A Framework for Cars to Join or Leave a Car Formation

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***Abstract*— We design a framework for a group of autonomous smart cars that allows them to come into a formation and for one to join the formation or leave the formation (we call it CJL). We propose a concept of switching distance to make the formation change more smoothly. Because a control input of any one of cars is constrained for a CJL, we will discuss its control algorithms. Some simulations will be shown in this paper. They will prove that the ability of the framework to realize a formation control.**

Index Terms—framework, formation control, autonomous smart car, switching distance, simulation.

I. INTRODUCTION

Serious traffic problems excited people's interests in intelligent transportation systems. Various subjects have been researched, for instance artificial transportation systems [1], traffic simulations, traffic control and management, incident detection, route plan, traffic theories, and many kinds of applications for transportation systems. Formation control for cars has been developed for decades. Many processes have been achieved. People believe that formation control of smart cars should help to solve many social problems, for example, traffic congestion, vehicle accidents, mapping of the unknown environments, searching and rescuing, transportation for large items [2], [3]. We can get some useful information about intelligent transportation systems in Refs. [4-7]. The advantages of formation control have been paid more attention by many researchers. More efforts are put into their researches on formation control.

The popular approaches to solve a formation control problem have been divided into three methods: behavior based [8], virtual structure [9],[10], and leader-follower [11]. The method of behavior based was derived from the biological field. Its main idea is that desired behaviors have been predesigned. When a specific behavior happens, the related controller will work. In this method, the cooperative task is completed through information sharing [8]. The main application of virtual structure was a formation control for aircrafts and satellites in Ref. [9]. It kept them to maintain a fixed geometry formation. This method is also apt for autonomous smart cars. A rigid body structure can be formed among them. A desired trajectory is not assigned to any single car but the whole formation. It is easy to specify the behavior of a car group and get the feedback of the formation control. Then high accuracy of the trajectory of the becoming formation process will be obtained. However, the flexibility of formation and adaptability for environment are not very good. The leader-follower method designs a leading car as a leader and a designated route, while the other cars will follow the leader maintaining a desired distance and orientation. It simplifies the formation control problem and converts it into an attitude tracking problem. Then the standard control theory can be applied to it. We can learn it well from Ref. [11]. Some robust control algorithms can be used to solve the tracking problem. We can see the stability of the formation which has been studied in Ref. [12].

Because the leader-follower method is simple and effective for the formation of autonomous smart cars, we will adopt it in this paper. We propose a framework for cars to join or leave a car formation based on the leader-follower method. The organization of this paper will be presented as follows. First, some current algorithms about the leader-follower method for formation control are presented in Section Ⅱ. Then, we propose the framework for car formation in Section Ⅲ, which means that formation control algorithms which make cars join the formation and leave the formation will both be studied. Following that, the simulations will be presented. Several examples are shown the effectiveness of this framework to add cars to a formation and leave the formation. Finally, in Section Ⅴ and Ⅵ, we talk about the future work and draw a conclusion.

II. CURRENT ALGORITHMS ABOUT LEADER-FOLLOWER METHOD FOR FORMATION CONTROL

We will discuss algorithms for formation control, which are the foundation for our work. We introduce three algorithms to realize the car formation as follows.

A. Input-output feedback linearization

The input-output feedback linearization is a basic leader-follower control method. We assume that there is a group of smart cars ($R_1, R_2, \ldots, R_{n-1}, R_n$). The car R_{i+1} follows the car R_i with the limitation of distance l_{ii+1}^d and desired relative bearing ψ_{ii+1}^d. The kinetic equations are given by

$$\begin{aligned} \dot{z}_{ii+1} &= G_1(z_{ii+1}+\beta_{ii+1})u_{i+1} + F_1(z_{ii+1})u_i \\ \dot{\beta}_{ii+1} &= \omega_i - \omega_{i+1} \end{aligned} . \quad (1)$$

By applying the input-output feedback linearization , we can get the control velocity for the car R_{i+1} .

$$u_{i+1} = G_1^{-1}(p_1 - F_1 u_i) \ , \quad (2)$$

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Where the speed of the first car is fixed and the speed of any other car is determined by the car which is in front of it. Readers can learn much more from Ref. [13].

B. PID control

The PID control utilizes the information of the cars' positions for a formation. ψ_{ii+1} and l_{ii+1} are the angle and distance between two close cars at any real time. We can see them in Figure 1. The desired angle ψ^d_{ii+1} and the desired distance l^d_{ii+1} between them are known. Here, cars are shown as rectangles. Actually, the angle of any car and the distance between two close cars in real time is varied in the becoming formation. Under the conditions, communications between two close cars are necessary. Their relative distance of those two cars can be calculated easily. We compare these relative distance and angle with their desired data to get their difference. Then, the speed of the rear car can be calculated through the PID control algorithm in Ref. [14]. The advantage is obvious. Even if we do not know the accuracy model of the car, we can also easily realize the formation of cars

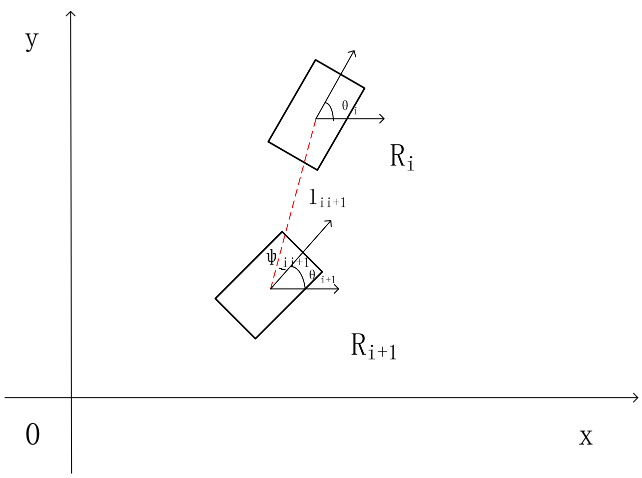

Fig. 1 Two cars formation under PID control

C. Robust control

The robust control is used for the formation of cars even if some kinematic disturbances occur. Researchers have proved that the position and orientation errors of the formation will converge to a small range which is around zero. The design of the robust control can be derived from a standard backstepping method in Ref. [12].

III. THE FRAMEWORK FOR CAR FORMATION

The main work of this paper is that we propose a framework for autonomous smart cars to get into a formation and any other car which is not in the formation joins it or one of the cars which is in the formation quits it. There is rarely any paper about it, although it will be a practical problem for the transportation systems in the coming future. Therefore, we believe that it is necessary to study the problems for cars to join the formation and quit the formation. We use the leader-follower method to get a car into the formation or quit it. The cars in the formation will be donated as $R_1, R_2, \ldots, R_{n-1}, R_n$ and R_{i+1} follows R_i as shown in Figure 2. Here, cars are shown as rectangles. Then we assume a car A wants to join the formation and to be at the position between R_i and R_{i+1}. We will describe the joining steps as follows. (1) The car A will aim to follow the car R_i no matter where it is. (2) The car A moves close to the car R_i. If the distance between those two cars is smaller than the predefined data (which is called switching distance d), the joining process will begin. (3) The car R_{i+1} will change the leader of itself and it will follow the car A. At the same time, any other car doesn't change their leaders. It is not difficult for us to imagine that with the help of the switching distance, the formation will change quickly and be stable very soon.

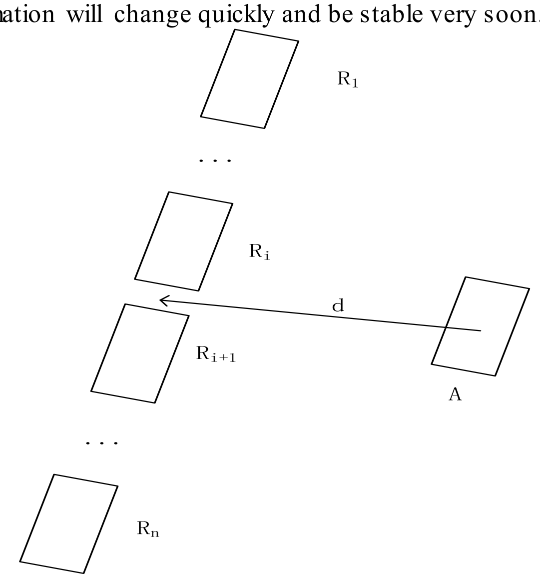

Fig. 2 Joining a formation for one car

In Figure 2, the rectangles A, $R_1, \ldots, R_i, R_{i+1}, \ldots,$ and R_n represent smart cars and d represents a switching distance.

IV. SIMULATIONS

We will execute some simulations to test the framework we proposed. In these simulations, we design the cars which belong to the differential drive, and they are controlled by the designated velocities of the right and left wheels. Those cars are a kind of nonholonomic robots.

The traditional dynamics of a car model are defined as:

$$\begin{aligned} \dot{x} &= v\cos(\theta) \\ \dot{y} &= v\sin(\theta)\ , \\ \dot{\theta} &= \omega \end{aligned} \tag{3}$$

where (x,y) represents the position coordinate of the car, θ means the angle between its speed and x-axis.

The differential dynamics of the car are defined as:

$$\begin{aligned} \dot{x} &= \frac{R}{2}(v_r + v_l)\cos(\theta) \\ \dot{y} &= \frac{R}{2}(v_r + v_l)\sin(\theta)\ , \\ \dot{\theta} &= \frac{R}{L}(v_r - v_l) \end{aligned} \tag{4}$$

where v_r represents the speed of the right wheel, v_l represents the speed of the left wheel, R represents the radius of the wheels, and L represents the distance between the wheels.

Therefore, we use a function to transform (v_r, v_l) to (v,ω). It is obvious that the car we talk about has input constraints and both the right and left wheels' speeds are limited. Its speed is defined as:

$$u\_ao\_gtg = m*u\_gtg + (1-m)*u\_ao, \quad (5)$$

where the u_gtg means the speed to go to a goal and the u_ao means the speed to avoid obstacles, u_ao_gtg blends those two speeds together, the magnitude of m influences the proportion of u_gtg and u_ao, which means one wants to go to the goal for priority or avoid the obstacle for priority. Through adjusting the m parameter, we can make the car aim to the goal even if the environment is complex.

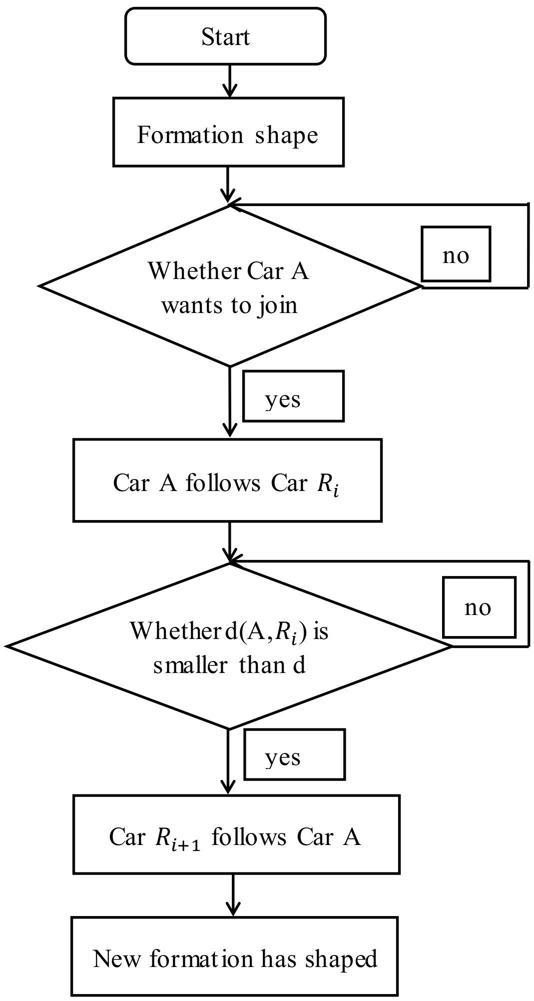

Fig. 3 Flow chart of the algorithm for a car how to join a formation

Then, we will describe the framework what we talked above. When the formation of a group of cars has been formed, any other car wants to join it and to be one of the formation. We assume that a car A gets the command to join the formation. It wants to follow the car R_i. There is no doubt that if we execute the formation control immediately when the car A is far from the car R_i, the time for changing the formation will be very long, and the formation of the cars will be a mess during an initial period. It is obvious that we do not want this to be happened. We hope to shorten the formation changing time as soon as we can so that we can improve the capability of the transportation systems. In order for that, we design a switching distance to make the formation control algorithm work. As follows, we introduce a car how to join or leave a formation and give some simulation results.

In this paper, we use an app in Matlab and the name of this app is Sim.I.am. It is a robotics simulator that can be used to learn how to apply controls to mobile robots. The environment is a 29*29 square, each car takes up about one unit, the edge of the map is marked with red straight lines. It is maintained by the Georgia Robotics and Intelligent (GRITS) Laboratory at the Georgia Institute of Technology.

A. Simulations how to join a formation

From Figure 2, we know that the switching distance is designated as d.

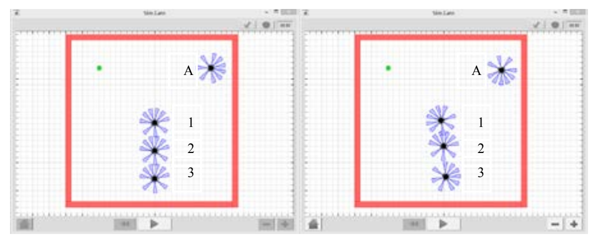

Fig. 4(a) .

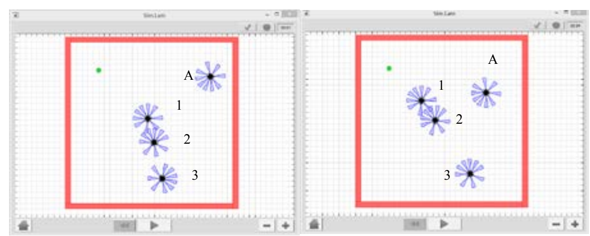

Fig. 4(b) .

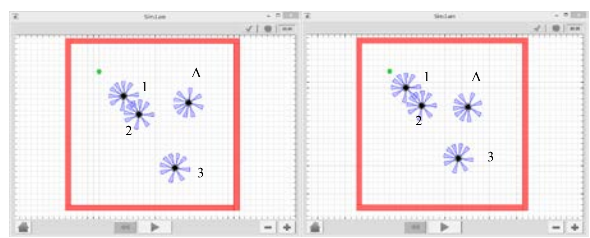

Fig . 4(c) .

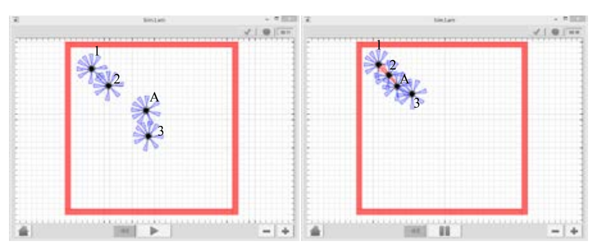

Fig . 4(d) .

Fig. 4 Simulations for a car joining a formation

When a car A gets the command to join a formation and it is required to follow the car R_i, the car R_{i+1} does not change its leader R_i immediately and still follow it. This is the first period. Next, when the distance between the A and R_i is smaller than d, the formation control algorithm will work and the formation change will begin. Immediately, the car R_{i+1} will change its follower and follow A, while the car A is still following the car R_i. Obviously, the switching distance is very important. It will influence the time for switching. In this paper, we choose it as about 5 times of the car's length in our simulation. At the initial time, the formation is becoming a mess due to the changing of the formation. Of course, we can modify the switching distance to get a better performance. We can see this process in Figures 4 (a)-(d). The car A wants to join the position between Car 2 and Car 3 here.

As the pictures show above, those three cars are in a line at first. The car A wants to join the line. Finally, it completes the work successfully. Those simulations show the process that how to join a line formation for a car.

B. Simulations how to leave a formation

When the cars drive in a formation, any other one can join the formation. Of course, one of them also can leave the formation. The exiting process is easier than the joining process for a car in this paper. Please see Figure 5. There are four cars driving in a line.

We assume that Car 3 change its destination and wants to leave the formation. Then the Car 4 will follow the Car 2 instead. From the Figures 6 (a)-(d), we can see that Cars 1, 2, and 4 keep the formation successfully.

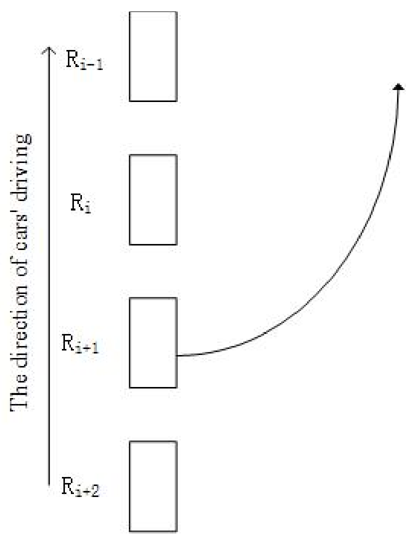

Fig. 5 Car 3 wants to leave the formation

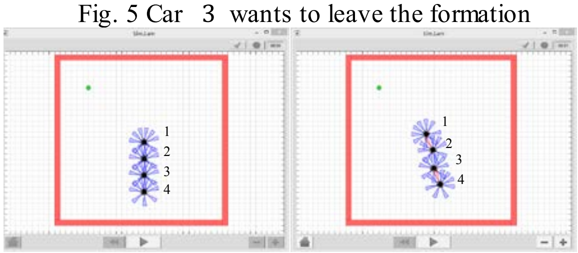

Fig. 6(a) .

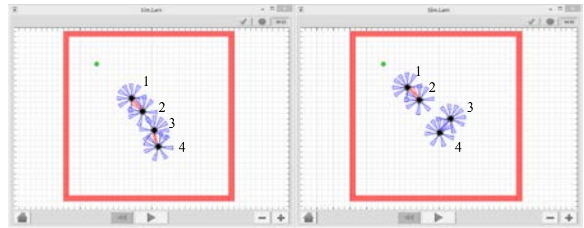

Fig. 6(b) .

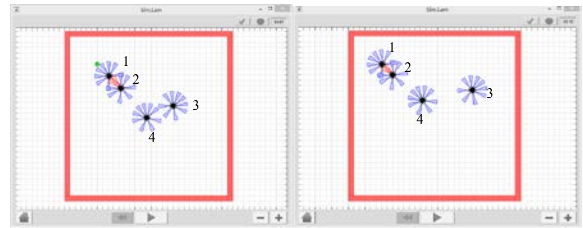

Fig. 6(c) .

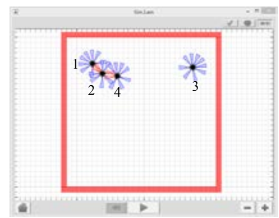

Fig. 6(d) .

Fig. 4 Simulations for a car leaving a formation

Of course, we can do some experiments to compare the consumption time between our proposed method with other methods. The test environment we used is too small and the switching distance is short. Therefore, the switching condition is easy to be triggered as soon as the experiment begins. It will be the future work for us to do when the test environment we used is big enough.

V. FUTURE WORK

Although the work on formation control for smart cars has been done for many years, there is rarely researches on the methods for cars to join or leave a formation. We think many works can be done for our coming researches. We share several ideas in our future work .

1) The environment of simulations is simple in this paper. Later on, we should do some researches in a complex environment. It is a practical problem for traffic systems. Large scales and some obstacles are necessary.

2) The standard for the efficiency of a CJL is not very explicit. We suggest that we should consider it in our following researches, such as, the time used to complete a CJL, and the trajectory variation of a formation at the process of CJL.

3) In this paper, a switching distance is very important. Nevertheless, how should we choose it or what will it depend on, we should go further work to research them.

4) The actuator fault should be considered in our proposed framework. Actually, we cannot make sure that the

actuator always works without any problems. Therefore, a fault tolerate control should be involved in it.

5) The algorithms used to keep formation can be substituted such as iterative learning control. Then, we can test this framework's ability to adopt different algorithms. Maybe the most suitable one can be found at that time.

These problems are meaningful for the study of a CJL. If they are solved, the ability for smart cars to cope with various faults and complex environment can be improved. There is no doubt that we can use this framework to enhance the service level of the transportation systems in the future.

VI. CONCLUSIONS

In this paper, we discuss our proposed framework for a car to join or leave a group of autonomous smart cars. We use the Matlab to validate it. As we can see, the framework is effective in our simulations. It is not difficult for us to imagine that CJL is very important for traffic systems in the future, however the literature research about CJL is little. Therefore, we think our proposed framework in this paper maybe help to solve traffic problems in the future. It is one of the main contributions of this paper. The other contribution of this paper is that we propose a "switching distance" which may improve the efficiency of the transportation systems.

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