Control of nonholonomic mobile robot formations: backstepping kinematics into dynamics

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Control of Nonholonomic Mobile Robot Formations: Backstepping Kinematics into Dynamics

Travis Dierks and S. Jagannathan

Abstract—In this paper, we seek to expand framework developed to control a single nonholonomic mobile robot to include the control of formations of multiple nonholonomic mobile robots. A combined kinematic/torque control law is developed for leader-follower based formation control using backstepping in order to accommodate the dynamics of the robots and the formation in contrast with kinematic-based formation controllers. The asymptotic stability of the entire formation is guaranteed using Lyapunov theory, and numerical results are provided. The kinematic controller is developed around control strategies for single mobile robots and the idea of virtual leaders. The virtual leader is replaced with a physical mobile robot leader and the assumption of constant reference velocities is removed. An auxiliary velocity control is developed allowing the asymptotic stability of the followers to be proved without the use of Barbalat’s Lemma which simplifies proving the entire formation is asymptotically stable. A novel approach is taken in the development of the dynamical controller such that the torque control inputs for the follower robots include the dynamics of the follower robot as well as the dynamics of its leader, and the case when all robot dynamics are known is considered.

Index Terms—Formation control, Lyapunov methods, kinematic/dynamic controller.

I. INTRODUCTION

Over the past decade, the attention has shifted from the control of a single nonholonomic mobile robot [1-2] to the control of multiple mobile robots because of the advantages a team of robots offer such as increased efficiency and more systematic approaches to tasks like search and rescue operations, mapping unknown or hazardous environments, and security and bomb sniffing.

There are several methodologies [3-9] to robotic formation control which include behavior-based [3], generalized coordinates [4], virtual structures [5], and leader-follower [6-10] to name a few. Perhaps the most popular and intuitive approach is the leader-follower method. In this method, a follower robot stays at a specified separation and bearing from a designated leader robot.

In [6] and [9], local sensory information and a vision based approach to leader-following is undertaken respectively. In both the approaches, the sensory information was used to calculate velocity control inputs. A modified leader-follower control is introduced in [7] where Cartesian coordinates are used rather than polar. In [8], it is acknowledged that the separation-bearing methodologies of leader-follower formation control closely resemble a tracking controller problem and a reactive tracking control strategy that converts a relative pose control problem into a tracking problem between a virtual robot and the leader is developed. A drawback of this controller is the need to define a virtual robot and the fact that dynamics are not considered. A characteristic that is common in many formation control papers [6-9] is the design of a kinematic controller thus requiring a perfect velocity tracking assumption and formation dynamics are ignored.

In this paper, we examine frameworks developed for controlling single nonholonomic mobile robots and seek to expand them to be used in leader follower formation control. Specifically, we examine tracking controllers in the form of [1]. Like [8], we seek to convert a relative pose problem into a tracking control problem, but without the use a virtual robot for the follower. We also seek to bring in the dynamics of the robots themselves thus incorporating the formation dynamics in the controller design. In [10], the dynamics of the follower robot are considered, but the effect the leader's dynamics has on the follower (formation dynamics) is not incorporated. The leader's dynamics become apart of the follower robot's control torque input through the derivative of the follower's kinematic velocity control, which is a function of the leader's velocity. In other words, the dynamical extension introduced in this paper provides a rigorous method of taking into account the specific vehicle dynamics to convert a steering system command into control inputs via backstepping approach. Both feedback velocity control inputs and velocity following control laws are presented for asymptotic stability of the formation.

II. LEADER-FOLLOWER FORMATION CONTROL

The two popular techniques in leader-follower formation control include separation-separation and separation-bearing [9]. The goal of separation-bearing formation control is to find a velocity control input such that

$$\lim_{t \to \infty} (L_{yd} - L_y) = 0 \quad \text{and} \quad \lim_{t \to \infty} (\Psi_{yd} - \Psi_y) = 0 \quad (1)$$

where $L_y$ and $\Psi_y$ are the measured separation and bearing of the follower robot with $L_{yd}$ and $\Psi_{yd}$ represent desired distance and angles respectively [6][9]. Only separation-bearing techniques are considered, but our approach can be extended to separation-separation control.

To avoid collisions, separation distances are measured from the back of the leader to the front of the follower, and
the kinematic equations for the front of the \( j \)-th follower robot can be written as
\[
\dot{q}_j = S_j(q_j)v_j = \begin{bmatrix}
\cos \theta_j & -d_j \sin \theta_j \\
\sin \theta_j & d_j \cos \theta_j
\end{bmatrix}
\begin{bmatrix}
v_j \\
\omega_j
\end{bmatrix}
\]  \( \tag{2} \)

where \( d_j \) is the distance from the rear axle to the to front of the robot, \( x_j, y_j \), and \( \theta_j \) are actual Cartesian position and orientation of the physical robot, and \( v_j \), and \( \omega_j \) are linear and angular velocities respectively.

Many robotic systems can be characterized as a robotic system having an \( n \)-dimensional configuration space \( \mathcal{C} \) with generalized coordinates \( (q_1, \ldots, q_n) \) and subject to \( m \) constraints described in detail in [1] and mathematically after applying the transformation described in [1] as
\[
\dot{M}_j(q_j)v_j + \dot{\bar{V}}_n(q_j, \dot{q}_j)v_j + \bar{F}_j(v_j) + \tau_j = \bar{B}(q_j)\dot{r}_j.
\]  \( \tag{3} \)

where \( M_j \in \mathbb{R}^{n\times n} \) is a symmetric positive definite inertia matrix, \( \bar{V}_n \in \mathbb{R}^{n\times n} \) is the centripetal and coriolis matrix, \( F_j \in \mathbb{R}^{n\times 1} \) is the friction vector, \( \tau_j \) represents unknown bounded disturbances, and \( \bar{F}_j = \bar{B}\tau_j \in \mathbb{R}^{n\times 1} \) is the input vector.

It is important to highlight the skew symmetric property common to robotic systems [1] as \( \bar{M}_j - 2\bar{V}_n(q_j, \dot{q}_j) = 0 \).

### A. Controller Design

The complete description of the behavior of a mobile robot is given by (2) and (3). Standard approaches to leader follower formation control deal only with (2) and assume that perfect velocity tracking holds. This paper seeks to remove that assumption by defining nonlinear feedback control input
\[
\tau_j = \bar{B}^{-1}(\bar{M}_ju_j + \bar{V}_n v_j + \bar{F}_j(v_j) + \tau_j)
\]  \( \tag{4} \)

where \( u_j \) is an auxiliary input. Applying this control law to (3) allows one to convert the dynamic control problem into the kinematic control problem [1] such that
\[
\begin{align*}
\dot{\hat{q}}_j &= S_j(q_j)v_j \\
\dot{\hat{v}}_j &= u_j.
\end{align*}
\]  \( \tag{5} \)

**Backstepping Design:** Tracking controller frameworks have been derived for controlling single mobile robots, and there are many ways [1-2] to choose velocity control inputs \( v_j(t) \) for steering system (2). To incorporate the dynamics of the mobile platform, it is desirable to convert \( v_j(t) \) into a control torque, \( \tau_j(t) \) for the physical robot. Contributions in single robot frameworks are now considered and expanded upon in the development a kinematic controller for the separation-bearing formation control technique. Our aim to design a conventional computed torque controller such that (2) and (3) exhibit the desired behavior for a given control \( v_j(t) \) thus removing perfect velocity tracking assumptions.

Consider the tracking controller error system presented in [1] used to control a single robot as
\[
\begin{align*}
\dot{e}_{j1} &= \cos \theta_j - \frac{d_j}{\sin \theta_j} v_j \\
\dot{e}_{j2} &= -\sin \theta_j - \frac{d_j}{\sin \theta_j} \omega_j \\
\dot{e}_{j3} &= 0
\end{align*}
\]  \( \tag{6} \)

where \( x_j, y_j, \) and \( \theta_j \) are actual position and orientation of the robot, and \( x_{rj}, y_{rj}, \) and \( \theta_{rj} \) are the positions and orientation of a virtual reference cart robot \( j \) seeks to follow [1].

In single robot control, a steering control input \( v_{jc}(t) \) is designed to solve three basic problems: path following, point stabilization, and trajectory following such that \( \lim_{t \to \infty}(q_j-q_{jr})=0 \) and \( \lim_{t \to \infty}(v_c-v_{jc})=0 \) [1]. If the mobile robot controller can successfully track a class of smooth control velocity inputs, then all three problems can be solved with the same controller structure [1].

The three basic tracking control problems can be extended to formation control as follows. The virtual reference cart is replaced with a physical mobile robot acting as the leader \( i \), and \( x_r, y_r \) are defined as points at a distance \( L_{ijd} \) and a desired angle \( \Psi_{ijd} \) from the lead robot. Now the three basic navigation problems can be introduced for leader-follower formation control as follows.

**Tracking:** Let there be a leader \( i \) for follower \( j \) such that
\[
\begin{align*}
\dot{x}_i &= \cos \theta_i - \frac{d_i}{\sin \theta_i} v_i \\
\dot{y}_i &= \sin \theta_i - \frac{d_i}{\sin \theta_i} \omega_i, \\
\dot{\theta}_i &= \omega_i
\end{align*}
\]  \( \tag{7} \)

where \( v_i \) is the time varying linear and angular speeds of the leader such that \( v_i > 0 \) for all time. Then define the actual position and orientation of follower \( j \) as
\[
\begin{align*}
x_{jr} &= x_i - d_i \cos \theta_i + L_{ijd} \cos(\Psi_{ijd} + \theta_i) \\
y_{jr} &= y_i - d_i \sin \theta_i + L_{ijd} \sin(\Psi_{ijd} + \theta_i), \\
\theta_{jr} &= \theta_i
\end{align*}
\]  \( \tag{8} \)

where \( L_{ijd} \) and \( \Psi_{ijd} \) is the actual separation and bearing of follower \( j \). In order to solve the formation tracking problem with one follower, find a smooth velocity input \( v_{jc}=f(e_{jc}, v_{jc}, \tau_{jc}) \) such that \( \lim_{t \to \infty}(q_j-q_{jr})=0 \), where \( e_{jc} \), \( v_{jc} \), and \( \tau_{jc} \) are the tracking position errors, reference velocity for follower \( j \) robot, and gain vector respectively. Then compute the torque \( \tau_{jc}(t) \) for the dynamic system of (3) so that \( \lim_{t \to \infty}(e_{jc}=v_{jc})=0 \). Achieving this for every leader \( i \) and follower \( j=1,2,\ldots,N \) ensures that the entire formation tracks the formation trajectory.

**Path Following:** Given a path \( P_i \) for leader \( i \) as well as the entire formation to follow, define a path \( P_j \) relative to \( P_i \) as the points at a distance \( L_{ijd} \) and an angle \( \Psi_{ijd} \) for the follower robot \( j \) to follow with a linear velocity \( v_{jc}(t) \). Find a smooth velocity
control input \( \nu_j = f(e_j, v_j, b_j, K) \), where \( e_j \) and \( b_j(t) \) are the orientation and distance errors between a reference point of the follower robot \( j \) and path \( P_j \), respectively, such that \( \lim_{t \to \infty} e_j = 0 \) and \( \lim_{t \to \infty} b_j = 0 \). Then compute the torque \( \tau_j(t) \) for the dynamic system given by (3) so that \( \lim_{t \to \infty} (v_j(t) - \nu_j(t)) = 0 \). Achieving this for every leader \( i \) and follower \( j = 1, 2, \ldots, N \) ensures that the entire formation follows a formation path \( P_j \) with a bounded error that is a function of \( L_{ijd} \) and \( \psi_{ijd} \).

Point Stabilization: Given an arbitrary configuration of leader \( i \) denoted as \( q_{ij} \), define a relative reference configuration for follower \( j \) as \( q_{ij} \). Then find a smooth control input velocity \( \nu_j = f(e_j, v_j, K) \) such that \( \lim_{t \to \infty} (e_j(t) - q_{ij}) = 0 \). Then compute the torque \( \tau_j(t) \) for the dynamic system of (3) so that \( \lim_{t \to \infty} v_j(t) = 0 \). Achieving this for every leader \( i \) and follower \( j = 1, 2, \ldots, N \) ensures the entire formation is stabilized about a reference point at the geometric center of the formation which is defined as the formation trajectory.

Leader-Follower Trajectory Tracking: Many solutions [6-9] to the leader-follower formation control problem of (1) and the kinematic model (2) have been suggested and smooth velocity control inputs for the follower have been derived. Unfortunately, dynamical models are rarely studied, and the velocity control inputs for the follower have been derived to the leader-follower formation control problem of (1) and calculating the specific alternative control velocity, these issues.

The contribution in this paper lies in deriving an additional terms are introduced as a result of (2) and (15). Now, using the derivative of (12), equation (15) and applying simple trigonometric identities, the error dynamics can be expressed as

\[
\begin{align*}
\dot{v}_{jc} & = v_i \cos \gamma - v_j \cos \gamma_j + d_j \omega_j \sin \gamma_j \\
\dot{\gamma}_{jc} & = -\omega_j \sin \gamma_j - d_j \omega_j \cos \gamma_j - L_{ijd} \sin(\psi_{ijd} + e_{j3})
\end{align*}
\]  

Examining (16) and the error dynamics of a tracking controller for a single robot in [1], one can see that dynamics of a single follower with a leader is similar to [1], except additional terms are introduced as a result of (2) and (15).

To stabilize the kinematic system, we propose the following velocity control inputs for follower robot \( j \) to achieve the desired position and orientation with respect to leader \( i \) as

\[
\begin{align*}
\nu_{jc} & = v_{jc} \\
\gamma_{jc} & = \gamma_{jc} + e_{j3}
\end{align*}
\]

where

\[
\gamma_{ejc} = \frac{e_{j2} \left( \omega_j (d_j + L_{ijd}) + (v_i + k_j k_j d_j + 1) \right)}{1 / k_j + e_{j2} d_j}
\]

Comparing this velocity control with the tracking controller designed for a single robot in [1], one can see that the two are similar except for the novel auxiliary terms which ensure stability for the formation of two robots using kinematics alone. Additionally, the design parameter \( k_j \) was added to ensure asymptotic stability holds even when \( v_j = 0 \).
Before we proceed, the following assumptions are needed.

**Assumption 1.** Complete knowledge of the $j^{th}$ follower and $i^{th}$ leader dynamics are known.

**Assumption 2.** Each follower has full knowledge of its leader’s dynamics.

**Assumption 3.** Follower $j$ is equipped with sensors capable of measuring the separation distance $L_{ij}$ and bearing $e_{ij}$ and that both leader and follower are equipped with instruments to measure their linear and angular velocities as well as their orientations $\theta_i$ and $\theta_j$.

**Assumption 4.** Wireless communication is available between the $j^{th}$ follower and $i^{th}$ leader with communication delays being zero.

**Assumption 5.** The $i^{th}$ leader communicates its linear and angular velocities $v_i$, $\omega_i$ as well as its orientation $\theta_i$ and control torque $r_i(t)$ to its $j^{th}$ follower.

**Assumption 6.** For the nonholonomic system of (2) and (3) with $n$ generalized coordinates $q_i$, $m$ independent constraints, and $r$ actuators, the number of actuators is equal to the number of degrees of freedom ($r = n - m$).

**Assumption 7.** The reference linear and angular velocities measured from the leader are bounded and $\dot{v}_{ij}(t) \geq 0$ for all $t$.

**Assumption 8.** $K = [k_1, k_2, k_3]^T$ is a vector of positive constants.

**Assumption 9.** Let perfect velocity tracking hold such that $\dot{v}_j = \dot{v}_{jc}$ (this assumption is relaxed later).

**Theorem 1:** Given the nonholonomic system of (2) and (3) with $n$ generalized coordinates $q_i$, $m$ independent constraints, and $r$ actuators, along with the leader follower criterion of (1), let Assumption 1-9 hold. Let a smooth velocity control input $v_{jc}(t)$ for the $j^{th}$ follower be given by (17), (18), and (19). Then the origin $e_j = 0$ consisting of the position and orientation error for the follower is asymptotically stable.

**Proof:** Consider the following Lyapunov function candidate

$$V_j = \frac{1}{2}(e_{jc}^2 + e_{j}^2) + \frac{1 - \cos(e_{jc})}{k_2}$$

(20)

Clearly, $V_j > 0$ and $V_j = 0$ only when $e_j = 0$.

Differentiating (20) and substitution of (16), (17), and (18) yields

$$\dot{V}_j = -k_1 e_{jc}^2 - d_j (v_i + k_2 e_{jc}^2 - (v_i + k_2) \sin^2 e_{jc}$$

$$- e_{j2}d_j \left(q + (v_i + k_2) \sin e_{jc} + \alpha L_{ij} \cos(e_{ij}) + e_{jc}\right)$$

$$- e_{j2} \sin e_{jc} - \gamma_{e_{jc}} \left(\frac{\sin(e_{jc})}{k_2} + e_{j2}d_j\right)$$

which can be rewritten as

$$\dot{V}_j \leq -k_1 e_{jc}^2 - d_j (v_i + k_2 e_{jc}^2 - \frac{k_1}{k_2} (v_i + k_2) \sin^2 e_{jc}$$

$$+ \frac{1 - \cos(e_{jc})}{k_2} + d_j + \gamma_{e_{jc}} \left(1 + \frac{d_j}{k_2} + e_{j2}d_j\right)$$

(22)

Clearly, the first three terms in (22) are strictly less than zero for $e_j \neq 0$. Now consider the last two terms of (22) in the inequality

$$\dot{V}_j \leq -k_1 e_{jc}^2 - d_j (v_i + k_2 e_{jc}^2 - \frac{k_1}{k_2} (v_i + k_2) \sin^2 e_{jc}$$

Substitution of (19) into (23) reveals

$$\dot{V}_j \leq -k_1 e_{jc}^2 - d_j (v_i + k_2 e_{jc}^2 - \frac{k_1}{k_2} (v_i + k_2) \sin^2 e_{jc}$$

(24)

Clearly $\dot{V}_j < 0$ for all $e_j \geq 0$, and the velocity control (17), (18), and (19) provides asymptotic stability for the error system (12) and (16) and $e_j \rightarrow 0$ as $t \rightarrow \infty$.

**Remark:** The asymptotic stability of the error system (12) and (16) is proved without the use of Barbalat’s Lemma which is required in [1]. Proving the stability of the formation is greatly simplified without the need for Barbalat’s Lemma for every follower robot.

Now assume that the perfect velocity tracking assumption does not hold making Assumption 9 invalid. Define the velocity tracking error as

$$e_{jc} = v_{jc} - v_j$$

(25)

Differentiating (25) and adding and subtracting $\dot{M}_j(q_j) \dot{v}_{jc}$ and $\dot{P}_m(q_j) \dot{v}_{jc}$ to (3) allows the mobile robot dynamics to be written in terms of the velocity tracking error and its derivative as

$$\dot{M}_j(q_j) \dot{e}_{jc} = -\dot{P}_m(q_j) \dot{v}_{jc} - \ddot{v}_{jc} + f_j(x_j) + \Phi_{dj}$$

(26)

where $f_j(x_j)$ in (27) will be used to bring in the dynamics of leader $i$ through $\dot{v}_{jc}$ by observing that

$$\dot{v}_{jc} = f_{vej}(v_i, \omega_i, v_j, \omega_j, e_j, \dot{e}_j)$$

(28)

The leader $i$'s dynamics can be written in the form of (3)

$$\dot{v}_i = M_i(q_i) \ddot{q}_i - \ddot{F}(q_i, \dot{q}_i)v_i - \dot{F}(v_i) - \tau_d$$

(29)

Substituting (29) into (28) results in the dynamics of the $i^{th}$ leader robot to become apart of $\dot{v}_{jc}$ as

$$\dot{v}_{jc} = f_{vej}(v_i, \omega_i, \theta_i, \tau_i, e_j, \dot{e}_j)$$

(30)

Under Assumptions 1-5, follower $j$ is able to construct $\dot{v}_{jc}$. Defining the auxiliary control input $u_j$ from (5) to be [1]

$$u_j = \dot{v}_{jc} + K_4 e_{jc}$$

(31)

the control torque for the $j^{th}$ follower robot can be written in the form

$$\tau_j = \overline{B}_j^{-1}(\dot{M}_j K_4 e_{jc} + f_j(x_j))$$

(32)

where $K_4$ is a positive definite matrix defined by
where \( e_{ic} \) and \( K_{id} \) are defined similarly to (25) and (33). The following additional mild assumptions are needed before proceeding.

**Assumption 12.** The reference linear velocity \( v_{re} \) is greater than zero and bounded and the reference angular velocity \( \omega_r \) is bounded for all \( t \).

**Assumption 13.** \( K=[k_{i1} k_{i2} k_{i3}]^T \) is a vector of positive constants.

**Theorem 3:** Given the kinematic system of (8) and dynamic system in the form of (3) for leader \( i \) with \( n \) generalized coordinates \( q_i, m \) independent constraints, and \( r \) actuators, let Assumptions 1-6 and Assumptions 10-13 hold. Let \( k_i \) be a sufficiently large positive constant. Let there be a smooth velocity control input \( v_{re}(t) \) for the leader \( i \) given by (38), and let the torque control for the lead robot \( i \) (39) be applied to the mobile robot system in the form of (3). Then the origin \( e_{ic}=0 \) and \( e_{ic}=0 \) which are the position, orientation and velocity tracking errors for leader \( i \) are asymptotically stable. This theorem is proved in [1].

**Remark:** The asymptotic stability of a formation consisting of 1 leader and \( N \) followers can be proved as well as the asymptotic stability of the formation for the case when follower \( j \) becomes a leader to follower \( j+1 \). Proofs of these claims are not presented here due to length constraints, but they follow as a result of Theorems 2 and 3.

### III. Simulation Results

A wedge formation of five identical nonholonomic mobile robots is considered where leader's trajectory is the desired formation trajectory, and simulations are carried out in MATLAB under two scenarios. First, only the kinematic steering system (2) under perfect velocity tracking such that \( v_j = v_{jc} \) and \( \dot{v}_j = \dot{v}_{jc} \) is considered for the leader and its followers in the absence of all dynamics. Then, the full dynamics as well as the kinematics of all the robots are considered. Under both scenarios, the leader's reference linear velocity is \( 5 \text{ m/s} \) while the reference linear velocity is allowed to vary. Results for the leader's tracking ability are presented in [1] and are therefore not shown here.

A simple wedge formation is considered such that follower \( j \) should track its leader at separation of \( L_{12d}=2 \) meters and a bearing of \( \Psi_{12d}=\pm 120^\circ \) depending on the follower's location, and the formation leader is located at the apex of the wedge. The following gains are utilized for the controllers:

<table>
<thead>
<tr>
<th>Leader</th>
<th>( K_{id}=\text{diag}[40] )</th>
<th>( k_{i1}=10 )</th>
<th>( k_{i2}=5 )</th>
<th>( k_{i3}=4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Follower ( j )</td>
<td>( K_{id}=\text{diag}[40] )</td>
<td>( k_{j1}=10 )</td>
<td>( k_{j2}=50 )</td>
<td>( k_{j3}=5 )</td>
</tr>
</tbody>
</table>

The following robotic parameters are considered for the leader and its followers: \( m=5 \text{ kg} \), \( I=3 \text{ kg}^2 \), \( R=175 \text{ m} \), \( r=0.08 \text{ m} \), and \( d=0.45 \text{ m} \). Friction is added to both the leader's and its followers' dynamics and modeled as
However, the formation trajectories are not the same. When the steering command is issued, the dynamics of the robots become an apparent influence on the formation trajectory. This is an important result that displays the importance of incorporating the dynamics of the robots into the control law. In an obstacle ridden environment, it is important that the formation follows a specific trajectory to ensure safe passage. Ignoring the dynamics of the robots, one cannot guarantee the trajectory the formation follows is the desired trajectory.

Figures 3 and 4 display the bearing and separation errors for the dynamical scenario. It is evident that both the bearing errors and separation errors converge to zero very quickly and remain there so that the wedge formation is maintained.

IV. CONCLUSION

An asymptotically stable tracking controller for leader-follower based formation control was presented that considers the dynamics of the leader and the follower using backstepping. The feedback control scheme is valid as long as the complete dynamics of the followers and their leader are known. Numerical results were presented and the stability of the system was verified. Simulation results verify the theoretical conjecture and expose the flaws in ignoring the dynamics of the mobile robots.

V. REFERENCES