performance compared to uncompensated MPC.

5.2 Delay Step Size d = 10

This section investigates the impact of longer communication delays between the on-board controller and actuators. The delay value is increased to $\tau\_\{in\} = 0.10$ s, introducing longer delays in the communication process. The new delay step size d is calculated using equation (34).

Experimental results show that under the longer delay step size $d = 10$, controllers without delay compensation exhibit more significant performance degradation, including increased overshoot, slower response, and more severe oscillatory non-convergence, as shown in [Figure 14: see original paper].

Additionally, [Figure 15: see original paper] presents the speed error and longitudinal acceleration comparison for $d = 10$. The results indicate that even under higher delay conditions, the delay-compensated MPC can still respond quickly, gradually stabilizing speed error and longitudinal acceleration to zero while avoiding oscillations. However, the performance of uncompensated MPC degrades significantly, with slow response and non-convergent oscillations, leading to abrupt acceleration or deceleration.

The trajectory of Vehicle 1 at d = 10 is shown in [Figure 16: see original paper]. Without delay compensation, Vehicle 1 responds noticeably slower with larger oscillation amplitudes than at d = 5. With delay compensation, Vehicle 1 requires more time to adjust lanes but still achieves the goal of maintaining the same lane as the lead vehicle, indicating that while the delay compensation mechanism remains effective at higher delay step sizes, its effectiveness decreases under extreme delay conditions.

The simulation results validate that the proposed formation control algorithm enables multiple vehicles to successfully change lanes, form convoys, and maintain specific distances and speeds. The communication delay compensation control algorithm allows vehicles with induced delay to effectively complete formation tasks, achieving stable longitudinal and lateral control. Compared with conventional MPC, the delay-compensated MPC effectively compensates for control performance degradation caused by communication delays. Conventional MPC exhibits increasing oscillation amplitude, slower response, and divergence tendency when faced with artificial communication delays. Particularly in trajectory tracking control, as delay step size increases, conventional MPC performance deteriorates progressively, manifested by larger oscillation amplitudes and slower response times, causing significant lateral control instability with frequent left-right swaying. In longitudinal control, conventional MPC causes abrupt acceleration and deceleration, increasing collision risk and affecting passenger comfort. In contrast, delay-compensated MPC demonstrates clear advantages in controlling vehicles more effectively, ensuring smoother driving experiences and reducing accident risks, as shown in [Figure 17: see original paper] and [Figure 18: see original paper].

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6. Conclusion and Future Work

This study implemented a formation trajectory tracking method for agricultural machinery during depot-return operations by integrating LQR and MPC controllers. A two-degree-of-freedom dynamic model and kinematic model were established for single agricultural machinery, laying a foundation for addressing formation driving problems. To solve the issue of poor lateral control accuracy caused by communication delays between on-board controllers and CAN systems, an MPC delay compensator was designed for agricultural machinery under different operating conditions. A joint simulation platform based on CarSim and Simulink was developed to test the formation operation algorithm, achieving robust cooperative control of multiple agricultural machines that maintains constant distance and speed during lane changes.

Currently, most multi-machine formation coordination is validated through simulation platforms, which offer advantages in safety, economy, and efficiency. However, a gap remains between idealized simulation models and real-machine experiments. Therefore, multi-machine formation operation of agricultural equipment still requires real-machine testing under sound legal and regulatory frameworks. Additionally, this study only considered constant time-invariant delays in CAN communication, whereas real-world scenarios involve time-varying delays affected by network transmission speed and signal quality. Future research should explore compensation methods for time-varying CAN communication delays.

Conflict of Interest Statement: The authors declare that they have no conflicts of interest regarding the publication of this research.

References

[1] LIU C L, LIN H Z, LI Y M, et al. Analysis on status and development trend of intelligent control technology for agricultural equipment[J]. Transactions of the Chinese society for agricultural machinery, 2020, 51(1): 1-18.

[2] LIU C L, GONG L, YUAN J, et al. Current status and development trends of agricultural robots[J]. Transactions of the Chinese society for agricultural machinery, 2022, 53(7): 1-22, 55.

[3] LI Z T, LI Y M, TANG X T, et al. Design of autonomous driving control system for rice hill-drop drilling machine[J]. Journal of agricultural mechanization research, 2019, 41(2): 150-154.

[4] ELBASI E, MOSTAFA N, ALARNAOUT Z, et al. Artificial intelligence technology in the agricultural sector: A systematic literature review[J]. IEEE access, 2023, 11: 46883-46904.

[5] FAGNANT D J, KOCKELMAN K. Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations[J]. Transportation research part A: Policy and practice, 2015, 77: 167-181.

[6] ZHOU Y, LIN G J, TANG Y, et al. FLYOVER: A model-driven method to generate diverse highway interchanges for autonomous vehicle testing[C]// 2023 IEEE International Conference on Robotics and Automation (ICRA). Piscataway, New Jersey, USA: IEEE, 2023.

[7] GU N, LIU Y J, PENG Z H, et al. Path-guided collision-free formation guidance law for a fleet of under-actuated autonomous surface vehicles[C]// 2019 Chinese Control Conference (CCC). Piscataway, New Jersey, USA: IEEE, 2019: 1199-1204.

[8] GUAN J S, ZHOU W D, KANG S B, et al. Robot formation control based on Internet of Things technology platform[J]. IEEE access, 2020, 8: ID 96767.

[9] DING W J, WANG S P, ZHANG C, et al. Formation control and obstacle avoidance of MAS with constraints of visibility and motion saturation[C]// 2021 IEEE 16th Conference on Industrial Electronics and Applications (ICIEA). Piscataway, New Jersey, USA: IEEE, 2021: 2107-2112.

[10] PAN Z H, ZHANG C X, XIA Y Q, et al. An improved artificial potential field method for path planning and formation control of the multi-UAV systems[J]. IEEE transactions on circuits and systems II: Express briefs, 2022, 69(3): 1129-1133.

[11] OBRADOVIĆ J, KRIŽMANČIĆ M, BOGDAN S. Decentralized multi-robot formation control using reinforcement learning[C]// 2023 XXIX International Conference on Information, Communication and Automation Technologies (ICAT). Piscataway, New Jersey, USA: IEEE, 2023: 1-7.

[12] HU H B, LI Y M, TANG X T, et al. The research and design of agricultural machinery navigation management system based on android platform[J]. Journal of agricultural mechanization research, 2019, 41(5): 179-183.

[13] ZHANG Y Q, XU Z H, WANG Z J, et al. Impacts of communication delay on vehicle platoon string stability and its compensation strategy: A review[J]. Journal of traffic and transportation engineering (english edition), 2023, 10(4): 457-474.

[14] KHATTAK Z H, RIOS-TORRES J, FONTAINE M D. Impact of communications delay on safety and stability of connected and automated vehicle platoons: Empirical evidence from experimental data[J]. IEEE access, 2023, 11: 29009-29023.

[15] HE J J. Integrated vehicle dynamics control using active steering, driveline and braking[D]. Leeds: University of Leeds, 2005.

[16] ARTUÑEDO A, MORENO-GONZALEZ M, VILLAGRA J. Lateral control for autonomous vehicles: A comparative evaluation[J]. Annual reviews in control, 2024, 57: ID 100910.

[17] CHEN Y J, YI G H, LI J F. Scheduling study of stereo garage access problem based on hybrid cross-entropy algorithm[C]// 2021 4th International Conference on Robotics, Control and Automation Engineering (RCAE). Piscataway, New Jersey, USA: IEEE, 2021.

[18] LIU S Y. Research of adaptive cooperative positioning technology for vehicular network[D]. Shanghai: Shanghai Jiao Tong University, 2019.

[19] SEHLA K, NGUYEN T M T, PUJOLLE G, et al. Resource allocation modes in C-V2X: From LTE-V2X to 5G-V2X[J]. IEEE Internet of Things journal, 2022, 9(11): 8247-8259.

[20] GAO H H, LIU C, LI Y, et al. V2VR: Reliable hybrid-network-oriented V2V data transmission and routing considering RSUs and connectivity probability[J]. IEEE transactions on intelligent transportation systems, 2021, 22(6): 3275-3287.

[21] KAMAL M, SRIVASTAVA G, TARIQ M. Blockchain-based lightweight and secured V2V communication in the Internet of vehicles[J]. IEEE transactions on intelligent transportation systems, 2021, 22(7): 3997-4004.

[22] KARAGIANNIS G, ALTINTAS O, EKICI E, et al. Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions[J]. IEEE communications surveys & tutorials, 2011, 13(4): 584-616.

[23] DEINLEIN T, GERMAN R, DJANATLIEV A. 5G-sim-V2I/N: towards a simulation framework for the evaluation of 5G V2I/V2N use cases[C]// 2020 European Conference on Networks and Communications (EuCNC). Piscataway, New Jersey, USA: IEEE, 2020.

[24] MARTIN-PEREZ J, KONDEPU K, DE VLEESCHAUWER D, et al. Dimensioning V2N services in 5G networks through forecast-based scaling[J]. IEEE access, 2022, 10: 12850-12862.

[25] TAHIR M N, MAENPAA K, HIPPI M. Pedestrian motion detection & pedestrian communication (P2I & V2P)[C]// 2020 International Conference on Software, Telecommunications and Computer Networks (SoftCOM). Piscataway, New Jersey, USA: IEEE, 2020.

[26] ITO H, MURASE T, SASAJIMA K. Congestion control and energy savings for V2P communication crash warnings with proximity relying[C]// 2016 International Conference on Connected Vehicles and Expo (ICCVE). Piscataway, New Jersey, USA: IEEE, 2016.

[27] YU C R, GONG L, FANG R, et al. Integration of agricultural wireless sensor networks to web-of-things through an edge-computing-enriched WSNs/WoT gateway[J]. International journal of interdisciplinary telecommunications and networking, 2022, 14(1): 1-15.

[28] LIU B, LUO X, ZHU J. Research on simulation of planning obstacle avoidance path for automated vehicles[J]. Computer simulation, 2018, 35(2): 105-110.

[29] XIONG S H, LI Y M, JIAO Z Y, et al. Research on CAN-bus monitoring system of rice and wheat combine harvester[J]. Journal of agricultural mechanization research, 2019, 41(4): 190-193, 199.

[30] GONG L, WU Y X, GAO B S, et al. Real-time dynamic planning and tracking control of auto-docking for efficient wireless charging[J]. IEEE transactions on intelligent vehicles, 2023, 8(3): 2123-2134.

[31] QIN Z W, HSU C, WU Y X, et al. Multi-stage perception, positioning and planning for automatic wireless charging of AGVs[C]// 2021 6th International Conference on Automation, Control and Robotics Engineering (CACRE). Piscataway, New Jersey, USA: IEEE, 2021.

[32] ASHOK KUMAR B, GAYATHRI S, SURENDHAR S, et al. Robust H-infinity controller for two degree of freedom helicopter[C]// 2019 IEEE International Conference on System, Computation, Automation and Networking (ICSCAN). Piscataway, New Jersey, USA: IEEE, 2019.

[33] LI Y M, WU T, XIAO Y F, et al. Path planning in continuous adjacent farmlands and robust path-tracking control of a rice-seeding robot in paddy

field[J]. Computers and electronics in agriculture, 2023, 210: ID 107900.

[34] KUNTZE H B, JACUBASCH A, RICHALET J, et al. On the predictive functional control of an elastic industrial robot[C]// 1986 25th IEEE Conference on Decision and Control. Piscataway, New Jersey, USA: IEEE, 1986.

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