An Approach to Formation Maneuvers of Multiple Nonholonomic Agents using Passivity Techniques

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Abstract: This paper studies the problem of formation maneuver of multiple nonholonomic agents. A dynamic feedback linearization method is used to transform each agent's dynamic model into two chains of 3rd order integrator. Then a decentralized discontinuous formation control law with inter-agent damping injection is derived. Asymptotical stability of the overall system is proved by using Lyapunov method. The proposed algorithm is applied to a nonholonomic multi-vehicles formation maneuver simulation, which shows the effectiveness of our strategy.

Key Words: Multiple nonholonomic agents, Formation, Full-state linearization, Passivity

1 INTRODUCTION

The major reason for studying formation of multiple agents is due to its challenging features and many applications, e.g., rescue mission, large object moving, troop hunting, and satellite clustering.

Formation control is closely related to the consensus problem. Most results on graph theory that relate the cooperative solutions to the consensus problem are obtained for linear agents [1, 2]. In these papers, the structure of the communication network between agents was described by Laplacian matrices. Each agent was treated as a vertex and the communication links between agents were treated as edges. The stability of the whole system was guaranteed by the stability of each modified individual linear system, where the modification to the linear system accounts for the structure of the communication network [1].

However, many practical formation maneuver applications involve the agents with nonlinear dynamics and nonholonomic constraints. In the well-known paper by Brockett [3], it was shown that the systems with nonholonomic constraints cannot be stabilized with continuous static state feedback. For the case of multiple agents, the problem becomes more complex. In [4], a distributed smooth time-varying feedback control law was proposed with analysis based on averaging theory for coordinating the motion of multiple nonholonomic mobile robots to capture/enclose a target. In [5], formation control of several mobile robots was considered with the aid of the dynamic feedback linearization technique, resulting in cooperative control laws based on multiple double integrator systems. In addition, several general control methods were proposed for multiple robots. There are behavior-based control [6], virtual structure [7], and leader-follower [8] methods.

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In this paper, we propose a formation control law by using passivity techniques for multiple agents with nonholonomic constraints. First, we generalize the full-state linearization method in [9] to transform each agent's dynamics into a linear system consisting of two chains of 3rd order input-output integrator; Second, we treat each agent as a MIMO linear system and use the consensus law in [10] to achieve formation maneuvers; Third, inter-agent damping is injected to eliminate the relative motion oscillatory and formation steady error. Finally, the asymptotical stability of the overall system is proved by using Lyapunov method.

The objective of this paper is to integrate the discontinuous control law for a single nonholonomic agent with the consensus law for multiple MIMO linear systems to obtain an effective formation control strategy for the multiple nonholonomic agents with exponential convergence rate and meanwhile depends on less inter-agent communication.

The rest of the paper is organized as follows. In section II, the relevant results in graph theory is briefly summarized. In section III, the agent's dynamical model and full-state linearization via dynamic feedback are introduced. In section IV, the main result of formation control strategy is given. In section V, the effectiveness of the proposed strategy is tested by a simulation. And finally, we conclude by summarizing the paper and providing some thoughts on future directions of research.

2 PRELIMINARIES

The concept of Graph is a useful tool to represent the structures of networks. Let $G=(V,A)$ be a graph of order N with a set of nodes $V=\{v_1,\cdots,v_N\}$ and a set of arcs $A\subseteq V\times V$. An arc (v_i,v_j) of G is graphically denoted by a section of line with arrow drawn from node v_j to node v_i . The set of neighbors of node v_i is

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denoted by $N_i = \left\{ v_j \in V : \left(v_i, v_j \right) \in A \right\}$. In multi-agent systems represented in the nomenclature of graph, the node $v_i \in V$ means the ith agent; the arc $\left(v_i, v_j \right)$ is the communication connection that the jth agent sends information to the ith agent. A graph Laplacian $L = \left[l_{ij} \right]$ is a matrix with its components defined by:

$$l_{ii} = \sum\nolimits_{j \neq i} a_{ij}, l_{ij} = -a_{ij} (i \neq j)$$
$$a_{ij} = 1 (v_j \in N_i) a_{ij} = 0 (v_j \notin N_i).$$

Assuming that the graph is strongly connected, the following properties hold [11]:

(1) There is a unique zero-eigenvalue of L.

(2) All eigenvalues of L are nonnegative.

(3) The eigenvector of the zero-eigenvalue of L is a column vector with all its components are ones.

(4) The eigenvalues of L can be presented as:

$$0 = \lambda_1(L) < \lambda_2(L) \leq \cdots \leq \lambda_N(L).$$

3 THE DYNAMICAL MODEL OF A NODE AND FULL STATE LINEARIZATION

In the sequel, we shall consider the formation maneuver problem for multiple agents with nonholonomic constraints from the viewpoint of complex networks. We treat each agent as a node in the network. The ith agent follows the node's dynamical equations below [5]:

$$\begin{bmatrix} \dot{r}_{xi} \\ \dot{r}_{yi} \\ \dot{\theta}_i \\ \dot{v}_i \\ \dot{\omega}_i \end{bmatrix} = \begin{bmatrix} v_i \cos\theta_i \\ v_i \sin\theta_i \\ \omega_i \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 1/m_i & 0 \\ 0 & 1/J_i \end{bmatrix} \begin{bmatrix} F_i \\ \tau_i \end{bmatrix}. \quad (1)$$

And the agent subjects to a 1st order nonholonomic constraint [4, 9]:

$$\dot{r}_{xi} \cdot \sin\theta - \dot{r}_{yi} \cos\theta = 0.$$

Physically speaking, the nonholonomic constraint means that the agent cannot move in the lateral direction instantaneously. It reduces each agent's instantaneous mobility, e.g., in real life, the mobile car can't move laterally instantaneously.

In the inertial coordinates frame, let $(r_{xi}, r_{yi})^T$ represent the inertial position of the ith agent, θ_i represent the orientation of the ith agent. Let v_i and ω_i represent the magnitudes of the ith agent's linear and angular velocities. Let τ_i and F_i be the applied torque and applied force. Let m_i and J_i represent the ith agent's mass and moment of inertial. For convenience, we assume unit mass and moment of inertial and let each node's output be:

$$h_i = \begin{bmatrix} r_{xi} \\ r_{yi} \end{bmatrix} \quad (2)$$

Unlike the I/O linearization method in [5] which needs a specific output variable selection, we generalize the dynamic feedback linearization method in [9], introduce a state variable $\xi_i = v_i$:

$$\dot{h}_i = \begin{bmatrix} \xi_i \cos\theta_i \\ \xi_i \sin\theta_i \end{bmatrix} \quad (3)$$

Differentiating (3) with respect to time gives:

$$\ddot{h}_i = \begin{bmatrix} \cos\theta_i & -\xi_i \sin\theta_i \\ \sin\theta_i & \xi_i \cos\theta_i \end{bmatrix} \begin{bmatrix} \dot{\xi}_i \\ \dot{\theta}_i \end{bmatrix} \quad (4)$$

Differentiating again gives:

$$\dddot{h}_i = \begin{bmatrix} \cos\theta_i & -\xi_i \sin\theta_i \\ \sin\theta_i & \xi_i \cos\theta_i \end{bmatrix} \begin{bmatrix} \ddot{\xi}_i \\ \ddot{\theta}_i \end{bmatrix} + \begin{bmatrix} -\sin\theta_i \cdot \dot{\theta}_i & -\dot{\xi}_i \sin\theta_i - \xi_i \cos\theta_i \cdot \dot{\theta}_i \\ \cos\theta_i \cdot \dot{\theta}_i & \dot{\xi}_i \cos\theta_i - \xi_i \sin\theta_i \cdot \dot{\theta}_i \end{bmatrix} \begin{bmatrix} \dot{\xi}_i \\ \dot{\theta}_i \end{bmatrix} \quad (5)$$

If $\xi_i \neq 0$, the dynamic feedback linearization control is given by:

$$\begin{bmatrix} \ddot{\xi}_i \\ \ddot{\theta}_i \end{bmatrix} = \begin{bmatrix} \cos\theta_i & -\xi_i \sin\theta_i \\ \sin\theta_i & \xi_i \cos\theta_i \end{bmatrix}^{-1} \cdot$$
$$\left[\begin{bmatrix} u_{1i} \\ u_{2i} \end{bmatrix} - \begin{bmatrix} -\sin\theta_i \cdot \dot{\theta}_i & -\dot{\xi}_i \sin\theta_i - \xi_i \cos\theta_i \cdot \dot{\theta}_i \\ \cos\theta_i \cdot \dot{\theta}_i & \dot{\xi}_i \cos\theta_i - \xi_i \sin\theta_i \cdot \dot{\theta}_i \end{bmatrix} \begin{bmatrix} \dot{\xi}_i \\ \dot{\theta}_i \end{bmatrix} \right] \quad (6)$$

which gives two chains of 3rd order integrator:

$$\dddot{h}_i = \begin{bmatrix} u_{1i} \\ u_{2i} \end{bmatrix} \quad (7)$$

Where $u_i = \begin{bmatrix} u_{1i} \\ u_{2i} \end{bmatrix}$ is the new input for the triple integrator system and the resulting dynamic compensator is:

$$\begin{aligned} \ddot{\xi}_i &= \cos\theta_i \cdot s_{1i} + \sin\theta_i \cdot s_{2i} \\ F_i &= \dot{\xi}_i \\ \tau_i &= \dot{\omega}_i = \frac{1}{\xi_i} \left(-\sin\theta_i \cdot s_{1i} + \cos\theta_i \cdot s_{2i} \right) \end{aligned} \quad (8)$$

Where:

$$s_{1i} = u_{1i} + 2\sin\theta_i \cdot \omega_i \cdot \dot{\xi}_i + \xi_i \cdot \cos\theta_i \cdot \omega_i^2$$
$$s_{2i} = u_{2i} - 2\cos\theta_i \cdot \omega_i \cdot \dot{\xi}_i + \xi_i \cdot \sin\theta_i \cdot \omega_i^2$$

The original system (1) has five states and the dynamic compensator (8) has one additional state. All these six states have appeared in the linear system (7), thus there is no internal dynamic left.

4 FORMATION MANEUVERS CONTROL

We adopt the behavior-based approach [5] in this paper.

Define error function E_g which describes the total error between the current position of N agents and the desired formation:

$$E_g = \sum_{i=1}^{N} \tilde{h}_i^T K_g \tilde{h}_i$$

where $\tilde{h}_i = h_i - h_i^d \in R^2$, (see Figure 1), $K_g \in R^{2\times 2}$ is positive definite.

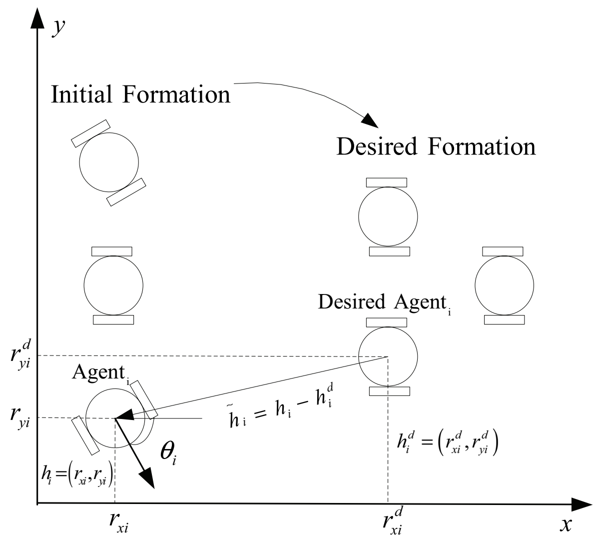

Fig. 1 Multiple Nonholonomic Agents' Formation

Similarly, define E_f as the formation error:

$$E_f = \sum_{j\in N_i} (\tilde{h}_i - \tilde{h}_j)^T K_f (\tilde{h}_i - \tilde{h}_j)$$

where $K_f \in R^{2\times 2}$ is positive definite. Therefore, $E_g = 0$ if and only if the agents achieve the desired formation position; $E_f = 0$ if and only if the agents keep formation while in motion. The total error for the formation maneuvers control is:

$$E = E_g + E_f \tag{9}$$

where K_f, K_g weight the relative importance of formation keeping versus goal convergence. The formation control objective is to drive $E \to 0$ asymptotically.

Toward this end, define the states transformation:

$$X_i = \begin{bmatrix} h_i - h_i^d \\ \dot{h}_i - \dot{h}_i^d \\ \ddot{h}_i - \ddot{h}_i^d \end{bmatrix} = \begin{bmatrix} \tilde{h}_i \\ \dot{\tilde{h}}_i \\ \ddot{\tilde{h}}_i \end{bmatrix},\ i = 1,\cdots,N$$

It's easy to verify that the formation control objective is equivalent to the zero consensus of:

$$\lim_{t\to\infty} X = \vec{\mathbf{1}} \otimes \alpha,\ X = \begin{bmatrix} X_1^T & \cdots & X_N^T \end{bmatrix}^T$$

$$\vec{\mathbf{1}} = \underbrace{[1,\cdots,1]}_{N}^T,\ \alpha = 0^6 \in \mathbb{R}^6$$

We study the problem in state space form:

$$\begin{aligned} \dot{X}_i &= AX_i + Bu_i \\ \tilde{h}_i &= CX_i \\ A &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \otimes I_2,\ B = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \otimes I_2, \\ C &= \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \otimes I_2 \end{aligned} \tag{10}$$

where I_n is the nth order identity matrix and $\otimes$ is the notion of kronecker product. It's obvious that: $\left[\begin{array}{c|c} A & B \\ \hline C & 0 \end{array}\right]$ is controllable and observable. The overall system can be presented as:

$$\begin{aligned} \dot{X} &= (I_N \otimes A) X + (I_N \otimes B) u \\ \tilde{h} &= (I_N \otimes C) X \end{aligned} \tag{11}$$

First, we utilize the consensus algorithm in [11]:

$$u_i = K \sum_{j\in N_i} (x_j - x_i)\ or\ \ u = -(L \otimes K)x$$

Using this state feedback control, (11) is expressed in a closed form as:

$$\dot{X} = \big((I_N \otimes A) - (L \otimes BK)\big) X \tag{12}$$

Lemma 1[10] Assume that $\Lambda_e + \Lambda_e^T > 0$, the communication network structure of (11) is strongly connected and (11) is also controllable and observable. Then the states of (12) achieve consensus value:

$$\alpha = N^{1/2} \exp(At)(l_1^T \otimes I_N) X(0)$$

Only if there is a positive definite matrix P and gain matrix K such that:

$$A^T P + PA - \lambda_1(\Lambda_e \Lambda_e^T) PBB^T P < 0$$

$$K = \frac{\lambda_{N-1}(\Lambda_e \Lambda_e^T)}{\lambda_1(\Lambda_e + \Lambda_e^T)} B^T P \qquad \text{(Digraph case)}$$

$$K = \frac{1}{2}\lambda_N(L) B^T P \qquad \text{(Undirected case)}$$

where $\Lambda = \begin{bmatrix} 0 & 0 \\ 0 & \Lambda_e \end{bmatrix} = SLS^{-1}$, S is any regular matrix which first row is $N^{-1/2}\vec{\mathbf{1}}^T$, l_1 is the left-eigenvector corresponding to zero-eigenvalue of L satisfying $l_1^T N^{-1/2} \vec{\mathbf{1}} = 1$.

As pointed in [10] that when using this method in digraph case, the states' non-zero consensus value brings formation steady error and oscillatory in agents' relative motion. This problem can be solved by introducing a virtual zero-state agent to drive the non-zero consensus to zero. Here, we propose an inter-agent damping injection technique based on passivity method [12, 13]. Since the map from $u_i \to \dot{\tilde{h}}_i$ is passive, so the feedback $\dot{\tilde{h}}_i \to u_i$ need to be strictly passive. We construct a strictly positive real linear system $C(s)$ from $\dot{\tilde{h}}_i$ to u_i :

$$\dot{\chi}_i = A_p \chi_i + \dot{\tilde{h}}_i$$
$$z_i = C_p \chi_i$$

From KYP lemma [14], there exist positive definite matrices P and Q such that:

$$A_p^T P + PA_p = -Q, P = C_p^T \tag{13}$$

So the map $\tilde{h}_i \to u_i$ is:

$$sC(s) = \left[\begin{array}{c|c} A_p & I \\ \hline PA_p & P \end{array}\right]$$

Then the augmented state space representation of each agent is:

$$\begin{bmatrix} \dot{X}_i \\ \dot{\chi}_i \end{bmatrix} = \begin{bmatrix} A & -BK \\ C & A_p \end{bmatrix} \begin{bmatrix} X_i \\ \chi_i \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u_i$$
$$\tilde{h}_i = \begin{bmatrix} C & 0 \end{bmatrix} \begin{bmatrix} X_i \\ \chi_i \end{bmatrix}$$

Using Lemma 1 again, we give the consensus control law with inter-agent damping injection:

$$\dot{\chi}_i = A_p \chi_i + \tilde{h}_i$$
$$u_i = -K_g \cdot \tilde{h}_i - D \cdot \dot{\tilde{h}}_i - A_c \ddot{\tilde{h}}_i - K_f \sum_{j \in N_i} \left(\tilde{h}_i - \tilde{h}_j \right)$$
$$-P \cdot \tilde{h}_i - PA_p \cdot \chi_i \tag{14}$$
$$A_c = k_1 \otimes I_2, D = k_2 \otimes I_2, K_g = k_3 \otimes I_2$$
$$k_i > 0, i = 1, 2, 3$$

Where $s^3 + k_1 s^2 + k_2 s + k_3 = 0$ satisfies Hurwitz criterion and P satisfies (13).

Remark 1: Note the presence of the agent's velocity and acceleration in the control law. Since this information is required for dynamic feedback linearization, we assume that it is available to the controller.

Remark 2: The state χ_i of dynamic controller represents, in a sense, the estimate of relative velocities between neighbors. It serves as inter-agent injected damping to eliminate the relative motion oscillation and formation steady error.

Theorem 1: The error function (9) converges to zero asymptotically, if the multi-agents system of (1) is subject to control strategy (8) and (14).

Proof: (14) can be written in a collective form:

$$\dot{\chi} = \left(I_N \otimes A_p \right) \chi + \tilde{h}$$
$$u = -\left[\left(I_N \otimes K_g \right) + \left(L \otimes K_f \right) + \left(I_N \otimes P \right) \right] \cdot \tilde{h}$$
$$-\left(I_N \otimes D \right) \dot{\tilde{h}} - \left(I_N \otimes A_c \right) \ddot{\tilde{h}} - \left(I_N \otimes P \right) \cdot \left(I_N \otimes A_p \right) \chi \tag{15}$$

Consider the Lyapunov function candidate:

$$V = \frac{1}{2} \tilde{h}^T \left(I_N \otimes K_g + L \otimes K_f \right) \tilde{h} + \frac{1}{2} \dot{\tilde{h}}^T \dot{\tilde{h}} + \frac{1}{2} \ddot{\tilde{h}}^T \ddot{\tilde{h}} + \frac{1}{2} \dot{\chi}^T \left(I_N \otimes P \right) \dot{\chi} \tag{16}$$

The time derivative of V is given by

$$\dot{V} = \dot{h}^T \left[\left(I_N \otimes K_g + L \otimes K_f \right) \tilde{h} + \ddot{\tilde{h}} \right] + \ddot{\tilde{h}}^T \cdot u + \frac{1}{2} \ddot{\chi}^T \left(I_N \otimes P \right) \dot{\chi} + \frac{1}{2} \dot{\chi}^T \left(I_N \otimes P \right) \ddot{\chi} \tag{17}$$

where: $\ddot{\chi} = \left(I_N \otimes A_p \right) \dot{\chi} + \dot{\tilde{h}}$,using the control law (15) and the fact that:

$$\left(I_N \otimes P \right) \left(I_N \otimes A_p \right) + \left(I_N \otimes A_p \right)^T \left(I_N \otimes P \right) = -\left(I_N \otimes Q \right)$$

we obtain:

$$\dot{V} = -\ddot{\tilde{h}}^T A_c \ddot{\tilde{h}} - \dot{\tilde{h}}^T D \dot{\tilde{h}} - \dot{\chi}^T \left(I_N \otimes Q \right) \dot{\chi} \tag{18}$$

which is negative semi-definite. Let:

$$\Omega = \left\{ \left(\tilde{h}, \dot{\tilde{h}}, \ddot{\tilde{h}}, \dot{\chi} \right), \dot{V} = 0 \right\}$$

and $\Omega -$ be the largest invariant set in Ω. On $\Omega -$, we have $u = 0$, therefore, (15) implies that the following two equalities hold:

$$\left(I_N \otimes A_p \right) \chi + \tilde{h} = 0$$
$$\left[\left(I_N \otimes K_g \right) + \left(L \otimes K_f \right) + \left(I_N \otimes P \right) \right] \tilde{h} + \left(I_N \otimes P \right) \left(I_N \otimes A_p \right) \chi = 0$$

Combing these two equations gives:

$$\left[\left(I_N \otimes K_g \right) + \left(L \otimes K_f \right) \right] \tilde{h} = 0 \tag{19}$$

From which asymptotic stability follows by application of LaSalle's invariance principle.

5 SIMULATION

We consider a nonholonomic four-agent formation maneuver problem where each agent is a two-wheeled vehicle governed by the node's dynamical model (1). The inter-agent communication digraph is fixed as shown in Figure 2:

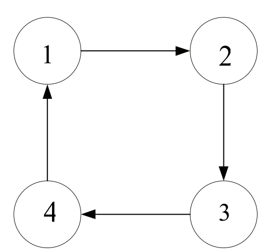

Fig. 2 Inter-agent communication digraph

The initial posture $\left(r_{xi}, r_{yi}, \theta_i \right)$ of the agents are: (-2,2,0), (-2,1,0), (-2,-1,0), (-2,-2,0). We plan the motion first to format a tight formation: (0,0.5,0), (0.5,0.25,0), (0.5,-0.25,0), (0,-0.5,0); then move along the x-axis at the speed of 0.25m/s while maintaining the tight formation. The dynamic controller's initial conditions are chosen as:

$$v_i(0) = v_{\max} = 0.3\text{m/s},\ \xi_i(0) = v(0)$$

$$\dot{\xi}_i(0) = F_{\max} = 0.1\text{m}^2/\text{s}$$

The controller's parameters are chosen as:

$$k_1 = 2, k_2 = 7, k_3 = 2.$$

To avoid singularity of the added dynamics, i.e., $\xi = 0$, in (3). [9] proposes a sufficient condition on the control gains so as to guarantee the correct relative rates of exponential convergence for the state variables, in such a way that v does not go to zero in finite time and ω is always bounded. But here, we adopt a straightforward solution that consists in resetting the state ξ of the compensator whenever its value falls below a given threshold.

An immediate consequence of v, ω 's exponential convergence to zero is that the orientation θ also converges to zero exponentially. The simulation results are as in Figure. 3 and Figure. 4:

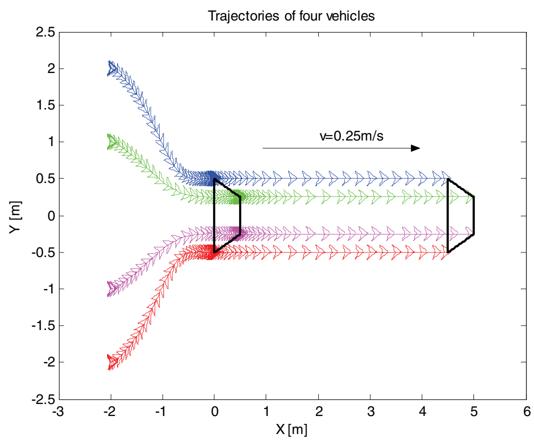

Fig. 3 Trajectories of four vehicles

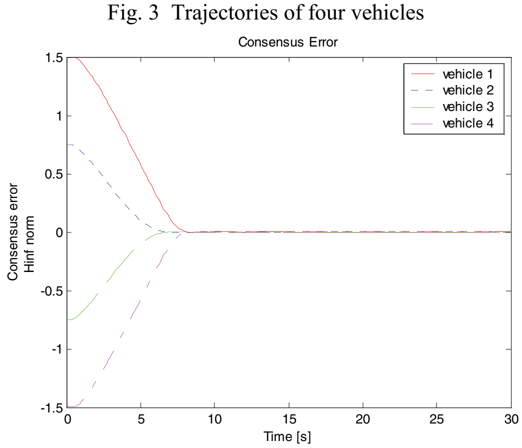

Fig. 4 Consensus error

In reality, the vehicle's velocities have been imposed with bounds constraints:

$$|v| \le v_{\max} = 0.3\text{m/s}, \quad |\omega| \le \omega_{\max} = 0.5\text{rad/s}$$

In view of these saturations, we adopt the method in [9] to perform a velocity scaling so as to preserve the curvature radius corresponding to the nominal velocities v , ω . The actual velocity inputs are shown in Figure. 5:

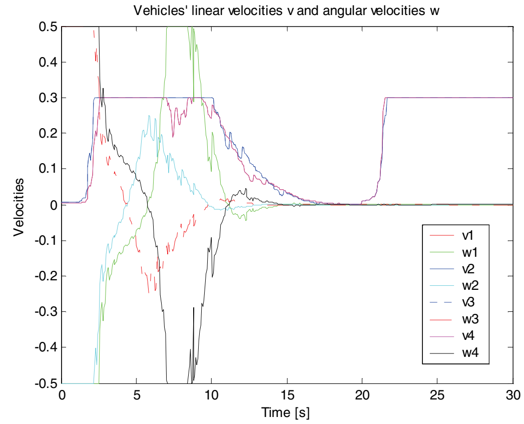

Fig. 5 Vehicles' linear and angular velocities

6 CONCLUSION

In this paper, a formation control law using passivity techniques is proposed for the formation maneuver problem of multiple agents with nonholonomic constraints. We first construct a dynamic compensator to full-state linearize each agent's dynamical model. Second, we obtain a decentralized discontinuous consensus law with exponential convergence rate based on linearization. Third, we inject the consensus law with inter-agent damping to eliminate the relative motion oscillatory and steady formation error. Finally, we prove the stability of the overall system via Lyapunov method. The proposed algorithm is applied to a multi-vehicles formation maneuver simulation to demonstrate the effectiveness of the strategy. The meaningful future researches may include robust formation control design with respect to model uncertainties and communication delays.

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