

Time-varying Formation Tracking with Collision Avoidance for Multi-agent Systems^{*}

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Abstract: This paper studies the collision avoidance problem in the time-varying formation tracking control for multi-agent systems. The proposed control strategy is decentralized, since agents have no global knowledge of the goal to achieve, knowing only the position and velocity of some agents. This control strategy allows a set of mobile agents to track a predetermined trajectory while they achieve a time-varying formation. For the collision avoidance, we add a repulsive vector field of the unstable focus type to the time-varying formation tracking control law. A leader-followers scheme is employed, using formation graphs to represent interactions between agents. The results are presented for the front points of differential-drive mobile robots. The theoretical results are verified by numerical simulation.

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Keywords: Multi-agent systems, time-varying formation, collision avoidance, differential-drive mobile robots, repulsive vector fields.

1. INTRODUCTION

Multi-agent Systems are conceived as bundles of multiple autonomous robots coordinated to accomplish cooperative tasks. In recent years, the study of multi-agent systems has gained special interest, because multiple agents can solve tasks working cooperatively; making them more reliable, faster and cheaper than it is possible with a single agent Cao et al. (1997).

The main applications of multi-agent systems include transport and manipulation of objects, localization, exploration and motion coordination Arai et al. (2002); Cao et al. (1997). The main idea of motion coordination is the strategic navigation of a group of agents. One of the main areas of research in the motion coordination is the formation tracking problem, where the goal is to track a preestablished trajectory while the agents maintain a desired pattern defined by relative position vectors.

The time-varying formation control can be applied as the solution to complex motion coordination problems and some examples can be found in Briñón Arranz et al. (2014); González-Sierra and Aranda-Bricaire (2013); Peñaloza Mendoza et al. (2011); Rendón-Benitez et al. (2012). In our case, the time-varying formation allows trajectory tracking with formations oriented to the heading angle of a leader robot, as well as changes in the physical dimensions of the formations. More specifically, the time-varying formation is composed of a predefined static formation which is transformed by a rotation matrix, that depends on the orientation of a specific leader robot, and a scaling matrix, that depends on a factor which varies with respect to time.

This time-varying formation allows the group of agents to behave as a rigid body which can be translated, rotated and scaled in the plane.

Another ubiquitous problem in all areas of motion coordination is the possible collision between agents when they try to achieve a desired position into a formation or during the trajectory tracking. In the literature, we can find different methods to avoid collisions. In Qianwei et al. (2003) a mechanism for collision avoidance based on traffic control type is presented. In De Gennaro and Jadbabaie (2006); Dimarogonas and Kyriakopoulos (2006); Dimarogonas et al. (2006) navigation functions and artificial potential functions are used to avoid collisions between agents. These non collision strategies are developed based on a combination of attractive potential functions (APF) and repulsive potential functions (RPF). Works Hernández-Martínez and Aranda-Bricaire (2009, 2013); Loizou et al. (2003); Yao et al. (2006) address the formation control problem without collisions using discontinuous vector fields.

The purpose of this paper is to design a decentralized control strategy for multi-agent systems that allows the trajectory tracking with a time-varying formation. In our control strategy the collision avoidance between agents is also considered and it is based on previous works Flores-Resendiz and Aranda-Bricaire (2014); Flores-Resendiz et al. (2015). We use bounded control strategies based on sigmoid functions adding a repulsive vector field.

To model the interaction topology between agents of a system we use formation graphs, where each agent is represented by a vertex and the sharing of information between agents is represented by an edge.

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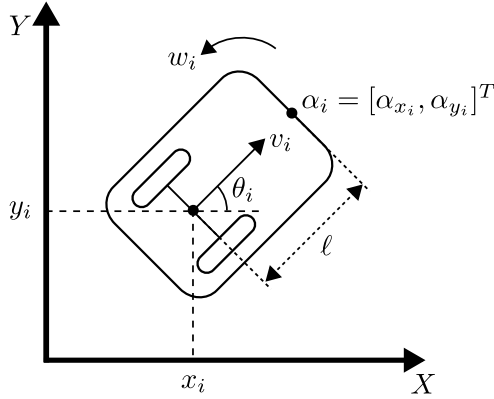


Fig. 1. Scheme of the differential-drive mobile robot.

2. PRELIMINARIES

2.1 Differential-drive Mobile Robots

Let $N = \{R_1, \dots, R_n\}$ be a set of differential-drive mobile robots moving on the plane with positions $\xi_i = [x_i, y_i]^T$, $i = 1, \dots, n$. The kinematic model for each robot, according to Fig. 1, is given by

$$\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{\theta}_i \end{bmatrix} = \begin{bmatrix} \cos \theta_i & 0 \\ \sin \theta_i & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_i \\ w_i \end{bmatrix}, \quad i = 1, \dots, n \quad (1)$$

where v_i is the longitudinal velocity of the middle point of wheels axis of the i -th robot, w_i its angular velocity and θ_i the orientation with respect to the X axis. Taking as output of the system (1) the position ξ_i , the so called decoupling matrix becomes singular. For this reason, to avoid singularities in the control law, it is common to study the kinematics of a point α_i off the wheels axis. The coordinates of point α_i are given by

$$\alpha_i = \begin{bmatrix} \alpha_{xi} \\ \alpha_{yi} \end{bmatrix} = \begin{bmatrix} x_i + \ell \cos \theta_i \\ y_i + \ell \sin \theta_i \end{bmatrix} \quad (2)$$

The kinematics of point α_i is given by

$$\begin{bmatrix} \dot{\alpha}_{xi} \\ \dot{\alpha}_{yi} \end{bmatrix} = \begin{bmatrix} \cos \theta_i & -\ell \sin \theta_i \\ \sin \theta_i & \ell \cos \theta_i \end{bmatrix} \begin{bmatrix} v_i \\ w_i \end{bmatrix} = A_i(\theta_i) \begin{bmatrix} v_i \\ w_i \end{bmatrix} \quad (3)$$

where $A_i(\theta_i)$ is the decoupling matrix for each robot R_i and this is non-singular since $\det(A_i(\theta_i)) = \ell \neq 0$.

2.2 Algebraic Graph Theory

Definition 1. (Formation Graph). Let $N = \{R_1, \dots, R_n\}$ be a set of mobile agents and N_i be the subset of agents which have a flow of information towards the i -th agent. A formation graph $G = \{V, E, C\}$ consists of 1) A set of vertices $V = \{R_1, \dots, R_n\}$ corresponding to the n agents of the system, 2) A set of edges $E = \{(R_j R_i) \in V \times V | j \in N_i\}$ where each edge represents a flow of information that goes from agent j towards agent i and 3) A set of labels $C = \{c_{ji} = R_i - R_j\}$ with $(R_j R_i) \in E$, $c_{ji} \in \mathbb{R}^2$, with c_{ji} being a vector specifying a desired relative position between of agent R_j with respect to agent R_i .

In the leader-followers scheme used in this work, the agent R_n is the leader, responsible for tracking a desired

trajectory. The $n - 1$ remaining agents are follower, responsible for performing a time-varying formation with respect to the leader. The leader agent does not know the position and velocities of the followers agents, only knows the desired trajectory and velocity. The followers do not know the desired trajectory and velocity, only knows the positions and velocities of others agents in the system.

Definition 2. (Laplacian). Let us have a formation graph G , the Laplacian associated with G is given by

$$\mathcal{L}(G) = \Delta - \mathcal{A}_d \quad (4)$$

where Δ is the degree matrix defined by

$$\Delta = \text{diag} \{g_1, \dots, g_n\} \quad (5)$$

where $g_i = \text{card} \{N_i\}$, $i = 1, \dots, n$ and \mathcal{A}_d is the adjacency matrix of G defined by

$$a_{ij} = \begin{cases} 1, & \text{if } (R_j, R_i) \in E \\ 0, & \text{otherwise.} \end{cases} \quad (6)$$

In the rest of this paper we make the following assumption

Assumption 1. For each follower agent, there is a communication either direct or indirect, with the leader agent; i.e., for all $R_i, i = 1, \dots, n - 1$ there are edges $R_n R_{m_1}, R_{m_1} R_{m_2}, \dots, R_{m_r} R_i \in E$.

For further details about algebraic graph theory, the reader is referred to Fax and Murray (2002); Desai (2002); Lafferriere et al. (2004).

2.3 Notations

Let us introduce some notation:

- Let $m(t) = [m_p(t), m_q(t)]^T$ be a continuously differentiable prestablished trajectory, where $\|\dot{m}(t)\| \leq \eta_m, \forall t \geq 0$.
- The desired relative position of the i -th follower within the desired time-varying formation is given by

$$\alpha_i^*(t) = \frac{1}{g_i} \sum_{j \in N_i} (\alpha_j(t) + C_{ji}(t)), \quad i = 1, \dots, n - 1,$$

where C_{ji} , defined in Section IV, is a time-varying position vector between the agents i and j . The time derivative of $C_{ji}(t)$ satisfies $\|\dot{C}_{ji}(t)\| \leq \eta_c, \forall t \geq 0$.

- Given a vector $z = [z_1, \dots, z_p]^T$, we define $\tanh(z) = [\tanh(z_1), \dots, \tanh(z_p)]^T$.
- Given a matrix $X \in \mathbb{C}^{n \times n}$ with $\lambda_1, \dots, \lambda_n$ eigenvalues, then its spectral radius $\rho(X)$ is defined as $\rho(X) = \max\{|\lambda_1|, \dots, |\lambda_n|\}$.

3. PROBLEM STATEMENT

The goal of this work is to design a decentralized control law $u_i = (\alpha_i, N_i)$, $i = 1, \dots, n$ that achieves

- Asymptotic tracking of a prescribed trajectory by the leader agent, i.e.

$$\lim_{t \rightarrow \infty} (\alpha_n(t) - m(t)) = 0.$$

- Asymptotic time-varying formation by the follower agents, i.e. for $i = 1, \dots, n - 1$

$$\lim_{t \rightarrow \infty} (\alpha_i(t) - \alpha_i^*(t)) = 0.$$

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