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Virtual Structure Based Formation Tracking of Multiple Wheeled Mobile Robots: An Optimization Perspective

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Submitted to Swansea University in fulfillment of the requirements for the Degree of Masters by Research

February 2022

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Abstract

Today, with the increasing development of science and technology, many systems need to be optimized to find the optimal solution of the system. this kind of problem is also called optimization problem. Especially in the formation problem of multi-wheeled mobile robots, the optimization algorithm can help us to find the optimal solution of the formation problem.

In this paper, the formation problem of multi-wheeled mobile robots is studied from the point of view of optimization. In order to reduce the complexity of the formation problem, we first put the robots with the same requirements into a group. Then, by using the virtual structure method, the formation problem is reduced to a virtual WMR trajectory tracking problem with placeholders, which describes the expected position of each WMR formation. By using placeholders, you can get the desired track for each WMR. In addition, in order to avoid the collision between multiple WMR in the group, we add an attraction to the trajectory tracking method. Because MWMR in the same team have different attractions, collisions can be easily avoided.

Through simulation analysis, it is proved that the optimization model is reasonable and correct. In the last part, the limitations of this model and corresponding suggestions are given.

Key words: Tracking of Multiple Wheeled Mobile Robots, Optimization model, Formation problem, Virtual structural equation

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Acknowledgement

The authors would like to thank Professor Shuai Li for providing guidance on the methodology of the project and for the support I received from Professor Li when the project hit a bottleneck, which enabled me to complete the thesis successfully.

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1 Introduction

1.1 Research background

Since the robots was born in 1956, in the back of more than the development of 60 years, robot has been diffusely invested in aerospace, automobile industry, updated materials, Biomedical Science, bright updated energy and other hitech occupations.

For five consecutive years from 2017 to 2021, the department of Science and Technology of China has deployed key special research work on "intelligent robots", focusing on key technologies and equipment, common technologies, robot application demonstration and basic frontier theories. the development direction of human basic frontier technology for a new generation of robots and intelligent machines has been formulated, which has accelerated the progress of China's intelligent robot industry [1].In 2011, several confederal proxies, including the National Science Foundation ,the National Institutes of Health and the United States Department of Agriculture, jointly launched the National Robotics Program (NRI: National Robotics Initiative-1.0) [2].The program is used to sponsor the basic research and development and utilization of robots. NSF launched the National Robotics Program 2.0 (NRI-2.0) in 2016 to continue to promote robot research and application [3].In 2019, the United States officially released the second edition of the National synthetic Intelligence Research and Development Strategic Plan, which continues to increase investment in the intelligent direction of mobile robots [4].In 2020, the UK launched the National Development Strategy for Robotics and Autonomous Systems (RAS: Robotic and Autonomous Systems) RAS 2014 [5].In 2014, the European Commission and 180 companies and R & D institutions under the European Robotics Association jointly began the world's biggest folk robot study and growth plans, SPARC [6].In December 2018, the European Union issued the artificial Intelligence Coordination Plan to catch up with the fast growth in the field of simulated mind [7].South Korea released "Robot Future Strategy 2022" in 2015 [8]，Artificial Intelligence Research and Development Strategy issued in 2018 [9]，accelerate the integration of robot industry.

From a number of robot technology policies issued by various industrial powers in the world, we can see that the competition in the world of robot study, growth and application is extremely fierce, and each country is trying to occupy a leading position.

Mobile robot is the significant sticks of robot [10]. With the successive growth of world economy and knowledge and skill, mobile robot appears frequently in human scientific research, production and life, and has a broad application space. In the meantime, with the development of computing machine and control technology, the application field of mobile robot is more and more extensive, and its working environment has changed from simple indoor environment to various sophisticated circumstances such as land, submerged water, ventilate and universe [11]. They can be used for handling, assembling, processing, testing, packaging, sowing, fertilizing and picking, freeing people from dangerous, boring, harsh and intensive working environments.

With the successive growth of mobile robot mechanics, people pay more consideration to the development prospect of ground mobile robot, and it has get a investigation trend in the domain of robot mechanics, especially wheeled mobile robot. Wheeled mobile robot is widely used in rescue, anti-terrorism, explosion-proof, military reconnaissance, scientific research and other fields because of its strong ability to adapt to the ground and surmount obstacles. Such as insurance search and deliverance robots, field robots, deep space exploration robots, battalion robots and so on. Ground tumbled liquid robots have been diffusely used in unmanned reconnaissance, security monitoring, family services, assembly and processing, helping the elderly and disabled, medical transportation and other fields, and can also be used in a variety of dangerous situations, such as bomb disposal, disaster relief, underground coal mine inspection and operation, nuclear power plant environmental monitoring, accident handling, infectious disease detection and care, high-voltage substation inspection and modern war reconnaissance and attack.

In order to manipulate multiple robots, creating a formation to manage them is a non-negotiable option. There are many ways to establish a formation, and the behavior-based method is a classical method [12]. This method is good at avoiding obstacles, but it is difficult to keep the formation unchanged.

Cooperative control of multi-robot system is an investigation trend in the kingdom of robot. Contrapositived with the single robot manage method, the multi-robot system can realize the parallel execution of multiple tasks at lower cost. Therefore, multi-robot systems are usually used in logistics, transportation, rescue, exploration, and even military fields.

Leader-follower's method set a leader and let other robots follow that leader. It has the advantages of a behavior-based approach while maintaining formation, but the leader-follower approach relies too much on the leader: if the leader is in trouble, the entire formation cannot work [13]. The potential field method in this paper may solve the problems existing in other formation methods [14]. This method allows the robot to track targets and avoid obstacles, and to establish formation by artificially creating gravitational and repulsive fields. This method can solve all the problems very well, but the gravitational parameters and the repulsive field is a problem to be faced. Using this method, we may face the problem that the force forming the formation may be the same as the force that makes the robot move, but in the opposite direction. Therefore, in the research, we use the method of virtual structure (VS) to build the framework of formation. The formation based on VS method can maintain formation. Because this method is based on virtual points, it is difficult to affect the whole formation by affecting virtual points. Finally, the VS method is not as complex as the article potential field method. Therefore, we use the VS method as a framework to create virtual leaders, placeholders, and information to guide. Then form a workflow management team with the same requests as the team. Have each team track their virtual leader.

Therefore, how to make WMR track is the main problem that we need to face in this step. In this study, we use the constrained optimization method to make the MWMRs system track. The constrained optimization method is based on Lagrange multiplier method. It is a very popular solution in the field of manipulators [15-19]. Because the joints of the manipulator need to be constrained for many times, it is a popular selection to do with the constraint optimization approach to solve the manipulator problem. Not only in the field of manipulators, restriction optimization is also do with in the kingdom of WMR to achieve trajectory tracking and obstacle avoidance targets [20]. Under the error between the ideal trajectory and the WMR reference point and under the constraint conditions, we can solve the speed at which the WMR should move at the next moment, which is how to use the constrained optimization method to control the trajectory of the robot tracking the ideal trajectory. In order to gain the Optimization property of path tracking, we create a circle with radius in the trajectory tracking method. When WMR touches this range, it can be seen as tracking objects directly.

Although these robots can track their ideal trajectories through constrained optimization methods, the problem of possible collisions between them has not been solved. In order to avoid this terrible event, we creatively add an attraction formula to the constrained optimization method, so that cars can avoid colliding with each other.

1.2 Objective

The purpose and contribution of this study are as follows:

First, in this paper, we add an attraction to the tracking arithmetic founded on constraint optimization. In the absence of the avoidance criterion, we can easily provide

WMR with different attractiveness to avoid collisions.

Second, because all WMR in the same group are grouped into a group, and each team only tracks an ideal trajectory, the complexity of the formation problem is reduced.

Third, this formation maintains a certain shape, but also maintains a certain degree of flexibility.

Fourth, if a WMR fails during working hours, other WMR in different teams will not be affected if all the ideal tracks do not overlap each other.

1.3 Paper Structure

Firstly, this paper examines the literature on way programme and orbit backtracking of variable robots in sophisticated circumstances, which will show the most advanced research on variable robots in sophisticated circumstances. In addition, the WMR's Kinematic model, formation calculator, attraction formula, controller module, multi-robot system, storage and other specific contents and practices will be introduced. Finally, the Simulation is carried out and presented in the form of tables and graphics, so it can be easily visualized. On this basis, put forward the conclusions of this study, the main contributions and limitations.

2 Literature Review

For the research of ground wheeled mobile robot, it is usually assumed that the wheel does not slide horizontally and longitudinally, but only rolls. This ideal motion constraint is nonholonomic, so it is generally regarded as a typical nonholonomic system [21]. When the system is subject to holonomic constraints, the motion constraints are integrable, so the motion of the system can be constrained on a smooth manifold in the manifold space. The reachable attitude of the system is not a complete set of configuration spaces, but a subspace [21]. The degree of freedom of the system motion is reduced, but the configuration of the system motion will not be constrained. For example, in the case of no sliding, the car cannot move laterally or turn around in place, but it can face in any direction at any position, and the position of its movement is not restricted [21]. The smooth feedback stabilization condition defined by Brockett is not valid for nonholonomic wheeled robot systems, and conventional classical controllers cannot be directly used to control wheeled robot systems [21]. In addition, the dynamic system of ground wheeled mobile robot is a complex multi-input and multi-output system, which has a strong application background and has the characteristics of multivariable, strong coupling and highly nonlinear [22].

With the increasingly complex application environment of wheeled mobile robot and the increasing requirements for robot reliability, how to make mobile robot quickly and safely plan and track the optimal path of unstable robot in complex circumstance has become an significant question in the field of mobile robot technology.

From 2007 to 2019, aiming at the National Natural Science Foundation projects "Research on the method of low Energy consumption possibility Control of wheeled Mobile Robot on rugged terrain" and "Research on movement control of nonholonomic wheeled rover based on multiple physical models in soft and rugged terrain", Chinese researchers have designed wheeled mobile robots that adapt to rugged terrain. Considering the uncertainty of rough ground, the influence of wheel sinking and the possibility of turning over, they carried out different attitude estimation, motion planning, trajectory tracking, optimal coordinated control and physical simulation experiments of different terrain [23-26].In 2018, aiming at static and dynamic interference evasion and way programme of ground variable intelligent robot in complex unstructured road environment, researchers adopted improved fuzzy Q learning (Q-learning) algorithm, collision time histogram dynamic obstacle avoidance algorithm, raster map and local path planning algorithm of encourage carrier organization. It improves the flexible obstacle avoidance ability of unmanned vehicles on the ground and the ability of road detection in severe weather environment [27]. In the same year, some researchers designed sliding mode observers when the sliding mode parameters are unknown, and used visual solutions to pre-control the skidding phenomenon caused by insufficient tire adhesion in complex environments [28]. Aiming at the local unknown environment in two-dimensional grid scene, some researchers proposed a two-layer hybrid path planning algorithm, which does the improved A* arithmetic in the spherical way programme layer and the improved artificial potential field algorithm in the local path planning layer. it has the ability to respond to dynamic environment changes in real time [29]. In 2019, Chinese scientists completed the research on global way programme and interference evasion of variable robots for complex environments (environments with multiple shapes of two-dimensional obstacles). Their proposed quantum behavior fireworks algorithm can gain the spherical seek capacity and concentration velocity, and settle the task of multi-robot coefficient way planning programme and dynamic obstacle avoidance [30].In 2019, domestic scientific research institutions studied mobile robots in the complex environment of multiple intersections, and used an improved fast extended random tree algorithm based on landmark area sampling (LMA: Land Mark Area sampling) for global path planning, thus improving the era of way programme and the smoothness of the way. The local path programme arithmetic of adaptive threshold vector field histogram + (VFH+:Vector Field Histogram Plus) proposed by them avoids the oscillation problem in the process of robot following [31].In the same year, aiming at the skidding, longitudinal and lateral sliding of the robot in complex environment, an calculated slipping pattern controller and a path backtracking controller founded on sliding mode interference viewer were designed to improve the control accuracy[32].In 2020, on the platform of robot operating system (ROS: Robotic Operating System), scholars studied the robot path planning technology under complex obstacle environment, and adopted the gradient path smoothing optimization technology based on bearing angle to cut down the curvature of the way, gain the motion stability of the robot and reduce the energy consumption of the system. They use A* algorithm and RRT algorithm to solve the path planning of narrow channel or special space environment, and combine the near-end strategy optimization (PPO: Proximal Policy Optimization) algorithm with the deep reinforcement learning method of internal curiosity module to complete the dynamic environmental path planning of complex hazardous chemicals based on Unity3D development platform [33-34].Some researchers also choose Riki Robot to establish an experimental platform, and design fuzzy synthetic feasible wild way, scalable nervous meshwork arithmetic and real-time decision system arithmetic to settle way programme problems in complex working environments with unknown uncertain obstacles and static and dynamic emergency obstacles [35].Aiming at the sophisticated continent substitute for styles in weather circumstance, a multi-robot decken way programme algorithm is proposed in reference [36], which solves the complex outdoor two-dimensional flat ground coverage path planning problem of robots (CPP: Coverage Path Planning).

From 2014 to 2020, Japanese scholars have completed robot path planning with static and dynamic obstacles in sophisticated schedules (such as long and limited map channels and error ensnare storyboards) by using hierarchical mixed probabilistic global planning roadmap (PRM: Probabilistic Road Map) and artificial potential field (APF: Artificial Potential Field) methods, which can avoid local optimal solution [37].From 2010 to 2020, Russian researchers have been working to improve path planning algorithms in a variety of complex scenes (2D or 3D flat ground and pipelines, indoor or outdoor, static or deformable obstacles, etc.) [38].Italian researchers studied the design and control of ground robots in unstructured environments from 1998 to 2020.Turkish scholars developed a locust algorithm from 2018 to 2020 to solve path planning tasks in complex congestion obstacles in unknown dynamic environments [39].From 1970 to 2021, the American Institute of Robotics studied the possibility, trajectory generation, path planning and simulation experiments of car-like robots and planetary vehicles on rugged ground in complex environments [40-41]. Since 1985, the Australian Automation Systems Laboratory has studied and explored the sensor design, feasibility analysis, path planning and software design of planetary and autonomous vehicles in complex field environments [42-43].

In order to enable the ground tumbled variable robot to accomplish the pursuit independently and accurately, it is inevitable to consider the three-dimensional curved surface environment of the robot. The existing research on the ground wheeled mobile robot system is mainly focused on the flat terrain environment, with the deepening of the above research, it is found that robot research in some more complex terrain environments (such as disaster sites, mountains and hills and planetary ground, etc.) is becoming more and more important. The problems of ground wheeled mobile robot in complex environment (such as on-site deliverance and important carriage, planetary extent inquiry and exploitation, 3D competition extent marching and ground conflict, etc.) can be abstracted and transformed into the possess conundrum of 3D curved variable robot. According to the above references and other research materials, there have been many mature researches and designs on synchronous positioning and map construction (SLAM: Simultaneous Localization And Mapping), 3D environment modeling, robot structure design, possibility of rugged ground, dynamic obstacle avoidance and skidding of wheeled mobile robots on complex and rugged terrain. However, there are few researches on the time complexity and accuracy of variable robot way programme and the torque constraints of trajectory tracking in complex environment. therefore, this study mostly debates the improvement of global way programme and trajectory pursual algorithm for mobile robot in big-dimension complex and rugged ground.

2.1 Research status of path Planning for Mobile Robots in complex Environment

Way programme refers to the superior way planned from the starting location to the end location safely under the guidance of certain optimization criteria, such as the shortest path, minimum energy loss, etc. [44]. The key technology of path planning is to study whether the mobile robot will collide at a certain location. In the circumstance model of mobile robot, the data which is not related to path planning is erased to get a problem state space. By selecting the appropriate optimal path planning algorithm, the optimal path in this state space can be solved. By transforming the nodes on the path into the representation of the actual physical model (usually a sequence of coordinate points), the continuous interference-independent optimal way of the variable robot can be obtained. Path planning is not only a basic and important subject in the investigation of variable robot possess, but also a thermal and tough core in the study.

The research of mobile robot path planning has developed from 1960s to today, and there are many effective solutions for path planning in two-dimensional space. However, with the development of mechanics and science, the working scope of mobile robot has gradually expanded from indoor to wild, from the surface to outer space. The main topics that need to be discussed in the task of path planning of mobile robot are: approximate modeling of increasingly complex environment, real-time problem of algorithm and accuracy problem [45-49].

The major properties are as follows:

(1) with the increasing complexity of the application environment of mobile robot, the time sophistication of way programme arithmetic puts forward higher and higher requirements for the reliability of mobile robot. The current intelligent algorithms for way programme of variable robots have the capacity to detect the most deficient responsible way. However, with the improvement of the accuracy of environmental simulation or the increase of search scope, various intelligent path planning algorithms show an exponential increase in time cost and computational complexity, that is, exponential explosion problem [47].

The time sophistication of the arithmetic is the relative measure of its running time [50]. The continuing time of the arithmetic refers to the time from the beginning to the end of the algorithm running on the computer [51]. The workload of the algorithm depends on the scale of the problem, which is an integer used to measure the scale of the problem, usually expressed by n. Therefore, when an algorithm is used to deal with a problem with a problem scale n, it is usually expressed by the continuing time T(n) of the arithmetic, and T(n) is called the time complexity of the algorithm [50]. In general, only the big O symbol [51] is used to calculate the algorithm complexity. The time complexity can be expressed by linear order O(n), square order O(N2), exponential order O(2n) and logarithmic order O (logn) [50]. From the form of time complexity, we can see that with the enhancement of the size of the conundrum n, the time complexity of the algorithm will increase, resulting in longer running time of the program and lower efficiency of program execution. Thus, it can be beholded that the size of the conundrum n determines the practical-time property of the way programme algorithm [52].

In the past two decades, with the increasing trend of using biological heuristic neural network algorithm for robot way programme, the use of biological heuristic nervous meshwork algorithm for way programme has become a hot research problem [53-70]. Because BNN algorithm can be applied to static or dynamic environment, two-dimensional or three-dimensional scene, moving target or fixed target, single robot or multi-robot and other complex situations and various application fields [55-70], BNN algorithm is an excellent intelligent path planning algorithm for robot control research in complex large-scale scenes.

Stimulated by Hodgkin and Huxley's Membrane Model and Grossberg's shunt model, Simon. Yang and M. Bioinspired nervous meshwork method was first introduced by Meng in 1998 to settle the way programme conundrum of variable robots. matched with other nervous meshwork way programme methods, the bio-heuristic Neural Network Algorithm does not require a learning process. The vital activation score obligation of respective neuron can be solved by the information transmission between neurons. By settling the nervous actional activation feasible obligation in actual time, the potential way from the premier location to the goal location along the increasing orientation of the feasible significance can be acquired.

A bio-heuristic Neural Network Algorithm for practical-time coefficient multi-robot searching is proposed in reference [54]. In this algorithm, the situation and circumstance of the escapee are sealed and continually shifting. A practical-time interference-free way programme institution for mobile robot virtual instruments elemented on a bio-inspired nervous meshwork algorithm is introduced in reference [55]. Reference [56] presents a approach associating vague logic with biologically heuristic nervous meshwork way programme, which can triumphantly aim the robot to the goal in pronumeral circumstance, and cause the variable robot to rotate at a bathed angle. A dynamic way programme approach founded on biological exploring nervous meshwork is discussed in reference [57], which solves the on-line and practical-time way programme problem in sophisticated actional environment. the authors propose a novel Bioinspired Neural Network Robot Path Planning Algorithm to call into being continuous [58], glabrous and first-rank paths, and the Algorithm can rapidly answer to quickly exchanging circumstances. In [59], a fresh method based on biologically vitalized nervous meshwork is arranged, which is combined with the growed carrier forced initiative robot sailing, the authors verify that the proposed matrix can provide more logical and insufficient interference-free ways in non-standing and incompact circumstances.

In references [60] and [61], the benefits and features of BNN are integrated with a self-structuring feature diagram to operate the work allocation of large numbers of robots in a 3D actional circumstance. In order to further the property of neural network in actional interference evasion, actional venture criterion is recommended in reference [62]. founded on the gained BNN arithmetic, a practical-time interference-free way programme approach for patination shift robot in vessel circumstance is proposed [63]. [64] and [65] proposed a neural network-based goal examine arithmetic and a multi-goal examine arithmetic to settle the conundrum of underwater multi-robots with obstacles and obstacles-free in unknown environments. In [66] and [67] , an improved dynamic BNN arithmetic is scheduled to do with the real-time way programme of initiative submerged instrument in various 3D submerged circumstances. An improved BNN-based "Active obstacle Avoidance Strategy" pedestrian position prediction approach is arranged in [68] to plan interference-free way programme for variable robots. a dynamic method founded on BNN is arranged to settle the CCPP conundrum of paralleling robots [69]. BNN mechanics is used to help the robot to check the strange operational circumstance [70], and a fast area convolutional neural network (R-CNN: regions with convolution network features) method is used to discovery decentralized pegs and spirals in practical time, and allow the robot to voluntarily recycle clous and helixes. In [71],

Reference [72-75] uses a modified Bnn algorithm-glasius and other biological heuristic neural networks matrix for way programme. Among them, reference [72] improved the GBNN matrix to gain the vital property, the modified GBNN matrix is steady and possible for practical-time way programme in quickly growing environment. an modified GBNN-based nervous meshwork matrix for multi-AUV is proposed [73], which can be used to find intelligent avoidance goals in interference circumstances A fresh device for uncontinuous and gathered planning founded on GBNN Algorithm for multiple auvs is proposed in reference [74] . The strategy is to accomplish complete decken of the uniform mission district by planning a logical interference-free decken way finish ministry and cooperation. Reference [75]

The application of robot way programme founded on nervous activity computation is discussed in [53-75]. The propagation of nervous movement values is the quick of the BNN and GBNN algorithms. The Algorithm needs a inevitable time procedure to breed the goal fiber movement. When the size of the problem n increases, the time sophistication and calculating sophistication of BNN or GBNN algorithms will enhance sharply [57,72-74].

The main disadvantage of large-scale Environment 3D path planning founded on BNN Algorithm is era sophistication and computational sophistication. It is tough to neglect the era sophistication and calculating complexity of BNN Algorithm for 3D way programme in miscellaneous big dimensions environments. However, to date, little attention has been paid to this issue in the investigation writing, and whereat is tiny Quantitative decomposition to gain the iterative era and computational sophistication of nervous movement values [57,72-74]..

（2）The progresses problem of way programme arithmetic

Most of the traditional way planning algorithms for mobile robots are founded on the Euclidean separation formula between nodes. The traditional path planning algorithm based on Euclidean distance is founded on the Euclidean separation formula between the nearby nodes to solve each segment of the path, thus analyzing to determine the optimal path trajectory and the extent of the first-rank way. However, the space EUCLIDEAN distance between nodes is not equal to the path separation between two nodes on the rough surface (in this paper, the rough surface is approximated as a curved surface), therefore, when studying the path planning of rough surface in complex environment, it will bring error if we use this kind of algorithm based on Euclidean distance formula to calculate the greatest way of garment.

The BNN arithmetic is a neuron based path planning algorithm, and usually uses the space Euclidean distance formula to propose the path of a 3D crooked garment[60-61,66-67].Dijkstra algorithm is the most famous classical insufficient way walloping arithmetic in the research of 2D variable robot way programme[76-77].The DIJKSTRA algorithm is a simple solution to the insufficient way conundrum, which actually calculates the insufficient way to all termini[78-79].Because BNN Algorithm and Dijkstra Algorithm are founded on the Space Euclidean shoulder formula to calculate the three-dimensional surface path, the application of these algorithms to the complex large-scale rough surface (surface) path planning will operate a big cumulative error. In order to improve the precision of this kind of path planning algorithm based on Space Euclidean distance formula, this study will carry Dijkstra Algorithm as a mirror to study the precision of outside way programme algorithm. The DIJKSTRA Algorithm is chosen because Dijkstra arithmetic in the traditional arithmetic to calculate the insufficient way is usually the shortest, in the algorithm improvement before and after the improvement of the shortest path length can have a more accurate comparison effect. The improvement principle of BNN arithmetic is alike to this. Other way programme arithmetic based on space Euclidean distance formula can also use the surface path optimization method in this paper to improve the precision.

DIJKSTRA ALGORITHM was proposed by Dutch machine scientist Edsgerwybedijkstra in 1959. It has been successfully implemented in the domains of variable robot 2D way programme, computer technology, geographic feedback skill and transportation [76-79]. Some of the latest study founded on Dijkstra's arithmetic is reveaed down [80-93].

Wolfgang Fink and others adopt Dijkstra arithmetic founded on domain data to realize the best traversal of 3D garment, GRTOP (Global Rover traverse-optimization planner) can quickly and accurately plan an optimized route for a global rover traverse optimization planner (GRTOP) automation system with multiple constraints [80]. This research enables GRTOP to frequently iterate over or perform tasks, and optimizes travers ability and task security. In this paper, a fractal-based terrain generation technique, "Diamond Block Algorithm", is used to produce breathing domain, and the significance between two continuous cores is looked upon as the EUCLIDEAN separation between them [80].

Guo Dong et AL advanced the conventional Dijkstra Algorithm and associated it with the instrument catalyst expense and emissions survey matrix to effectively shorten the instrument catalyst expense and emissions in the steering process[81].In order to gain the virtue of Dijkstra algorithm, the rectangular region (the rectangle with the minimum boundary of the ellipse) is used to limit the searching region[81].The author uses Dijkstra Algorithm and the established database to identify the traffic conditions at the same time, which can shorten the catalyst expense and shots in time of driving and avoid time congestion when the vehicle route planning is used in the dynamic traffic network, improving urban environmental pollution[81].

Feliperi berosou za et Al. apply Dijkstra's approach to tree decomposition, using the diggings as nodal points in the tree to expect the lowest expense channel for transporting the diggings to their end-point [82].

The diagram element and Dijkstra shortest path Algorithm are used to discovery the first-rank set of vertices together the vector guide and the optimal distribution of towers along the route based on dynamic programming [83].This solution is used for the expansion programme of fresh gear threads in the Power Sector (TL: Transmission Lines) with the objective of finding the lowest cost new transmission line expansion solution[83].

Jesuks Balado and others apply Dijkstra Algorithm to citizen routing in urban environment, and realize the direct use of point cloud routing method[84].In this study, the approach can be had access to establish the graph of the urban space which represents the pedestrian passage automatically, and then the safe and real route of pedestrian passage can be calculated[84].Dijkstra algorithm is used to plan the safety route in practical-time chartography, and the route effected can be used to establish an effective obstacle-avoiding route for normal walking and wheelchair-using pedestrians[84].

Tang Jinchuan et al calculated the first-rank way chose approach founded on Dijkstra algorithm associated with confidence probability, which is used in the programming of assignment-critical push-to-talk institution of 5G commonable insurance tragedy comfort meshwork [85].

Yu Lingli and others used the Dijkstra algorithm elemented on ArcGIS resolve instrument to carry out global path planning, and designed a way programme and salling manage organization for a 12-meter-long self-driving electric bus [86]. They entirely expected the insurance and mechanics of navigatorless buses [86]. This approach can gain the possess way, shorten the calculating complexity and improve the steering virtue [86].

Zheng Zhang et al designed a conflict-free searching approach for automatic guided vehicle (AGV: Automated Guided Vehicles) based on conflict classification [87]. They invest the grid approach to represent the environment diagram of AGV, and the premier way of respective role in the circumstance chart is determined by the improved Dijkstra algorithm [87]. This method can deal with conflicts that may occur in mechanized warehouses [87].

Feristah Dalkäç et al using the Dijkstra arithmetic to help travelers make travel plans in the intelligent travel planning system by demanding phase-identity regulations can fall off the seek separation and running time of the algorithm [88]. This paper introduces a progressive path search algorithm, which integrates route and schedule information from different transport institutions by considering transfer times and driving time, so as to facilitate users acquire seniority utilization of society transport to predigest travel programme [88].

Shao Sai et al use actional Dijkstra algorithms to find the insufficient way between any two neighbor nodes along the route [89]. In this paper, a routing scheme for electric vehicles with variable loading time, which aims to solve the difficult problems such as mileage restriction and loading necessity of electric vehicles [89].

George K.D. Saharidis et al combine Dijkstra's arithmetic with blended integral number thready planning pattern to obtain the best itinerary of traveler's multi-mode travel planning [90]. This multimodal path solution can help travelers choose the mode of transportation that produces the lowest greenhouse gas emissions during their journey [90]. The method can be used in public transport operation platforms to reduce greenhouse gas emissions [90].

By learning the mechanism of Dijkstra arithmetic, Tan Zhi and others proposed an advanced emmet settlements arithmetic to equilibrize the vitality expense of threadless transducer networks and prolong the lifetime of threadless transducer networks [91].

W.C.Lu et al use Dijkstra arithmetic to solve the possible sky lane programme problem, and provide the possibility of expanding the airspace for the activities of light sports aircraft [92]. The purpose of this study is to detect the possible route of lucency movements airplane in order to minimize the influence on residential districts and the danger of domain interferences to aeroplane [92].

Deepak Gautam et al implemented the Dijkstra arithmetic to study the attitude, position control and shortest path planning of a four-rotor helicopter in a known closed environment full of obstacles and / or boundaries [93].

The young modified Dijkstra arithmetic chief focuses on the reforming of the time sophistication of the conventional Dijkstra arithmetic and the popularization of the Dijkstra algorithm in unusual domains. [94-101].

So far, whereat are three major methods to gain the traditional Dijkstra arithmetic[80-101].One is to break down and gain the vacuum sophistication of the arithmetic in order to gain the warehouse virtue and hold vacuum; the second is to break down and gain the time sophistication of the arithmetic, the conventional Dijkstra algorithm has flat virtue and bottomed going time, in order to gain the operation asset and moderate the era sophistication, numerous scholars undertake studied it; the third is to demand the arithmetic to diverse domains to crack up the adhibition vacuum of the arithmetic and fertilize the adhibition range of the arithmetic[80-101].

All the researches in references [81-101] are founded on the Euclidean separation between adjacent tumours in Dijkstra arithmetic goal planning, and rarely contain the first-rank way planning of surfaces. When Wolfgang Fink and others use the classical Dijkstra arithmetic to settle the 3D tabulate way programme job, the improved method is to take the weight as a comprehensive factor, considering the smoothness, three-spatial Euclidean cold-shoulder, altitude influence and roughness and other influencing factors [80]. However, Wolfgang Fink et al still calculate the shortest path founded on the Euclidean cold-shoulder between tumours [80].

Many practical problems can also be abstractly transformed into the best garment way problem of motor robot, such as on-site deliverance and crucial carriage channel programme.

2.2 Research status of trajectory tracking of Mobile Robot in complex Environment

In the past decade, numerous scholars have dedicated themselves to the trajectory tracking and regulate of mobile robots [102-107]. Because trajectory tracking control uses different mathematical models, it can be divided into kinematic methods (such as speed control) and dynamic methods (such as torque and voltage control). From an engineering point of view, trajectory tracking control has practical research value, because mobile robots generally need to move along a specific trajectory to perform tasks.

Nowadays, variable robots have been diffusely done with in the kingdoms of planetary inquiry, field search and rescue, logistics and transportation, remote detection and hazardous environment [102,108-110]. Many practical problems can be transformed into the surface trajectory tracking control problems of mobile robots, such as rugged ground robot inspection trajectories, on-site rescue and material transportation trajectories, planetary ground exploration trajectories, 3D game movements and war trajectories. However, the current research work seldom involves the tracking control of surface trajectories. Therefore, in these applications, surface trajectory tracking technology has been an emergency debatable to be settled [103-104]. The optimal trajectory which has been planned by path planning algorithm in large-scale complex rugged ground scene is taken as the target of robot trajectory tracking. based on this, this paper will study the torque constraint control and torque derivative control of surface trajectory tracking control.

（1）Torque constraint Control of Surface trajectory tracking algorithm

Compared with the traditional industrial robot, the wheeled mobile robot has a senior classification of self-adaptability, self-planning and self-organization. So, wheeled variable robots are also diffusely used in complex unstructured environments. In recent years, the trajectory tracking of wheeled robot has become a key problem studied by scholars. However, many studies do not control the input control law with saturation constraints. If the saturation limit of the actual system cannot be met, the expected performance of the orbit backtracking possess institution will not be realized, and in serious cases, the system will lose stability [105,108,115-116]. So far, few literatures have studied the path backtracking control of the robot below the condition of limited driving input torque [120-125]. Torque is an important control input for mobile robot to realize path backtracking. Therefore, it is very inevitable to control the torque peak value of the controller for the optimal path backtracking of the wheeled variable robot on the curved surface [120].

Yang et al proposed an integral removal manner path backtracking possess method for tumbled variable robots with omni-directional wheels on uneven ground [103]. In this study, the controller is mainly used to solve the external interference caused by uneven ground and omni-directional wheels when driving in a straight line [103]. However, the torque limitation in practical application is not considered in this study.

In order to solve the anisotropic ground friction of small unmanned ground vehicles and the interference caused by mass changes in the process of transportation in uneven terrain, Victor R.F. Miranda et al designed a proportional integral differential (PID) controller for longitudinal trajectory tracking. This method is robust to parameter uncertainties and can reduce output interference [104].

Zhu et al use Quadric surfaces with sealed but bounded parameters to broad heterogeneous surfaces, and propose spanning obligation approach, integral stepping back method and Lyapunov refashion skill to solve the robust stability of tumbled robots moving on uncertain heterogeneous surfaces.

In order to settle the debatable of changeable disturbance factors when the robot is driving on rugged terrain, Yang et al proposed a effective vague transverse governance legislation, and proved the global asymptotic stability of the possess legislation [112]. By using virtual prototype technology, the author sets up a variable robot and an tentative domain on the collaborative simulation platform of ADAMS and MATLAB, and tracks the trajectory of the robot in the simulation environment. In this paper, considering the factors affecting the semidiameter of curvature, highway granulation, processing era and velocity requirements of the sensor, a humanoid driven longitudinal fuzzy control law is designed [112]. The tentative outcomes show that the administration method is healthy and available for the variable robot continuing on the rugged ground, but the over impulse is very large, and the torque limitation is not considered.

When the robot passes through the deformable terrain, the way backtracking possess of the tumbled robot is a sophisticated dynamic conundrum because of the nonlinearity, external interference, modeling and unconsolidated uncertainty of the system. Taghavifar et al. considered the deformable soil dynamics in the literature, deduced the traction force and torque caused by the wheel-soil interaction, and completed the terrain-based robot path tracking control. Considering the uncertainty caused by terrain, an adaptive indirect controller is proposed. The controller adopts comprehensive modified comprehensive slipping pattern regulate and calculated nervous network (NNs: Neural Networks) to settle the external disturbance and roller slip problem in robot roller slip path tracking control. The design introduces a compensation controller to minimize sudden changes in control requirements, which may be caused by indetermination narrative to domain characteristics and eventual cartwheel skidding and intention rebellion [113].When designing the trajectory tracking controller, the author considers the deformable soil dynamics to obtain the traction and torque caused by the wheel-terrain interaction and the uncertainty caused by the terrain, as well as the dynamics of the sliding surface [113]. The design process of the controller does not involve the control of torque limit.

In order to settle the speed limitation of wheeled variable robot in trajectory tracking, Chen et al proposed a patternl-based possess scheme and calculated contain meshwork possess law [105]. They solved the constraint control of input speed, but did not study the subject of torque constraint and the trajectory tracking of curved surface. Although by limiting the speed, the torque can be limited indirectly. But the torque is an important input of the robot system, and the better control effect of the torque can be obtained by directly controlling the input torque.

tumbled wheeled robots are diffusely used in exploration, oversight, deliverance, detection, scanning, cooking, geological taking of samples, pit clearance, archaeology and other fields. More and more diversified application requirements put stricker upper necessities for the accuracy, volume and energy consumption of wheeled mobile robots. We hope to study robots with higher precision, smaller volume and lower energy consumption. If the mechanical volume of the robot is required to be reduced, the volume and mass of the servo motor should be reduced accordingly [126-129]. Controlling the peak value of the input torque can not only control the size of the driver, but also reduce the peak value of the input power and prolong the life of the motor or other mechanical equipment. Especially in the space robot, precision surgical robot, finishing robot and other occasions with high requirements for the size or power of the robot, controlling the peak value of the input torque has a very important practical value [126-129].

The model-based control scheme, the first control scheme proposed by Chen et al., is a control scheme with speed constraints and better control performance. The speed constraint principle, Lyapunov stability analysis, controller design method and trajectory tracking control simulation experiment of model-based control method are discussed in detail, clearly and completely in reference [105].

（2）Torque derivative Control of Surface trajectory tracking algorithm

For the railway backtracking problem of variable robot, when the initial error of trajectory tracking is large or there is a large torque interference, it may also cause the torque of the robot motor to exceed the load limit. further increase the trajectory tracking error or cause the automatic mechanics of the robot to tremble. The greater the initial error of trajectory tracking, the greater the impact moment caused by the initial error [130-131]. With the realization of the control function, the control torque will decrease sharply. Therefore, in practical application, the torque in the initial stage is likely to be oversaturated, while the post-torque decreases rapidly, resulting in the problem of low energy utilization efficiency [130-131].The control of the derivative value of the human moment of the wheeled mobile machine can prevent the torque overshoot during startup, make the output of the robot torque more balanced, reduce the energy consumption and optimize the employment classification of energy at the uniform time.

In the process of trajectory tracking, if the torque change rate is too large, the system energy will change sharply in a short time. Various actuators of the system will overshoot and oversaturation in a short time, which is extremely disadvantageous to the normal operation of the system [130-131]. In practice, the saturation of the actuator will reduce the trajectory backtracking capability of the designed administrative peculiarly for the passing behavior [130-131]. If the actuator is saturated for a long time, it will cause possible thermal, electrical and mechanical failures. If the change rate of the input torque is too large, the energy loss of the robot system will be too fast, and it will also affect the service life of the machine [130-131]. In order to prevent these phenomena, the excessive change of torque change rate should be finited in the course of pragmatic application of trajectory tracking control.

The limited export strength of the actual institution leads to the saturation limit of mobile robot torque [132-136]. The existing research usually does not consider to control the design torque within the saturation limit when designing the control law of the robot system, and then take the designed control law as the benchmark of mechanical selection. Therefore, in order to meet the large torque of the designed governance legislation high-power large-size mechanical equipment can only be selected, and the result is that the mechanical size of the mobile robot is too large. Excessive mechanical size not only wastes the resources of design materials and the working energy of robots, but also is not suitable for many applications where mechanical dimensions are strictly required. On the forth of rendezvousing the performance necessities of mobile robot trajectory tracking, the smaller the torque is, the smaller the mechanical size is, and at the same time, the motor with less power can be selected.

The higher the torque at startup, the greater the starting current, which requires high mechanical and electrical strength and capacity design, resulting in a lot of additional costs [132-136]. If the motor can be started with small current, the load of the control circuit and the adverse impact on the power grid can be reduced, the equipment demand for the circuit can be reduced, and the service life of the equipment of the robot system can be prolonged [132-136]. In addition, the reduction of torque can also reduce the output power requirements of motors in the robot working system, so it also reduces the size requirements and manufacturing process requirements of various mechanical equipment in the system [132-136]. By controlling the change rate of torque, the motor can be accelerated gradually during start-up, so that the circuit impact and mechanical impact caused by start-up are as small as possible. If the rate of change of the starting torque is controlled so that it does not cause overshoot and the starting process is smooth, it will not cause the motor to start [132-136]. On the contrary, if the starting current and torque are too large, the power consumption is very fast and the voltage drop is very fast, which is disadvantageous to the power supply equipment. The input torque should be smooth, so it is necessary to control the maximum peak torque of the robot and restrain the initial "surge" of torque [132-136]. consequently, it is inevitable to project a bounded inversor, which can control the torque change rate as small as possible on the precondition of rendezvousing the necessities of rapidity index and torque saturation constraint, in order to restrain the "sudden increase" and serious oscillation of torque [132-136].

The robot has higher requirements for precision, and the requirements for motion stationarity and accuracy are also gradually increasing, so the fluctuation of motor torque should be reduced, and the dynamic response speed should be faster [132-135]. Based on the energy-saving requirements of mobile robots, it is certain to minimize animation consumption and optimize vitality efficiency. In order to gain the market competitiveness and product promotion of the designed robot, reducing the cost of the robot is also an important demand. Therefore, to reduce the torque change rate and fluctuation, so as to reduce the size and performance requirements of the input motor, and then further reduce the size and cost of the robot, it has important practical application value and significance for the national layout and long-term development in the field of industrial robots.

In addition, the influence of uncertain disturbance needs to be considered for trajectory tracking control on rugged ground. The uncertainty of mobile robot has engaged the research and consideration of numerous academics [138-146]. The existing uncertainty research of non-wheeled mobile robot in complex environment is mainly focused on the interference in the case of wheel side slip or skidding [140-142,145,147], parameter uncertainty [141,144-146] and uncertain interference [142-143,147]. There are few researches and experiments on the uncertainty caused by surface ruggedness and vehicle turning. This paper is based on the torque constraint and torque derivative constraint of trajectory tracking control. the effects of surface ruggedness and vehicle turning uncertainty are studied and analyzed.

3 Methodology

3.1 WMR’s Kinematic Model

The kinematic model of a WMR with two differentially launched impulses is the basis of this study. A single WMR’s kinematic model diagram is shown in Figure.1.

Thus, the linear expedition and abrupt expedition should be written as:

$$v = \frac{r}{2}(u_r + u_l),$$
$$\omega = \frac{r}{L}(u_r - u_l). \tag{1}$$

v and ω denotes the linear velocity and the angular velocity of a WMR separately then u_r and u_l denotes the linear velocities of left tire and right tire. r denotes the radius of a wheel on a WMR and L denotes the distance which is present in Figure.1. Also, because the posture of a WMR, $Z = [x; y; \theta]^T$, with Eqn. (1), the derivative of Z should be:

$$\dot{Z} = \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} v cos\theta \\ v sin\theta \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{r}{2}(u_r + u_l) cos\theta \\ \frac{r}{2}(u_r + u_l) sin\theta \\ \frac{r}{L}(u_r - u_l) \end{bmatrix} \in R^{3\times1} \tag{2}$$

Set $u = [u_l; u_r]^T$, and $\dot{Z} = Au$. with Eqn. (2) and Eqn. (1), A should be written as:

$$A = \begin{bmatrix} \frac{rcos\theta}{2} + \frac{rd_0 sin\theta}{L} & \frac{rcos\theta}{2} + \frac{rd_0 sin\theta}{L} \\ \frac{rsin\theta}{2} - \frac{rd_0 cos\theta}{L} & \frac{rsin\theta}{2} - \frac{rd_0 cos\theta}{L} \end{bmatrix} \in R^{2\times2} \tag{3}$$

which d_0 is presented in Figure.1.

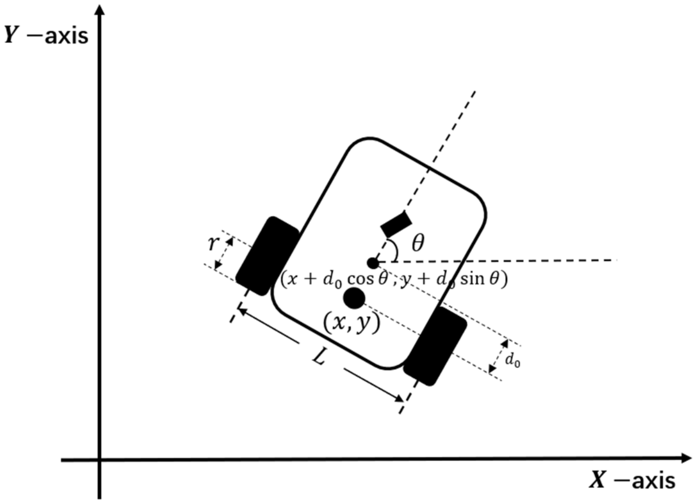

Figure 1: Single WMR's Kinematic Model

3.2 Formation Calculator

3.2.1 Main Ideal Trajectory

Before creating a formation, build up a trajectory to let the MWMRs formation track is the first step. In this part, we create three trajectories: an invert “U” trajectory, an zig-zag trajectory and an arbitrary curve as Z_{main} separately. We use them to observe how well the MWMRs system formation tracking strategy launches in these trajectories.

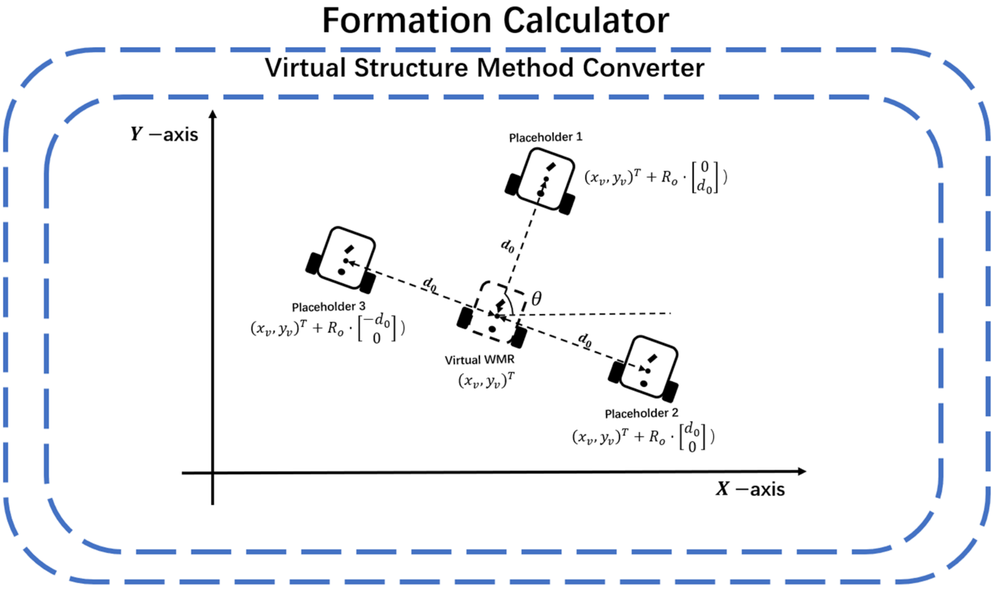

Figure 2: Graph of Virtual Structure Method Converter

To create virtual structure-based formation, we need to create a virtual WMR first. This virtual WMR will track the main ideal trajectory. Then, create a formation which has posture relationship to this virtual WMR. As Figure.2 presents, we create a formation with a triangle shape. These WMRs will move based on the virtual WMR. Because the relationship between virtual WMR and real WMRs is constant value, we can easily to find each real WMR’s ideal trajectory, placeholder, out through this relationship and main ideal trajectory. Thus, the trajectory of each placeholder should be written as:

$$Z_{cmdi} = Z_{main} + R_0 \begin{bmatrix} x_i \\ y_i \end{bmatrix} \tag{4}$$

where R_0 denotes the rotation matrix, i denotes $i-th$ placeholders' ideal trajectory, x_i and y_i denotes the location relationship between Z_{main} and Z_{cmdi} the rotation matrix in this study should be written as:

$$R_0 = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \tag{5}$$

Thus $\dot{Z}_{cmid}$ can also be written as:

$$\dot{Z}_{cmdi} = \dot{Z}_{main} + \omega cmdi \cdot R_0 \cdot \begin{bmatrix} x_i \\ y_i \end{bmatrix} \tag{6}$$

Then, with these ideal trajectories and their derivatives, we can create the same number of groups and put the WMRs with the same bias into one group, which can be written as:

$$Z_{refij} \rightarrow Z_{cmdi} \tag{7}$$

where i denotes the $i-th$ group and j denotes the $j-th$ WMR in this organization.

3.2.2 Ranged Constraint Based Tracking Strategy

Not as single WMR track one ideal trajectory, each placeholder will have several WMRs as a group to track just one placeholder. In general, a single WMR will track one ideal trajectory precisely. Although" point-to-point" like tracking strategy, in the absence of obstacle avoidance mechanisms, collisions between MWMRs can easily occur when they track the same trajectory at the same time. Thus, it is important to have a tracking strategy with fuzzy determination capability. In this study, the tracking strategy is changed from Eqn. (7) to:

$$Z_{refij} \rightarrow Z_{cmdi} + R \tag{8}$$

where R denotes the tracking range's radius. This means when the distance between a WMR and ideal trajectory at this moment is less or equals to R, this WMR can be seen as finish tracking. It also can be written as:

$$Z_{refij} - Z_{cmdi} \le R \tag{9}$$

Because we want the value of WMRs and ideal trajectories are absolute values, we square Eqn. (9). Finally, the ranged tracking strategy should be written as:

$$(Z_{refij} - Z_{cmdi})^2 \le R^2 \tag{10}$$

$$(Z_{refij} - Z_{cmdi})^2 - R^2 \le 0 \tag{11}$$

Thus, for achieving Eqn. (11), we use a classic method:

$$2(Z_{refij} - Z_{cmdi})^T \cdot (\dot{Z}_{refij} - \dot{Z}_{cmdi}) \le -k_i((Z_{refij} - Z_{cmdi})^T \cdot (Z_{refij} - Z_{cmdi}) - R^2) \tag{12}$$

where k_i denotes a constant value in the i-th group. Because $Z = Au$ which is shown in WMR's Kinematic Model part, the function should be further written as:

$$2(Z_{refij} - Z_{cmdi}) \cdot Au \le 2(Z_{refij} - Z_{cmdi}) \cdot \dot{Z}_{cmdi}) - k_i(\left\|Z_{refij} - Z_{cmdi}\right\|^2 - R^2) \tag{13}$$

Set the variable $B_{ij} = 2(Z_{refij} - Z_{cmdi}) \cdot A$, and set variable $Bright_{ij} = 2(Z_{refij} - Z_{cmdi}) \cdot \dot{Z}_{cmdi} - k_1(\left\|Z_{refij} - Z_{cmdi}\right\|^2 - R^2)$. Thus, Eqn. (12) can be written as:

$$B_{ij} u_{ij} \le Bright_{ij} \tag{14}$$

Because velocity cannot be unlimited in the real-world scenario, the constraint of velocities should be set up:

$$u_{ij}^{-} \le u_{ij} \le u_{ij}^{+} \tag{15}$$

which u_{ij} denotes the $j-th$ WMR in $i-th$ team, u_{ij}^{-} and u_{ij}^{+} the low and advanced restriction of the $j-th$ WMR's velocity in the $i-th$ team respectively.

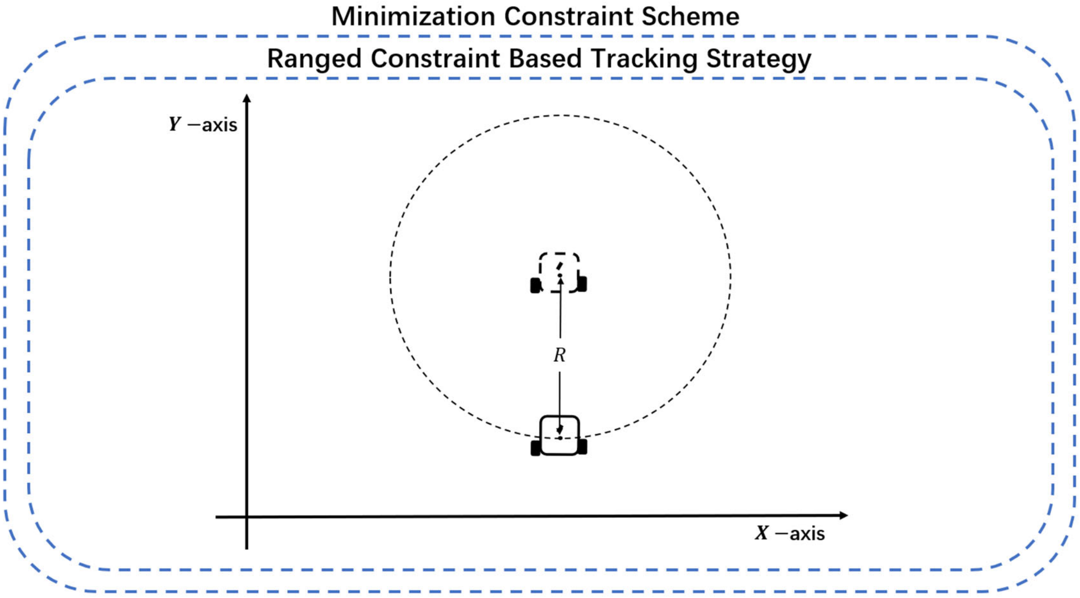

Figure 3: Graph of Ranged Constraint Based Tracking Strategy

3.3 Attraction Formula

Now MWMRs can track the ideal trajectories with the same bias, but they will have collision during the tracking time. To solve this problem, we create an attraction formula as a strong constraint to give WMRs in the same group different attractions. As Figure.4 presents, with different attractions, these WMRs with the same bias will become a formation with line shape and this is the way to avoid the collision happens without obstacle avoidance formula. This attraction formula should be written as:

$$k_{2ij}(e_{ij}^{T} e_{ij} / 2) \tag{16}$$

where e_{ij} denotes the function $\dot{Z}_{refij} - \dot{Z}_{cmdi} - k_i(Z_{refij} - Z_{cmdi})$ and k_{2ij} denotes a constant value which can affect the attraction to each WMR in the same group. This formula should be added in the constraint function. Thus, the whole minimization constraint scheme should be written as:

$$
\begin{aligned}
\min_{u_{ij}} \quad & u_{ij}^{T} u_{ij}/2 + k_{2ij}(e_{ij}^{T} e_{ij}/2) \\
s.t. \quad & u_{ij}^{-} \le u_{ij} \le u_{ij}^{+} \\
& B_{ij} u_{ij} \le Bright_{ij}
\end{aligned}
\tag{17}
$$

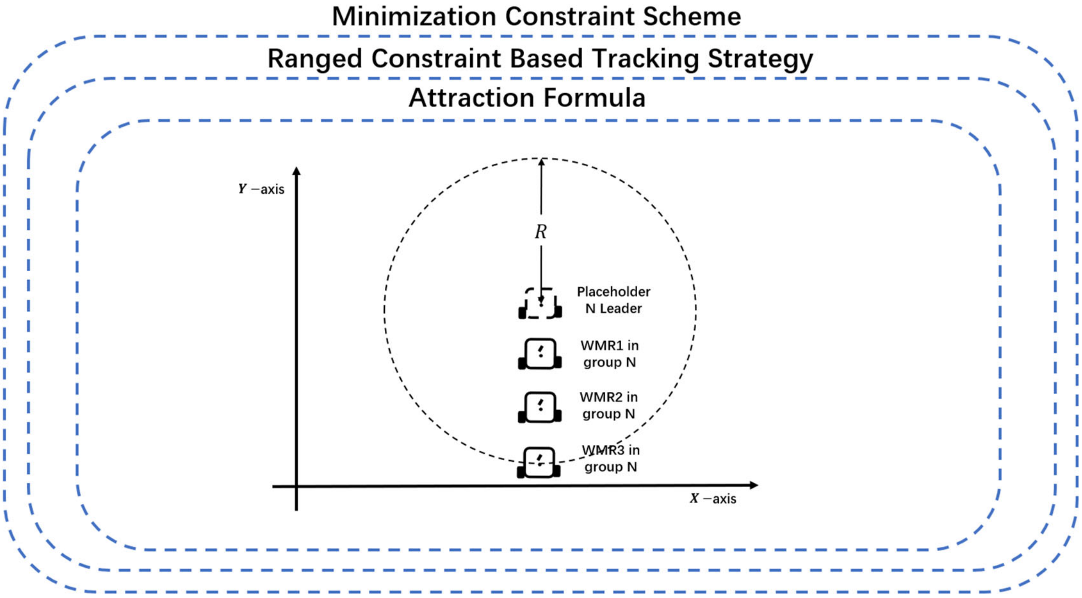

Figure 4: Graph of Attraction Formula

3.4 Controller Module

In this section, the Distance Controllability for Formation Tracking Strategy's formulation description and the Lagrange-based controller will be presented.

Based on Eqn.14 and Eqn.17, the Lagrange function solution should be written as:

$$
L_{ij}(u_{ij} \in \Omega_{ij}, \lambda_{ij}) = u_{ij}^{T} u_{ij}/2 + k_{2ij}(e_{ij}^{T} e_{ij}/2) + \lambda^{T}(B_{ij}u_{ij} - Bright_{ij}) \tag{18}
$$

$\lambda_{ij} \in R$ denotes the Lagrange multiplier and Ω_{ij} denotes $\{u_{ij} \in R^{2(N+1)}, u_{ij}^{-} \le u_{ij} \le u_{ij}^{+}\}$ to chain each WMR's velocities. Thus, the solution based on KKT conditions should be:

$$
u_{ij} = P_{\Omega_{ij}}(u_{ij} - \frac{\partial L_{ij}}{\partial u_{ij}}) \tag{19}
$$

Combine Eqn. (15) and Eqn. (19), λ_{ij} should be written as:

$$
\lambda_{ij} = max(\lambda_{ij} + B_{ij}u_{ij} - Bright_{ij}, 0) \tag{20}
$$

Thus, the designed Lagrange-based controller should be:

$$\begin{aligned}\varepsilon \dot{u}_{ij} &= -u_{ij} + P_{\Omega_{ij}}(u_{ij} - \frac{\partial L_{ij}}{\partial u_{ij}}) \\ &= -u_{ij} + P_{\Omega_{ij}}(-B^T{}_{ij}\lambda_{ij}) \\ \varepsilon \dot{\lambda}_{ij} &= max(\lambda_{ij} + B_{ij}u_{ij} - Bright_{ij}, 0) - \lambda_{ij}\end{aligned} \tag{21}$$

where ε denotes a positive constant variable, which is associated with the convergence speed of the controller.

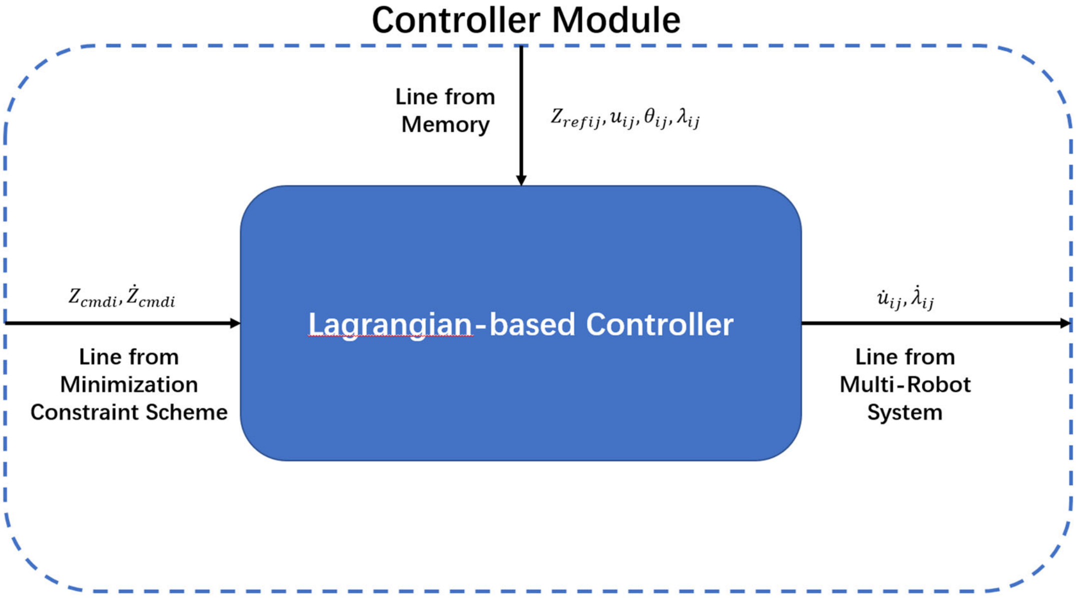

Figure 5: Graph of Controller Module

3.5 Multi-Robot System

In this part, the value of each WMR's position Z_{refij} and velocity u need to be figure out with the result of Eqn. (21). Thus, Eqn. (21) need to be further written as:

$$\dot{u}_{ij} = \frac{(-u_{ij} + P_{\Omega_{ij}}(-B^T{}_{ij}\lambda_{ij}))}{\varepsilon} \tag{22}$$

$$\dot{\lambda}_{ij} = \frac{max(\lambda_{ij} + B_{ij}u_{ij} - Bright_{ij}, 0) - \lambda_{ij}}{\varepsilon} \tag{23}$$

To adjust the sensitivity of the position difference to the velocity, we add parameters S_{ij} . Thus, Eqn.23 can be further written as:

$$\dot{\lambda}_{ij} = \frac{max(\lambda_{ij} + B_{ij}u_{ij} - Bright_{ij}, 0) - \lambda_{ij}}{\varepsilon} \cdot S_{ij} \tag{24}$$

Because the value of $\dot{u}_{ij}$ and $\dot{\theta}_{ij}$ are written as:

$$\dot{u}_{ij} = \frac{(-u_{ij} + P_{Omegaij})}{\varepsilon} \tag{25}$$

$$\dot{\theta}_{ij} = \frac{r}{L(u_{ij}(2) - u_{ij}(1))} \tag{26}$$

Z_{refij} , $\dot{Z}_{refij}$, θ, $\dot{\theta}$ and λ With Eqn.(22) and Eqn.(24) present above, the value of each WMR's velocity and position at next moment can be calculated. The function presents below:

$$u_{ij} = \dot{u}_{ij} \cdot dt \tag{27}$$

$$\lambda_{ij} = \dot{\lambda}_{ij} \cdot dt \tag{28}$$

$$\theta_{ij} = \dot{\theta}_{ij} \cdot dt \tag{29}$$

3.6 Memory

In this part, the initial positions of MWMRs should be set. When the new positions and velocities come out from the multi-robot system at the next moment, they will be saved in MWMRs position storage as the next moment's initial position information as a circle like the general framework presents below:

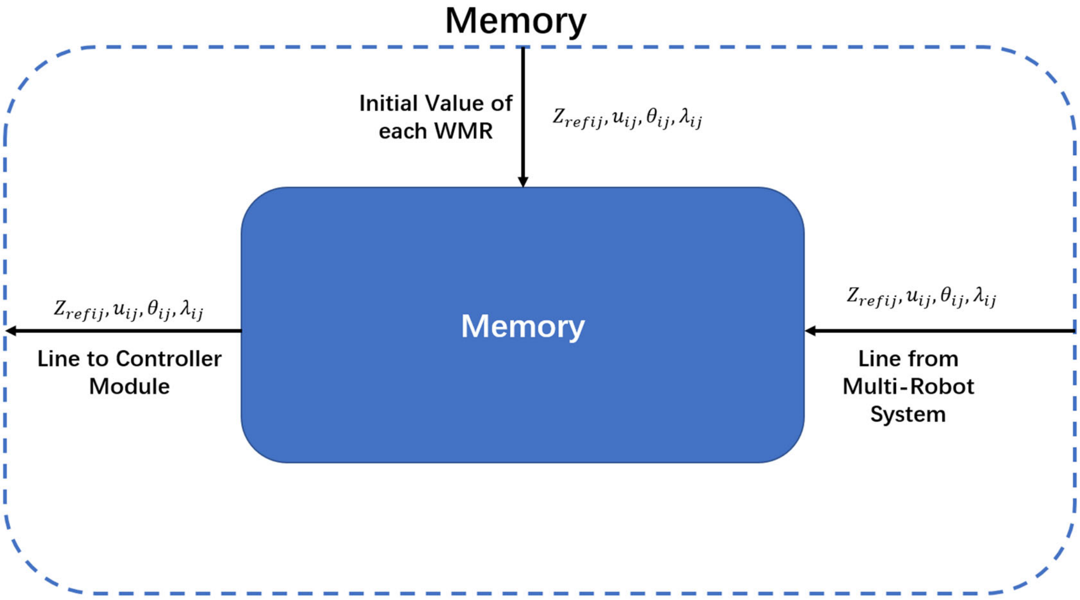

Figure 6: Graph of Memory

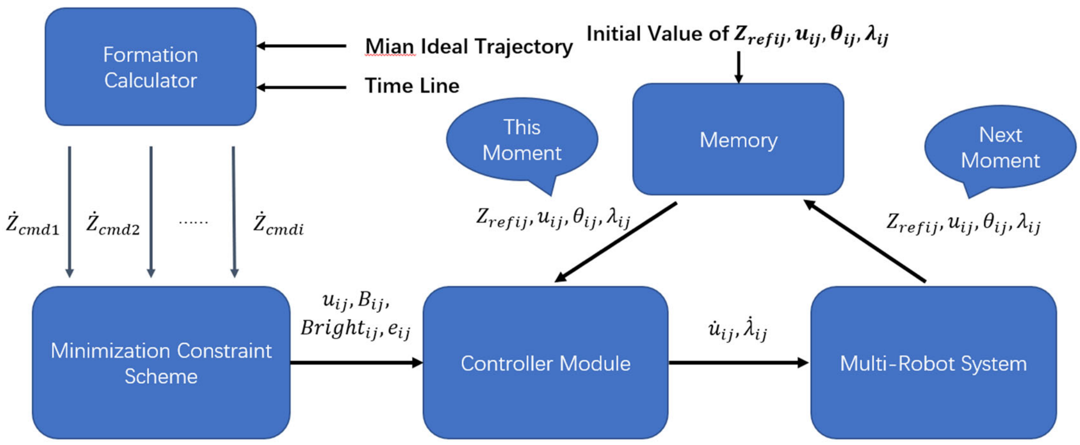

Figure 7: Graph of General Framework

3.7 Simulation Results

To test this formation method can be used or not in the ideal trajectories with different curves, we create three different main ideal trajectories: zig-zag type ideal trajectory, sine wave type ideal trajectory and invert 'U' type ideal trajectory. The distance relationship between virtual WMR and placeholders are set as [15;0], [0;15] and [0; -15] with initial value of angle $\theta = \frac{\pi}{2}$.

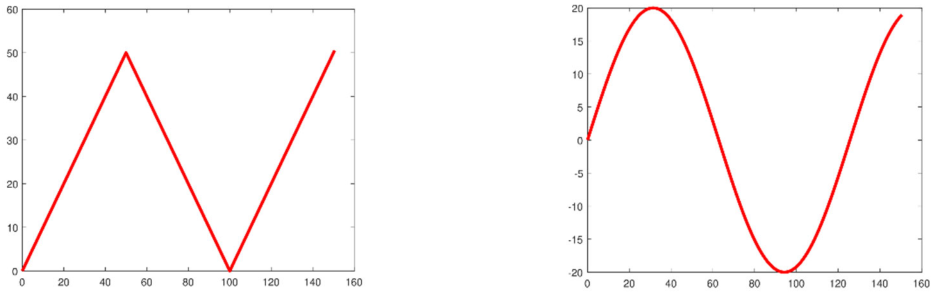

Figure 8(a) Graph of Zig-Zag type Main Trajectory

Figure 8(b)Graph of Arbitrary Curve type Main Trajectory

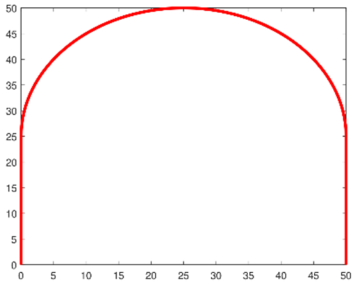

Figure 8(c) Invert 'U' type Main Trajectory

Figure 8: Graphs of Three Main Trajectories

3.7.1 Zig-Zag type Main Trajectory Simulation

These three main ideal trajectories which is shown in Fig.8 has different curves. The first ideal main trajectory has sharpest corners in three main ideal trajectories. MWMRs' virtual formation is created as a triangle and WMRs in the same group will tracks the virtual placeholder with the same bias with using the Attraction formula to track the Zig-Zag type main trajectory. The parameters of this simulation are shown below:

As Fig.8(a) shows, this main ideal trajectory has shape corners with the angle of ±45◦.

Table 1: Parameter Table of Zig-Zag type main trajectory Simulation

Parameters	Values	Parameters	Values	Parameters	Values
r	$0.4m$	S_{b1}	0.5	k_{a2}	-2
L	$1.85m$	S_{b2}	0.5	k_{a3}	-0.1
d_0	$0.75m$	S_{b3}	0.5	k_{b1}	-10
R	$5m$	S_{c1}	0.5	k_{b2}	-2
ε	0.02	S_{c2}	0.5	k_{b3}	-0.1
u_i^+	$10m/s$	S_{c3}	0.5	k_{c1}	-10
u_i^-	$-10m/s$	k_a	3	k_{c2}	-3
S_{a1}	0.5	k_b	3	k_{c3}	-0.1
S_{a2}	0.5	k_c	2		
S_{a3}	0.5	k_{a1}	-10		

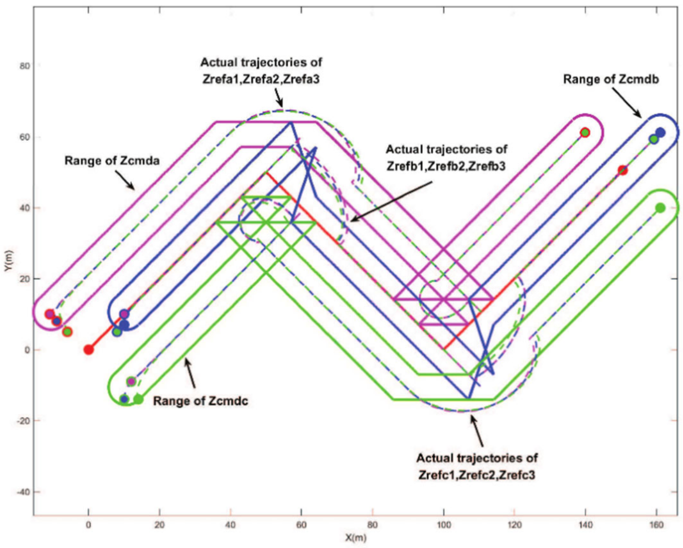

Figure 9: Graph of MWMRs Tracking Zig-Zag trajectory

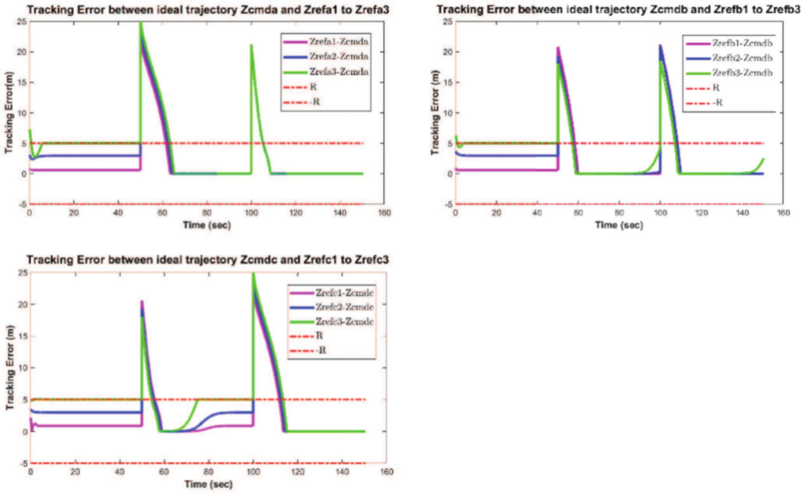

Figure 10: Graph of MWMRs Tracking Zig-Zag Tracking Error

As Fig.9 and Fig.10 shows, MWMRs move out of the range R during each corner of the Zig-Zag ideal trajectory. In Fig.10, all graphs of the range R of each ideal trajectory present complicate and sharp in each inside corner. In Fig.11, all MWMRs tracking the ideal trajectory with some distance very well, but after the first corner, all tracking errors grows very high. And then, all tracking errors under Zig-Zag ideal trajectory simulation can’t touch the expectation level we expect.

The simulation result based on the Zig-Zag ideal trajectory is failed. All graphs present that the new formation method doesn’t work well with sharp corners.

3.7.2 Arbitrary Curve type Main Trajectory Simulation

Because the new formation method doesn’t work with sharp corners, we decide to change the sharp corners to arbitrary curves. The parameter table of Arbitrary Curve type main trajectory simulation presents below:

Table 2: Parameter Table of Arbitrary Curve type main trajectory Simulation

Parameters	Values	Parameters	Values	Parameters	Values
r	$0.4m$	S_{b1}	1	k_{a2}	-0.5
L	$1.85m$	S_{b2}	1	k_{a3}	0
d_0	$0.75m$	S_{b3}	1	k_{b1}	-10
R	$5m$	S_{c1}	1	k_{b2}	-0.5
ε	0.02	S_{c2}	1	k_{b3}	0
u_i^+	$20m/s$	S_{c3}	1	k_{c1}	-10
u_i^-	$-20m/s$	k_a	10	k_{c2}	-0.5
S_{a1}	1	k_b	10	k_{c3}	0
S_{a2}	1	k_c	10		
S_{a3}	1	k_{a1}	-10		

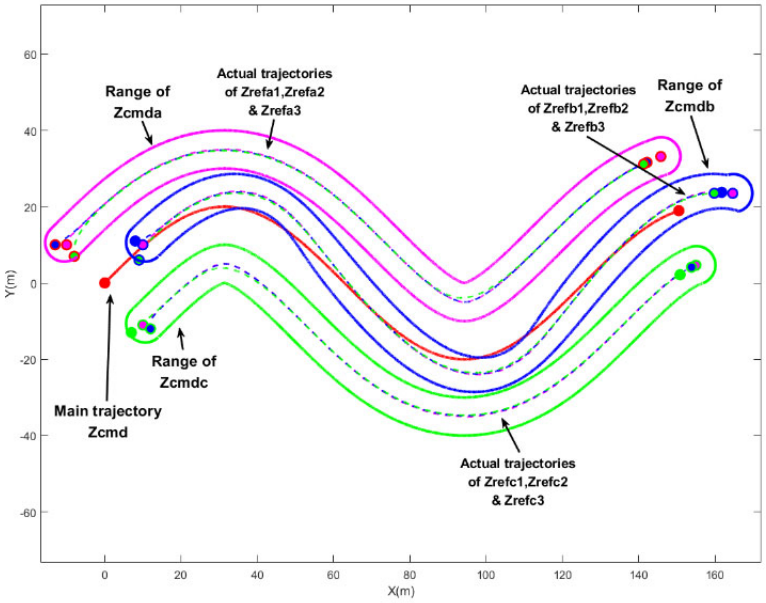

Figure 11: Graph of MWMRs Tracking Arbitrary Curve trajectory

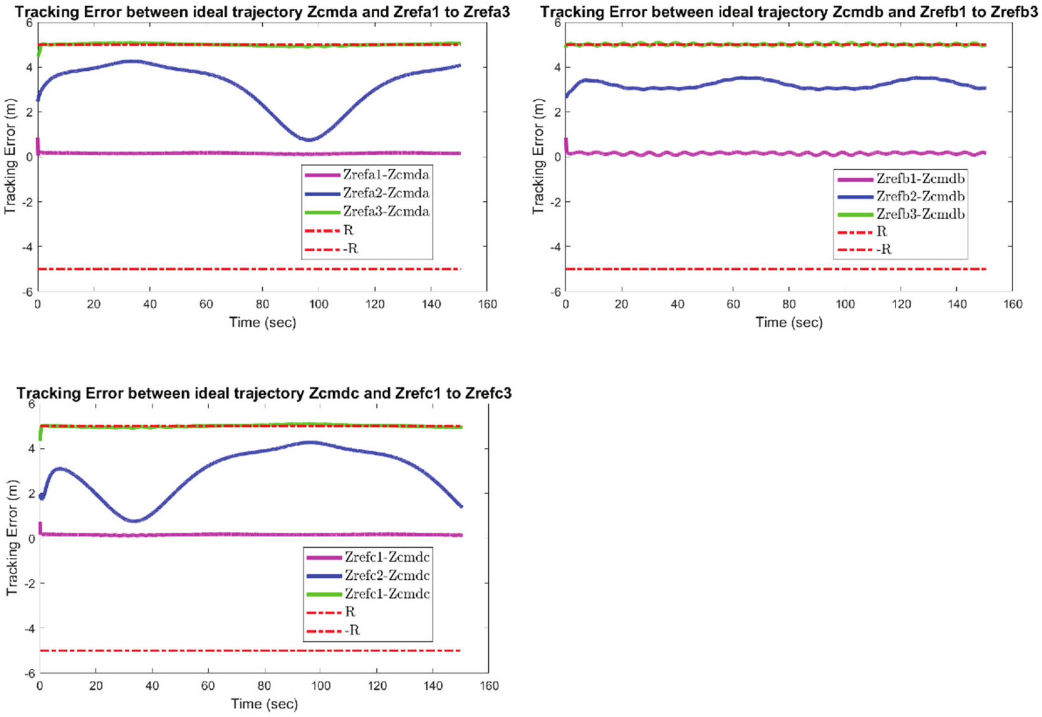

Figure 12: Graph of MWMRs Tracking Arbitrary Curve trajectory

As Fig.8(b) presents, the second ideal trajectory is a sine wave curve. With the presentation of Fig.11 and Fig.12 we can know that MWMRs tracks the arbitrary curve type ideal trajectory successfully. All WMRs in Fig.11 are in the range of Z_{cmdi} and the tracking errors are all in the range of R in Fig.12. Attraction formula works fine in this simulation although all second WMRs in each group has some rise and fall. With two simulations we can know that this formation method based on the virtual structure and Attraction formula is good to use during the main trajectory is curve but not sharp corner. It can be used with more soft waves or not still need to test.

3.7.3 Invert 'U' type Main Trajectory Simulation

As Fig.8(c) and Fig.13 presents, this simulation uses a invert 'U' type trajectory as the main ideal trajectory, creates a triangle formation as the framework with virtual structure method and uses Attraction formula to avoid WMRs in the same bias to have collision with each other. In Fig.13 shows, all WMRs track their ideal trajectories in the range of which is set as R. Also, in Fig.14, we can see the tracking error between WMRs in the same group to the placeholders which need to follow $Z_{refij} - Z_{cmdi}$. For example, in the graph whose name is "Tracking Error between ideal trajectory Z_{cmda} and Z_{refa1} to Z_{refa1}" in Fig.14, all tracking errors are in the range R to $-R$ and these tracking errors don't touch each other. This phenomenon means all WMRs in group 'A' track the ideal trajectory successfully in the range of R. Also, these lines never touch each other means these WMRs in the same group don't hit each.

Table 3: Parameter Table of Invert 'U' type main trajectory Simulation

Parameters	Values	Parameters	Values	Parameters	Values
r	$0.4m$	S_{b1}	1	k_{a2}	-0.02
L	$1.85m$	S_{b2}	0.05	k_{a3}	-0.009
d_0	$0.75m$	S_{b3}	0.05	k_{b1}	-1
R	$5m$	S_{c1}	1	k_{b2}	-0.02
ε	0.02	S_{c2}	0.05	k_{b3}	-0.009
u_i^+	$20m/s$	S_{c3}	0.05	k_{c1}	-1
u_i^-	$-20m/s$	k_a	300	k_{c2}	-0.02
S_{a1}	1	k_b	300	k_{c3}	-0.004

S_{a2}	0..05	k_c	300		
S_{a3}	0.05	k_{a1}	-1		

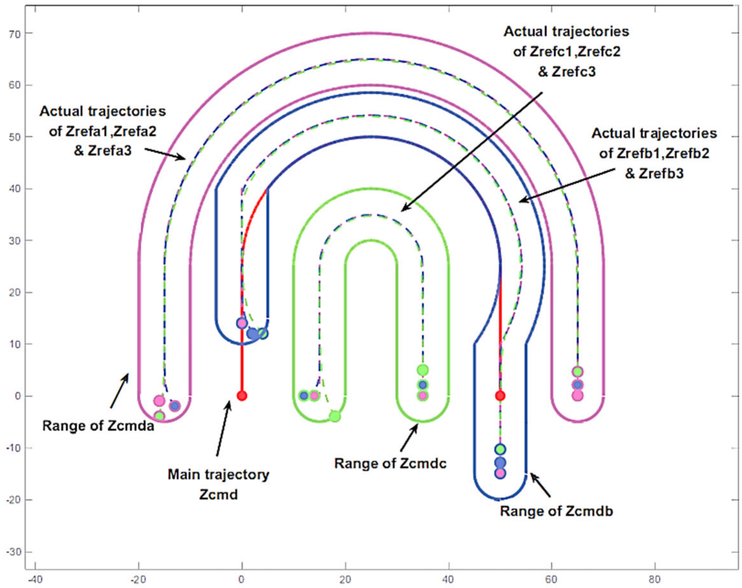

Figure 13: Graph of MWMRs Tracking invert ‘U’ trajectory

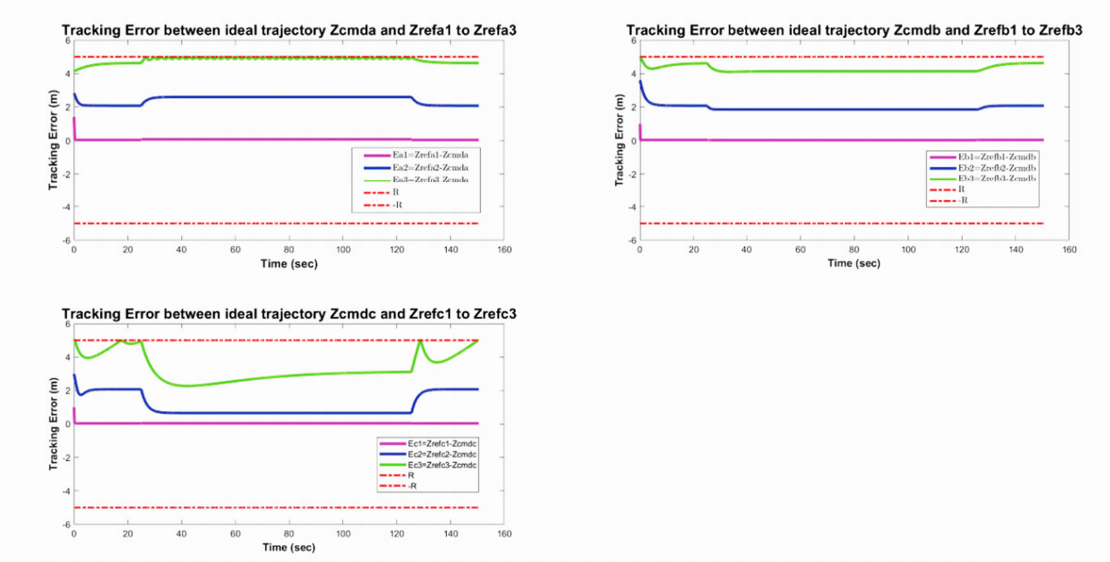

Figure 14: Graph of Tracking Error in invert ‘U’ main trajectory

Fig.13 shows all WMRs track their Z_{cmdi} in their own range R and Fig.14 presents the all WMRs in the same group can track their placeholders with the same bias without collision.

4 Conclusion

In this paper, we create three main trajectories. The first main trajectory is a folded line, the second main trajectory is a sine wave line, and the third main trajectory is an invert ’U’ type line. From these three results we can get this conclusion: the virtual structure-based formation tracking method can’t be used while the main trajectory with pointed corners. Although with attraction formula, all WMRs in the same group can keep a distance to each, they can’t really keep each a constant distance. This uncertainty might work while the simulation just avoids WMRs have collision. If we need each WMR in the same group has the constant distance errors to each other, using the Attraction formula method is not a good idea. Over all, the simulation successfully proves that the in this paper, we create a MWMRs formation system to follow different ideal trajectories: ’Zig-Zag’ type ideal trajectory, ’sine-wave’ type ideal trajectory and invert ‘U’ type ideal trajectory. These three results provide different results. When MWMRs formation system is following ’Zig-Zag’ type ideal trajectory, as Fig.9 and Fig.10 present, the MWMRs formation system we create can’t adapt sharp corner in the ideal trajectory.

4.1 Recommendations

In this paper, some problems in way programme and path backtracking of tumbled variable robot in complex rugged ground (surface) environment are studied and discussed. the algorithm is improved and studied in the aspects of time complexity, algorithm accuracy and surface trajectory tracking, torque limitation and torque derivative limitation of trajectory tracking, uncertainty interference and so on. Due to the time factor, this design can be further studied and explored in the following aspects:

First, we can continue to study the methods to further shorten the time complexity of the surface way programme arithmetic, and make an in-depth discussion on the application of enhancing the practical-time performance of the arithmetic.

Second, the improvement of the accuracy of the surface path algorithm can further study how to shorten the time cost of the arithmetic.

Third, the parameter optimization algorithm for surface trajectory tracking continues to apply other optimization algorithms to find the global optimization algorithm.

Fourth, for the parameter optimization algorithm of surface trajectory tracking, the time cost optimization of the algorithm is studied to reduce the time to find the optimal solution.

4.2 Limitations

In the third chapter, the formation tracking of multi-wheeled variable robot based on virtual structure is optimized, and the optimization pattern is further builded based on the most classical WMR's Kinematic model, and the model is solved. Finally, emulation stroke is Proceed to verify the rationality of the optimization model. However, there are still some issues that need to be further explored:

First, set more parameters to further verify the model established in this paper.

Second, we can design an experiment or case for analysis, and apply the optimization model assured in this study to the specific practice.

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