Abstract
In this paper, we study cooperative control problems with trajectory tracking and reconfigurable formation for a multi-vehicle system expressed as a first-order system. Specifically, we describe a problem that cooperatively controlled vehicles keep geometric configuration among the multiple vehicles while the vehicles are moving in formation. In other words, each of the vehicles must change its position individually to keep the geometric configuration while the vehicle is moved by a cooperative control. In order to achieve this objective, we basically extend our previous result which was a control algorithm to surround a moving target by a group of vehicles cooperatively. The algorithm was based on a consensus algorithm which was cooperative control. In addition, we apply a leader-follower structure to our cooperative algorithm so that a leader can individually provide each of the followers with commands. Finally, the proposed approach is validated by some simulations.

Key words: Formation, Consensus, Cooperative Control, Leader-Follower

1. Introduction
In recent years, problems of cooperative control for a multi-agent system have been attracting a lot of attention from many researchers\(^{(1)}\). These problems are expected to be applied to actual vehicles such as UAVs\(^{(2)}\), artificial satellites and autonomous mobile observation robots as well as sensor networks.

There is a possibility that a multi-agent system can perform tasks more efficiently than a single highly-functional agent does. Let us consider some examples of this efficiency. First, the multi-agent system carries out tasks more quickly than the single agent does. Second, the multi-agent system has much better fault-tolerance than the single agent does. For example, when an agent breaks down and the breakdown results in an inability to go on with tasks, there is a possibility that a group of healthy agents fulfills the tasks with no change in the original objectives using the surviving healthy agents. The last, compared to the single agent, the multi-agent system has a cost advantage. Now, suppose two agents: one has highly sophisticated function but is too costly, the other has only limited function and deliver only poor performance but is affordable. The cooperative system composed of a group of the latter agents performs tasks as similarly as or better than the former agent does.

Now let us consider what is essential to carry out some tasks by a multi-agent system cooperatively. A network is crucial for a multi-vehicle system because it is necessary for agents to exchange information with one another. As you look at recent information and communication technology, it has been progressing rapidly in recent years. Technologies such as networks and computers are now making remarkable progress, and a multi-agent system is expected to be applied to an actual system.

Agreement problems of formation and consensus are particularly important to cooperative control problems of a multi-agent system because setting the states such as a position and velocity at the same value is often useful for actual problems. Hence, the formation control
problems have been widely studied. These problems are classified as centralized control and decentralized control. The main feature of the former is that a leader calculates control inputs for every follower collecting information from the followers. On the other hand, the main feature of the latter is that each of the followers calculates its control inputs by itself exchanging information. This means that the former largely depends on a highly reliable network.

Most studies focus on a decentralized approach using graph theory to express a network structure of a multi-agent system. A network is not always continuously or statically connected to each other. For this reason, cooperative control problems concerning dynamical networks or communication delays have also been studied by many researchers. They show that the stability is still maintained in case of dynamical changes of a network or communication delays.

We have also been focusing on formation control problems. We studied a consensus problem of a multi-vehicle system which was expressed as a linear system, and studied a problem with surrounding a moving target object by a group of vehicles cooperatively. In Ref. (15), we proposed a control algorithm for multiple vehicles to surround a moving columnar target object cooperatively without depending on a network structure. However in this method, geometric configuration of the vehicles with respect to a fixed system of coordinates is still fixed even when the target object changes the traveling direction because both the target object and the vehicles have a cylindrical shape, that is, neither of them have directivity. For this reason, when we apply this algorithm with no change to formation control problems of vehicles which have directivity, formation will not be achieved because the geometric configuration of vehicles with respect to a fixed system of coordinates is still fixed even when a leader moves changing its traveling direction as shown in Fig. 1. Therefore, based on our algorithm in Ref. (15), and individually providing information such as target positions for each of the followers using a leader-follower structure, we propose a control algorithm to move in formation and also to arbitrarily change the geometric configuration.

An outline of this paper is as follows. In section 2, a multi-vehicle system and a control objective are defined. In section 3, we propose a control algorithm to achieve the control objective and we prove a theorem. Section 4 presents simulation results to validate the proposed approach, and finally, concluding remarks are stated in Section 5.

2. Problem Statement

2.1. Modeling a Multi-vehicle System

Suppose that there are $N$ vehicles which have the same motion characteristics, and they move on a 2D plane. Also each vehicle is expressed as a first-order dynamical model given by

$$\dot{r}_i = u_i, \quad (i = 1, 2, \cdots, N),$$  

where $r_i \in \mathbb{R}^2$ is a position of the vehicle $i$, and $u_i \in \mathbb{R}^2$ is a control input of the vehicle $i$.

A multi-vehicle system is modeled as a group of dynamical system which exchanges information with one another. To describe this network structure composed of the multiple vehicles, we use graph theory.

We use a graph $G = (V, A)$ to model the information interaction among vehicles. $V = \{v_1, v_2, \cdots, v_N\}$ is a set of nodes, and $A \subseteq V \times V$ is a set of edges. The edge $(v_i, v_j)$ in the edge set of the graph denotes that there is a network path from the vehicle $i$ to the vehicle $j$. This means that the vehicle $j$ can obtain information from the vehicle $i$.

There are two types of graphs. An undirected graph is one where both the node $i$ and the node $j$ can obtain information from each other. On the other hand, a digraph is one where the node $i$ can obtain information from the node $j$, but can not obtain in the reverse direction. One of the important characteristics of a graph is its connectivity. A graph is defined as connected if there is a network path between the node $i$ and the node $j$ for every pair of the different vertices. This means that all vehicles can get information from each other through a network.
In addition, a graph is defined balanced if a number of communication links arriving at a node is equal to a number of communication links leaving the node.

Let $\mathcal{A} \in \mathbb{R}^{N \times N}$, $\mathcal{D} \in \mathbb{R}^{N \times N}$ and $\mathcal{L} \in \mathbb{R}^{N \times N}$ be an adjacency matrix, a degree matrix and a graph Laplacian matrix related to a graph $\mathcal{G}$, respectively. The component of the adjacency matrix $\mathcal{A} = [a_{ij}]$ is given by

$$a_{ij} = \begin{cases} 1, & \text{for } (v_j, v_i) \in \mathcal{A} \\ 0, & \text{for otherwise} \end{cases} \tag{2}$$

This means that if the vehicle $i$ is obtaining information from the vehicle $j$ through a network, $a_{ij}$ is set to one, otherwise $a_{ij}$ is set to zero.

The degree matrix $\mathcal{D}$ is an in-degree matrix given by

$$\mathcal{D} = \text{diag}(\text{deg}(v_1), \text{deg}(v_2), \cdots, \text{deg}(v_N)) \tag{3}$$

where $\text{deg}(v_i)$ is a number of communication links arriving at the node $v_i$.

The graph Laplacian matrix is defined as

$$\mathcal{L} = \mathcal{D} - \mathcal{A} \tag{4}$$

The graph Laplacian $\mathcal{L}$ has the following properties: if a graph is connected, $\mathcal{L}$ has a single eigenvalue at zero, and all nonzero eigenvalues of the graph Laplacian have positive real part.

2.2. Control Objective

In this paper, a control objective is defined as follows. $N$ vehicles follow their leader, and both the vehicles and the leader move in formation as shown in Fig. 2. In addition, each of the vehicles has an ability to arbitrarily change the geometric configuration of formation. Note that both an actual and a virtual leader are acceptable. Also, vehicles are called as followers since the vehicles follow their leader.

Specifically, each follower $r_i(t)$ will converge to a time-variant target position $r_L(t) + d_i(t)$. The time-variant target position for a desired geometric configuration of formation is commanded by a leader. $r_i$ is a position of the follower $i$, $d_i \in \mathbb{R}^2$ is a relative position between the follower $i$ and the leader, and $r_L \in \mathbb{R}^2$ is a position of the leader as shown in Fig. 3.

To achieve this control objective, we make a set of assumptions as follows:

**Assumption 1** Every follower must be connected from a leader, but all of the followers are not necessarily directly connected from the leader.

**Assumption 2** The network between the followers is undirected graph.

**Assumption 3** The network paths from the followers to the leader do not exist.
3. Proposed Approach

In this section, we propose a controller to achieve the control objective as mentioned in section 2.2.

We have already proposed a control algorithm to surround a moving columnar target object by a group of columnar vehicles cooperatively in Ref. (15). When we apply this control algorithm to achieve the control objective as it is, though every vehicle tends to follow their leader, geometric configuration of the vehicles with respect to a fixed system of coordinates remains fixed as shown in Fig. 1. This is because the algorithm in Ref. (15) was designed for both a cylindrical target object and cylindrical vehicles, that is, directivity was not considered in the algorithm in Ref. (15).

Based on the control algorithm in Ref. (15) to achieve the control objective, we propose a control algorithm as follows.

The control law which should be applied to the follower $i$ is given by

$$u_i = \frac{1}{N+1} \sum_{j=1}^{N+1} a_{ij} \left[ -k(\hat{r}_i - \hat{r}_j) + \dot{r}_j + (d_i - d_j) \right], \quad (i = 1, 2, \ldots, N),$$

(5)

$$a_{ij} = \begin{cases} 1, & \text{for the vehicle } i \text{ connected from the vehicle } j \\ 0, & \text{otherwise} \end{cases},$$

(6)

$$\hat{r}_i = r_i - d_i, \quad (i = 1, \ldots, N + 1),$$

(7)

where $k \in \mathbb{R}$ is a positive control gain, the subscript $N + 1$ denotes a leader, and $\hat{r}_i$ is defined as a vector subtracting a relative target position $d_i$ between the follower $i$ and the leader from
a position of the follower $i$. Note that $a_{ij}$ is a value which indicates whether the follower $i$ obtains information from the follower $j$ or not. If obtaining some information, $a_{ij} = 1$, otherwise $a_{ij} = 0$.

We apply a leader-follower structure so that a leader individually provides each of the followers with the time-variant relative positions $d_i$, for all $i = 1, \cdots, N$. The leader commands the information to give each of the followers the target positions for a desired geometric configuration of formation. In other words, the commands from the leader will lead to changes in the geometric configuration of formation.

For the control input and the multi-vehicle system composed of the leader and the followers, a following theorem concerning desired convergence is derived.

**Theorem 1** Suppose that a multi-vehicle system composed of $N(\geq 1)$ followers expressed as (1) and a leader. When the control protocol (5) is applied to each of the followers, then each of the followers converges to a time-variant targeted position for a desired geometric configuration of formation if the requirements of the assumption 1,2 and 3 are satisfied.

**Proof.** Applying the control protocol (5) to the follower $i$ expressed as (1), we get

$$\dot{r}_i = \frac{1}{N+1} \sum_{j=1}^{N+1} a_{ij} \left[ -k(\hat{r}_i - \hat{r}_j) + r_i + (d_i - d_j) \right], \quad (i = 1, 2, \cdots, N), \quad (8)$$

and get

$$\sum_{j=1}^{N+1} a_{ij} (\dot{r}_i - r_j) = \sum_{j=1}^{N+1} a_{ij} (\hat{r}_i - r_j) + k(r_i - r_j) + (d_i - d_j), \quad (i = 1, 2, \cdots, N), \quad (9)$$

Note that $r_i$, $d_i$, and $\dot{d}_i$ are two-dimensional. (9) is rewritten in a matrix-vector form as

$$(\mathcal{L} \otimes I_2) \hat{\mathbf{r}} = -k(\mathcal{L} \otimes I_2) \hat{\mathbf{r}} + (\mathcal{L} \otimes I_2) \hat{\mathbf{d}}, \quad (10)$$

where $\mathcal{L} \in \mathbb{R}^{(N+1) \times (N+1)}$ is the graph Laplacian of the multi-vehicle system defined as (11), $\otimes$ is the kronecker product, $I_2$ is a two-dimensional unit matrix, $\hat{\mathbf{r}} = [\dot{r}_1^T \ r_2^T \ \cdots \ r_N^T \ \dot{r}_{N+1}^T]^T \in \mathbb{R}^{2(N+1)}$, and $\hat{\mathbf{d}} = [\dot{d}_1^T \ d_2^T \ \cdots \ d_N^T \ \dot{d}_{N+1}^T]^T \in \mathbb{R}^{2(N+1)}$.

Note that $d_{N+1} = 0$, because the subscript $N + 1$ denotes a leader and $d_i$ is a relative position between the vehicle $i$ and the leader. Also, the following identities concerning the rows of the matrix $\mathcal{L}$ always hold.

$$a_{N+1} a_{ij} = \sum_{j=1}^{N+1} a_{ij} - a_{i1} - a_{i2} - \cdots - a_{iN}, \quad a_{ii} = 0, \quad (i = 1, 2, \cdots, N), \quad (12)$$

and get

$$\begin{bmatrix}
\sum_{j=1}^{N+1} a_{1j} & -a_{12} & \cdots & -a_{1N} \\
-a_{21} & \sum_{j=1}^{N+1} a_{2j} & \cdots & -a_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
-a_{N1} & -a_{N2} & \cdots & \sum_{j=1}^{N+1} a_{Nj} \\
0 & 0 & \cdots & 0
\end{bmatrix} \begin{bmatrix}
\dot{r}_{N+1} \\
\dot{r}_{N+2} \\
\vdots \\
\dot{r}_{N(N+1)}
\end{bmatrix} = \begin{bmatrix}
\sum_{j=1}^{N+1} a_{1j} & -a_{12} & \cdots & -a_{1N} \\
-a_{21} & \sum_{j=1}^{N+1} a_{2j} & \cdots & -a_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
-a_{N1} & -a_{N2} & \cdots & \sum_{j=1}^{N+1} a_{Nj}
\end{bmatrix} \begin{bmatrix}
\dot{r}_L \\
\dot{r}_L \\
\vdots \\
\dot{r}_L
\end{bmatrix}, \quad (13)$$
Now, using $d_{N+1} = 0$ and (13), we separate (11) for the leader and the followers as
\[(M \otimes I_2)(\dot{r} + kr) = (M \otimes I_2)(\dot{r}_{N+1} + k\tilde{r}_{N+1} + \dot{d} + kd), \tag{14}\]
and get
\[(M \otimes I_2)(\dot{r} + kr - \dot{r}_{N+1} - k\tilde{r}_{N+1} - \dot{d} - kd) = 0, \tag{15}\]
where $M \in \mathbb{R}^{N \times N}$ is defined as (16), $r = [r_1^T \ r_2^T \ \ldots \ r_N^T]^T \in \mathbb{R}^{2N}$, $\dot{r}_{N+1} = [\dot{r}_1^T \ \dot{r}_2^T \ \ldots \ \dot{r}_N^T]^T \in \mathbb{R}^{2N}$, and $d = [d_1^T \ d_2^T \ \ldots \ d_N^T]^T \in \mathbb{R}^{2N}$. Note that the matrix $M$ is similar to the graph Laplacian of the multi-vehicle system, but not equal to the graph Laplacian.

\[
M = \begin{bmatrix}
\sum_{j=1}^{N+1} a_{1j} & -a_{12} & \ldots & -a_{1N} \\
-a_{21} & \sum_{j=1}^{N+1} a_{2j} & \ldots & -a_{2N} \\
\vdots & \vdots & \ddots & \vdots \\
-a_{N1} & -a_{N2} & \ldots & \sum_{j=1}^{N+1} a_{Nj}
\end{bmatrix} \tag{16}
\]

Now, the solution of (15) changes depending on whether the inverse matrix of the matrix $M$ exists or not. To check this problem, we examine whether the matrix $M$ is positive definite or not. To verify this, we check whether a quadratic form of the matrix $M$ is positive or not.

When the requirement of the assumption 2 is satisfied, the matrix $M$ is symmetric. Using this symmetric property, the quadratic form is described as
\[x^T M x = \frac{1}{2} \sum_{i=1}^{N} \sum_{j=1}^{N+1} a_{ij}(x_i - x_j)^2 + \sum_{i=1}^{N} a_{i(N+1)} x_i^2. \tag{17}\]
Here, the first term of (17) is zero when $x_i = x_j \neq 0$. On the other hand, when the requirement of the assumption 1 is satisfied, the second term of (17) is always positive for all $x_i \neq 0$ because one or more $a_{i(N+1)}$s are one. This shows that the quadratic form (17) is positive for all $x_i \neq 0$ when the requirements of the assumption 1 and 2 are satisfied. Consequently, the matrix $M$ is positive definite, that is, the inverse matrix of the matrix $M$ exists. Therefore, we get next equation (18) from (15).
\[\dot{r} + kr - \dot{r}_{N+1} - k\tilde{r}_{N+1} - \dot{d} - kd = 0. \tag{18}\]

Hence, we get a general solution of the differential equation (18).
\[r(t) = (r(0) - \tilde{r}(0)) e^{-kt} + \tilde{r}(t)_{N+1} + d(t), \tag{19}\]
where $r(0) = [r(0)_1^T \ r(0)_2^T \ \ldots \ r(0)_N^T]^T \in \mathbb{R}^{2N}$ is initial positions of the followers. Also, $\tilde{r}(0)_{N+1} = [\tilde{r}_1(0)^T \ \tilde{r}_2(0)^T \ \ldots \ \tilde{r}_N(0)^T]^T$ and $d(0) = [d_1(0)^T \ d_2(0)^T \ \ldots \ d_N(0)^T]^T$ are initial commands of a leader. Note that a leader individually provides both its own position $r_{N+1}$ and relative positions $d$ for each of the followers.

The first term of (19) will converge to zero, if and only if $k > 0$.
\[
\lim_{t \to \infty} (r(0) - \tilde{r}(0)) e^{-kt} = 0. \tag{20}\]
Hence, we can get
\[
\begin{align*}
    r_1 & \to r_L + d_1 \\
    r_2 & \to r_L + d_2 \\
    & \vdots \\
    r_N & \to r_L + d_N
\end{align*}
\] (21)

Therefore, it is proved that the control objective is asymptotically achieved when the control protocol (5) with a positive controller gain is applied to the followers.

**Corollary 1** Suppose that the control protocol (5) with a positive controller gain is applied to the multi-vehicle system. Then, for any network structure satisfying the requirements of assumption 1,2 and 3, each of the followers converges to a time-variant targeted position for a desired geometric configuration of formation, and convergence speed does not depend on the network.

**Proof.** As long as every assumption is satisfied, we can get (18) which does not depend on the matrix $M$ representing a network structure. This means that convergence does not depend on the network but only depends on the controller gain $k$.

## 4. Simulation Results

In this section, we present some simulation results to validate the performance of the proposed formation control algorithm.

### 4.1. Simulation Setup

First, we consider a case where a group of three followers and a leader is trying to move in formation. Simulations are carried out for four cases as shown in Table 1.

<table>
<thead>
<tr>
<th>Conditions of numerical simulations</th>
<th>C-I</th>
<th>C-II</th>
<th>C-III</th>
<th>C-IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controller Gain ($k$)</td>
<td>5</td>
<td>5</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Network Structure</td>
<td>NET1</td>
<td>NET2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leader’s Path</td>
<td>LEAD1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Formation Configuration</td>
<td>FOM1</td>
<td>FOM2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.1.1. Network Structure

We consider two types of network structures. As shown in Fig. 4, every follower can get information directly from their leader on the network NET1. On the other hand, as shown in Fig. 5, only the first follower can get information directly from their leader on the network NET2. The other followers get information from their leader through the others indirectly.

![Fig. 4 A network structure [NET1]](image)

### 4.1.2. Leader’s Path

We consider only one leader’s path, which is named LEAD1. A leader moves in an elliptical orbit whose major axis is 10 (m), minor axis is 8 (m), and cycle is 20 (s). Also, the initial position of the leader is [0 0] (m).
4.1.3. Formation Configuration  We consider two types of configuration. The first configuration, which is named FOM1, is as follows: each follower keeps a certain distance from the leader, and also keeps a certain azimuth from the traveling direction of the leader. Note that the traveling direction of the leader is defined as a unit velocity vector \( \dot{r}_{N+1} \). We describe this information as a relative position \( d_i \) between the follower \( i \) and the leader. This is formulated as

\[
\begin{align*}
  d_i &= \frac{|d_i|}{|r_{N+1}|} R(\theta_i) \dot{r}_{N+1} & (|r_{N+1}| \geq 0.1), \\
  d_i &= |d_i| R(\theta_i) r_0 & (|r_{N+1}| < 0.1),
\end{align*}
\]  

(22)

where as shown in Fig. 6, \( |d_i| \) is a relative distance between the follower \( i \) and the leader, \( \theta_i \) is an azimuth which goes counterclockwise from the unit velocity vector of the leader, and \( r_0 = [1 \ 1]^T / \sqrt{2} \). Also, \( R(\theta_i) \) is a two-dimensional rotation matrix given by

\[
R(\theta_i) = \begin{bmatrix} \cos(\theta_i) & -\sin(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i) \end{bmatrix}.
\]  

(23)

Note that the relative position \( d_i \) is set to a certain fixed point which does not depend on the leader’s traveling direction while the velocity is slower than 0.1 (m/s).

The second configuration, which is named FOM2, is as follows: each follower changes a distance from the leader periodically while keeping a certain azimuth from the traveling direction of the leader. We describe this information as a relative position \( d_i \) between the follower \( i \) and the leader. This is formulated as

\[
\begin{align*}
  d_i &= \frac{|d_i| + \sin(2\pi/T_{FOM})}{|r_{N+1}|} R(\theta_i) \dot{r}_{N+1} & (|r_{N+1}| \geq 0.1), \\
  d_i &= |d_i| R(\theta_i) r_0 & (|r_{N+1}| < 0.1),
\end{align*}
\]  

(24)

where \( T_{FOM} \) is a cycle of the relative distance change, which is \( T_{FOM} = 4 \) (s). The values of \( |d_i| \) and \( \theta_i \) are shown in Table 2.
Table 2 Parameters for a target position

<table>
<thead>
<tr>
<th>Follower</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Distance $d_i$(m)</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Azimuth $\theta_i$(deg)</td>
<td>0</td>
<td>90</td>
<td>270</td>
</tr>
</tbody>
</table>

4.2. Simulation Results

We show the results of the simulation which is carried out for 16 (s) under the cases shown in Table 1. Fig. 7 and Fig. 8 show the results of the case C-I, Fig. 9 and Fig. 10 show the results of the case C-II, Fig. 11 and Fig. 12 show the results of the case C-III, and Fig. 13 and Fig. 14 show the results of the case C-IV.

Figs. 7, 9, 11, and 13 show the trajectories and the positions every 2 seconds. In addition, Figs. 8, 10, 12, and 14 show the difference from the target position.

Here, let us examine the results. First, comparing the results of the case C-I with C-II, we can see that the control objective is achieved even when every follower does not keep getting the information directly from their leader, and the convergence speed does not depend on the network structure. Second, comparing the results of the case C-II with C-III, we can see that the convergence speed in the case of C-II is faster than the speed in the case of C-III. Hence the convergence speed depends only on the control gain $k$. The last, from the results of case IV, we can see that the vehicles periodically change the geometric configuration while the vehicles are cooperatively move in formation exchanging information with one another.

![Fig. 7 Simulation result (trajectory) [C-I]](image1)

![Fig. 8 Simulation result (time response of difference from the target position) [C-I]](image2)

![Fig. 9 Simulation result (trajectory) [C-II]](image3)

![Fig. 10 Simulation result (time response of difference from the target position) [C-II]](image4)
5. Conclusions and Future Work

We showed that a multi-vehicle system can be modeled using graph theory, then proposed a control algorithm to change geometric configuration among the vehicles arbitrarily while the cooperatively controlled vehicles are moving in formation. We advanced the control protocol, which was based on consensus, to surround a moving cylindrical target object cooperatively and applied a leader-follower structure so that a leader can individually provide the information of a target position for each of the vehicles. To achieve this control objective, the network composed of the leader and the vehicles must satisfy the requirements that every vehicle must be connected from the leader and the network between the vehicles is bidirectional. For any network structure satisfying these requirements, we showed the control objective was asymptotically achieved and convergence speed did not depend on the network.

Extensive simulation results showed that the proposed algorithm was validated and effective for controlling geometric configuration of formation among a group of the vehicles and the leader.

In this paper, we assumed that a vehicle was a first-order model, so studying and designing a controller for a more general model which has dynamics and kinematics will be a challenging problem for future work in this area.

References

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