Decentralized Cohesive Motion Control of Multi-Agent Formations

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Abstract—This paper presents a set of decentralized control laws for the cohesive motion of 2-dimensional multi-agent formations. We consider rigid and constraint-consistent formations that can be modeled by directed graphs. We analyze both of the two main hierarchical structures for such 2-dimensional formations: The leader-follower and the three-coleader structures. For each structure, we derive a control scheme that moves a given rigid and constraint-consistent formation whose initial position and orientation are specified to a new desired position and orientation cohesively, i.e., without deforming the shape of the formation during the motion. We elaborate our designs considering the path smoothness, chattering, and agent kinematics issues and demonstrate their effectiveness via a set of simulation results.

I. INTRODUCTION

In recent years, the topics of cooperative control and control of multi-agent formations has gained a lot of attention [1-3] in parallel with the interest in their real-life applications such as the ones involving groups of combat robots, unmanned aerial vehicles, ground vehicles, underwater vehicles, etc. [4-7]. Beside the usual requirement of decentralized decision making, the foci and approaches of the formation control studies are diverse depending on the considered agent dynamics, control goals and strategies, inter-agent information structure, etc.

In this paper, we focus on the cohesive motion of the entire formation rather than individual agent behaviours. Hence, we assume a point-agent system model and represent each multi-agent formation by a directed graph, the so-called directed underlying graph of the formation, where each agent $A_i$ is represented with a vertex $i$ and each neighbor agent pair $(A_i, A_j)$, viz. a pair the distance between which is required to be explicitly maintained at a desired value $d_y$, is represented by a directed edge, say $(i, j)$. The direction of the edge $(i, j)$ from $i$ to $j$ implies that agent $A_i$ is responsible to keep the distance between $(A_i, A_j)$ at the desired value $d_y$, i.e., $A_i$ has the constraint of staying at a distance $d_y$ from $A_j$. In this case we also say that $A_i$ follows $A_j$ or $A_j$ is a follower of $A_i$.

A formation is called rigid if the distance between each pair of agents remains constant, i.e., the formation shape is maintained during any continuous motion provided that each agent satisfies all the distance constraints on it [8]. In a rigid formation, (explicit) maintenance of the distances between neighbor agents result in (implicit) maintenance of the remaining inter-agent distances and hence the formation shape as well. If each agent in a formation is able to satisfy all the constraints on it once all the other constraints within the formation are satisfied, then the formation is called constraint-consistent. A formation that is both rigid and constraint-consistent is called persistent [9]. For a given persistent formation $F$, if removal of any single edge (in the underlying graph) makes $F$ non-persistent then $F$ is called minimally persistent, i.e., a minimally persistent formation preserves its persistence with a minimal number of edges. Rigorous definitions and analysis of rigidity, constraint-consistence and persistence can be found in [8,9].

The main contribution of this paper is providing a decentralized control strategy for cohesive motion of 2-dimensional persistent formations where each of the agents makes decisions based only on its own observations and state. The aim is to move a given persistent formation with specified initial position and orientation to a new desired position and orientation cohesively, i.e., without violating the persistence of the formation during the motion.

In 2-dimensions, based on the distribution of the distance constraints of the agents, minimally persistent formations can be categorized into two groups [8] which shall be elaborated more in Section II: The formations with the leader-follower structure and those with the three-coleader structure. In our work, we consider each of these groups separately. We develop control schemes assuming a simple integrator model for each agent, which is used in many other works in the field [4,5]. However, our designs can be generalized for other kinematic models as well, as demonstrated for the nonholonomic unicycle model [6,10] in Section V. We demonstrate the effectiveness of the control laws developed for each case via simulation results.

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II. PROBLEM DEFINITION

In this paper, we consider 2-dimensional point-agent formations whose shapes are required to be maintained during any motion by explicitly maintaining the distances between certain agent pairs. Representations of such formations via directed graphs as well as definitions of rigid, constraint-consistent and (minimally) persistent formations were given in Section I. Next we provide some fundamental characteristics of persistent formations relevant to our work, whose details can be found in [8,9].

Noting that the out-degree of a vertex in a directed underlying graph is equal to the number of distance constraints on the corresponding agent, the degree of freedom (DOF) of an agent (for its motion in $\mathbb{R}^2$) can be defined based on the out-degree of its representative vertex in the underlying graph. Given an agent $A_i$, if the out-degree of its representative vertex $i$ is 0 then $A_i$ has 2-DOF, i.e., it can move freely in $\mathbb{R}^2$. If the out-degree is 1 then $A_i$ can only rotate around the agent it follows in order to meet its distance constraint and hence has 1-DOF. If the out-degree is 2 or more then the motion of $A_i$ completely depends on the agents it follows, i.e. it has 0-DOF.

For a persistent formation, it has been shown in [8,9] that the sum of DOFs of individual agents is at most 3 and for a minimally persistent formation, exactly 3, which is the same as the DOF of a free rigid (non-vertex) object in $\mathbb{R}^2$ (2 for translation and 1 for rotation). Based on the distribution of these 3 DOFs, minimally persistent formations can be divided into two categories: Formations with the leader-follower structure where one agent has 2-DOF, another has 1-DOF and the rest have 0-DOF, and the 3-coleader structure where three agents have 1-DOF and the rest have 0-DOF. In the leader-follower structure, the 2-DOF agent is called the leader and the 1-DOF is called the first follower. In the 3-coleader structure, the 1-DOF agents are called the coleaders. In both structures the 0-DOF agents are called the (ordinary) followers.

From [8], it can be seen that the underlying graph of a formation with leader-follower structure is always acyclic (cycle-free) while any formation with the three-coleader structure has at least one cycle. Due to the presence of a cycle, the motions of the three coleaders are cyclically dependent on each other and hence the motion control for the formation requires a more implicit strategy. Some stability properties of leader-follower structures are investigated in [6]. However, to our best of knowledge, there is no existing literature that deals with motion control of persistent (or rigid) formations with cycles.

In our work, we consider both of the two categories above. One can verify via simple examples that there exist (minimally) persistent formations with the leader-follower structure where the first follower does not directly follow the leader but another (ordinary follower) agent, and there exist (minimally) persistent formations with the 3-coleader structure where the coleaders do not directly follow each other but some other agents. For simplicity, we assume that the first follower directly follows the leader in a leader-follower structured formation and the three co leaders follow each other in a 3-coleader structured formation.

Our control task is to move a given persistent formation $F$ with say $m \geq 3$ agents $A_1, \ldots, A_m$ whose initial position and orientation are specified, to a new desired position and orientation in $\mathbb{R}^2$ (the $xy$-plane) cohesively, i.e., without violating the persistence of $F$ during motion, using a decentralized strategy. The initial and final positions and orientations of $F$ are defined by the initial positions $p_{i0}$ and final positions $p_{if}$ of the individual agents $A_i$ for $i = 1, \ldots, m$, respectively. We assume that the final positions $p_{if}$ are consistent with the desired inter-agent distances $d_{ij}$ between neighbor agent pairs $(A_i, A_j)$.

For each agent, we assume a velocity integrator kinematics, i.e., for each agent $A_i$ we assume that

$$\dot{p}_i(t) = v_i(t)$$

where $p_i(t) = (x_i(t), y_i(t)), v_i(t) = (v_{ix}(t), v_{iy}(t)) \in \mathbb{R}^2$ denote the position and velocity of $A_i$ at time $t$, respectively. The velocity $v_i(t)$ is considered as the control signal to be generated by the individual controller of agent $A_i$. It is required that $v_i(t)$ is continuous and satisfies $|v_i(t)| \leq \bar{v}$ for some constant maximum speed limit $\bar{v} > 0$ at any $t \geq 0$ for any $i \in \{1, \ldots, m\}$. We assume that each agent $A_i$ knows its final desired position $p_{if}$ and can sense its own position $p_i(t)$ and velocity $v_i(t)$ as well as the position $p_j(t)$ of each agent $A_j$ it follows at any time $t \geq 0$. It is also assumed that the distance sensing range for a neighbor agent pair $(A_i, A_j)$ is sufficiently larger than the desired distance $d_{ij}$ to be maintained.

For each 1-DOF agent, the control laws below are chosen so that meeting the distance constraint has a higher priority than reaching to the final desired position, i.e., a 1-DOF agent can undergo its DOF movement, only when its priority than reaching to the final desired position, i.e., a 1-DOF agent can undergo its DOF movement, only when its distance constraint is satisfied within a certain error bound.

Based on the agent kinematics (1) and the assumptions above, in the next two sections we develop control schemes to address the cohesive motion task defined above for both the leader-follower and the 3-coleader structures.

III. CONTROL FOR THE LEADER-FOLLOWER STRUCTURE

In this section, we derive control laws for the cohesive motion of a persistent formation with the leader-follower structure. We illustrate our designs on a formation with one
leader $A_1$, one first-follower $A_2$ and two (ordinary) followers $A_3$ and $A_4$ depicted in Fig. 1.

Fig. 1. The directed underlying graph of a persistent graph with the leader-follower structure.

For optimality considerations and to cope with constant velocity requirements in certain UAV and other flight formation cases, we assert the following two guidelines in our control design: (i) Any agent will move at the constant maximum speed $\overline{v} > 0$ at any time instant $t \geq 0$ unless it is impossible to do that at that particular instant $t$ due to, e.g., initial and final zero-velocity constraints, etc. (ii) Any agent with distance constraints moves through a path of shortest distance in order to satisfy these constraints.

Based on these two assertions and the earlier assumptions, the derivation of our control law to address the cohesive motion task in Section II uses basic vector analysis and borrows ideas from the virtual vector field concept, details of which can be found in [4] and the references therein. The main idea in the virtual vector field approach is obtaining the overall velocity vector (for each agent) as the superposition of the vectors defining each of the separate motion tasks (of this agent). In our case the two separate motion vector types of an agent are (i) to maintain a distance constraint with each of the agents it follows and (ii) to move towards a final destination.

A. Control Law for the Ordinary Followers

Consider an (ordinary) follower agent $A_i$ (for example $A_3$ in Fig. 1) and the two agents $A_j$ and $A_k$ it follows ($A_2$ and $A_4$ for the example). Due to the distance constraints of keeping $|p_j(t) - p_i(t)|$ and $|p_k(t) - p_i(t)|$ at the desired values of $d_{ij}, d_{ik}$ respectively, at each time $t \geq 0$, the desired position $p_{ij}(t)$ of $A_i$ is the point whose distances to $p_j(t)$ and $p_k(t)$ are $d_{ij}, d_{ik}$ respectively and which satisfies continuity of $p_{ij}(t)$. Assuming $|p_j(t) - p_{ij}(t)|$ is sufficiently small, $p_{ij}(t)$ can be explicitly determined as $p_{ij}(t) = \overline{p}_{jk}(t, p_i(t)) = (\overline{v}_{jk}(t, p_i(t)), \overline{v}_{jk}(t, p_i(t)))$

where $\overline{p}_{jk}(t, p)$ for any $p \in \mathbb{R}^2$ denotes the intersection of the circles $C(p_j(t), d_{ij})$ and $C(p_k(t), d_{ik})$ that is closer to $p$, and in the notion $C(\cdot, \cdot)$ the first argument denotes the center and the second denotes the radius. Based on this observation, we propose the following control law for the follower agents:

\[
v_i(t) = \overline{v}_i(t) + \sqrt{1 - \beta_i^2(t)} v_{ij}(t)
\]

\[
\beta_i(t) = \left\{ \begin{array}{ll}
0, & |\overline{p}_{jk}(t)| < \varepsilon_k \\
\varepsilon_k / \delta_{ij}(t), & |\overline{p}_{jk}(t)| \leq 2 \varepsilon_k \end{array} \right.
\]

where $\overline{v}_i(t) = \overline{v}_i(t)\overline{v}_{ij}(t)$ and $\overline{v}_{ij}(t)$ is introduced to avoid chattering due to small $\varepsilon_k$.

B. Control Law for the First-Follower

Let agent $A_i$ be the first-follower and $A_j$ the leader.

First, observe that once the first-follower satisfies its distance constraint with the leader, it is free to rotate around the leader. For the example in Fig. 1, the first-follower can move on the circle with center $A_j$ and radius $d_{21}$ provided that it does not need to use the whole of its velocity capacity to satisfy $|A_1A_2| = d_{21}$. Based on this observation and the assumption in Section II for 1-DOF agents, we propose the following control scheme for the first-follower agent $A_i$:

\[
v_i(t) = \overline{v}_i(t) + \sqrt{1 - \beta_i^2(t)} v_{ij}(t)
\]

\[
\delta_i(t) = (|\delta_{ji}(t)|, |\delta_{ki}(t)|) = p_j(t) - p_i(t)
\]

\[
\overline{p}_{jk}(t) = (\overline{v}_{jk}(t, p_i(t)), \overline{v}_{jk}(t, p_i(t)))
\]

where $\overline{v}_{ij}(t) = \overline{v}(\overline{v}_{ij}(t), \overline{v}_{ij}(t))$ and $\overline{v}_{ij}(t)$ is a small design constant. In (2), the switching term $\beta_i(t)$ is introduced to avoid chattering due to small but acceptable errors in the desired inter-agent distances.

1 However, the virtual vector field approaches described in these works are different from our approach, as in these works, the inter-agent distance constraints are not considered hence do not constitute a vector field.
\( \varepsilon_k, \varepsilon_f > 0 \) are small design constants and \( \langle \cdot, \cdot \rangle \) denotes the dot product operation. In (3), via the switching term \( \bar{\beta}_i(t) \), the controller switches between a translational action (4) to satisfy \( |A_i A_j| = d_{ij} \) and a rotational action (5) to move the agent \( A_i \) towards \( p_{ij} \), which can take place only when \( |A_i A_j| \) is sufficiently close to \( d_{ij} \).

In (5), \( \bar{\delta}^\perp_{ij}(t) \) is the unit vector perpendicular to the distance vector \( \delta_{ij}(t) = p_{ij}(t) - p_i(t) \) with clockwise orientation with respect to the circle \( C(p_j(t), d_{ij}) \), and the term \( \text{sgn} \left( (\delta_{ij}(t), \bar{\delta}^\perp_{ij}(t)) \right) \) determines the orientation of motion that would move \( A_i \) towards \( A_j \). The switching term \( \bar{\beta}_i(t) \) is for avoiding chattering due to small but acceptable errors in the final position of \( A_i \).

**C. Control Law for the Leader**

If a given agent \( A_i \) is the leader of the formation (e.g., \( A_1 \) in Figure 1), since it does not have any constraint to satisfy, it can use its full velocity capacity only to move towards its desired final position \( p_{if} \). Hence the velocity input at each time \( t \) can be simply designed as a vector with magnitude \( \tau \) in the direction of \( p_{if}(t) - p_i(t) \):

\[
v_i(t) = \tau \bar{\beta}_i(t) \delta_{ij}(t) / |\delta_{ij}(t)|
\]

\[
\bar{\beta}_i(t) = \begin{cases} 
0, & |\delta_{ij}(t)| < \varepsilon_f \\
\frac{|\delta_{ij}(t)| - \varepsilon_f}{\varepsilon_f} & \varepsilon_f \leq |\delta_{ij}(t)| < 2\varepsilon_f \\
1, & |\delta_{ij}(t)| \geq 2\varepsilon_f
\end{cases}
\]

The switching term \( \bar{\beta}_i(t) \) again prevents chattering due to small but acceptable errors in the final position of \( A_i \).

**D. Simulation Results**

The control laws (2)-(6) have been successfully tested via a number of simulations on various formations with leader-follower structure for various initial and desired final settings. We present the results for the formation depicted in Fig.1 for a sample initial and desired final setting pair. Assuming that the desired distance between each neighbor agent pair \( (A_i, A_j) \) is \( d_{ij} = 1 \) m and choosing the design parameters as \( \tau = 1 \) m/s and \( \varepsilon_k = 0.01 \). Figure 2 shows the motion of the formation for the following initial and desired final positions of the agents (units are all in m):

- \( p_i(0) = (0,0) \), \( p_j(0) = (-\sqrt{3}/2, 0.5) \), \( p_{ij}(0) = (-\sqrt{3}/2, -0.5) \),
- \( p_i(0) = (-\sqrt{3}, 0) \), \( p_{ij} = (-5, 2) \), \( p_{xj} = (-5 - \sqrt{3}/2, 2.5) \),
- \( p_{yj} = (-5 - \sqrt{3}/5, 2.15) \), \( p_{ix} = (-5 - \sqrt{3}/2) \).

**IV. CONTROL FOR THE THREE-COLEADER STRUCTURE**

**A. Control Law Design**

In this section, we derive the counterparts of the control laws designed in Section III for persistent formations with the 3-coleader structure. Again to illustrate our designs, we use a simple formation with three co-leaders \( A_1, A_2, A_3 \) and one (ordinary) follower \( A_4 \) as depicted in Fig. 3.
constraints for a 0-DOF agent, satisfying its single distance constraint and then moving to its desired final position for a 1-DOF agent, and moving to its desired final position for a 2-DOF agent. The corresponding control laws are derived as (2), (3)-(5), and (6), respectively.

Using the same argument and noting that each co-leader has 1-DOF and each follower has 0-DOF in a persistent formation with the 3-coleader structure, we simply select (2) as the control scheme for the followers and (3)-(5) as the control law for each of the three co-leaders.

B. Simulation Results

Similarly to the tests reported in Section III, we have successfully tested the control scheme designed in Section IV.A via a number of simulations for the 3-coleader structure. We present the results for the formation depicted in Fig. 3 for a sample initial and desired final setting pair.

Assuming that the desired distance between each neighbor agent pair \((A_i, A_j)\) is \(d_{ij} = 1\) m, Fig. 4 shows the results for the same design parameters and initial and final agent positions as the example in Section III.D. Note that the motion paths are not simply along the lines connecting the initial and final agent positions as in Section III, which is mainly due to guidance of the formation by three 1-DOF (co-leader) agents with constrained (circular) motions.

V. REDESIGN FOR NONHOLONOMIC AGENT KINEMATICS

In Sections III and IV, we have designed control schemes for cohesive motion of persistent formations based on the integrator model (1) for the agent kinematics. In this section we discuss the effects of assuming an agent model other than (1) and redesign our schemes in Sections III and IV for the nonholonomic unicycle model [7]. For each agent \(A_i\), we consider the following kinematic model for unicycle nonholonomic robots:

\[
\begin{align*}
\dot{x}_i &= v_i \cos \theta_i, \\
\dot{y}_i &= v_i \sin \theta_i, \\
\dot{\theta}_i &= \omega_i,
\end{align*}
\]

(7)

where \(p_i(t) = (x_i(t), y_i(t))\) denotes the position of \(A_i\) as before and \(\theta_i(t)\) denotes the orientation of the agent with the convention depicted in Fig. 5 (a). The control inputs are the translational speed \(v_i\) and the angular velocity \(\omega_i\).

Next we redesign the control schemes presented in previous sections based on the agent kinematics (7). Due to space limitations, we only present our redesign for formations with the 3-coleader structure. We illustrate the use of our control design again on the formation depicted in Fig. 3. In the redesign of the control scheme of Section III, we employ the “separation-separation” control idea that was published in [7]. We first describe the idea for a virtual setting where one agent with kinematics (7) follows two other agents keeping a specific distance from each. Then we present our redesign based on this idea.

Consider an agent \(A_i\) that follows two other agents, \(A_j\) and \(A_k\) (all with kinematics (7)). Suppose that it is desired for \(A_i\) to keep distances \(d_{ij}\) and \(d_{ik}\) from \(A_j\) and \(A_k\), respectively. The “separation-separation” control law for this task is given as follows [7]:

\[
\begin{align*}
\dot{x}_i &= s_a \sin \gamma_a - s_k \sin \gamma_k + v_a \cos \psi_a \sin \gamma_a - v_k \cos \psi_k \sin \gamma_k \sin(\gamma_i - \gamma_a) \\
\dot{y}_i &= s_a \cos \gamma_a + s_k \cos \gamma_k - v_a \cos \psi_a \cos \gamma_a + v_k \cos \psi_k \cos \gamma_k \\
\dot{\theta}_i &= \frac{k_1 \sin(\gamma_i - \gamma_a)}{s_a} \\
s_a &= k_1 (d_{ij} - |p_i - p_j|), \quad \gamma_a = \psi_a + \theta_i - \theta_j, \quad \text{for } i \in \{j, k\}
\end{align*}
\]

(8)
where \( \psi_{ij} \) is the separation angle defined in Fig. 5 (b) and \( k_1, k_2 > 0 \) are some design coefficients.

In a persistent formation with the 3-coleader structure, we can use \( (8) \) directly for a follower agent \( A_i \) that follows agents \( A_j \) and \( A_k \) since the task of \( A_i \) as a follower is the same as the above “separation-separation” control task.

However, if \( A_i \) is a co-leader following an agent \( A_j \), one cannot use \( (8) \) directly. In this case we consider a virtual agent \( A_{ik} \) (with speed \( v_{ik}(t) \)) which lies on the line segment \([p_i(t) , p_k(t)] \) \( \forall t \) and a corresponding time-varying desired distance \( d_{ik}(t) \) which are explicitly defined as follows:

\[
p_{ik}(t) = \begin{cases} p_{ij}(t) + \left( \frac{p_k - p_i(t)}{p_k - p_i(t)} \right) \| p_k - p_i(t) \|, & \text{if } \| p_k - p_i(t) \| > 1 \\ p_k, & \text{otherwise} \end{cases}
\]

\[
\theta_{ik}(t) = \arccos \left( \frac{\langle p_j - p_k(t), p_i(t) - p_j(t) \rangle}{\| p_j - p_k(t) \| \cdot \| p_i(t) - p_j(t) \|} \right),
\]

\[
v_{ik}(t) = \begin{cases} \left\lfloor \frac{m}{s} \right\rfloor & \text{if } \| p_k - p_i(t) \| > 1 \\ \| p_k - p_i(t) \|, & \text{otherwise} \end{cases}
\]

\[
d_{ik}(0) = \begin{cases} 1 \left( m \right) & \text{if } \| p_k - p_i(t) \| > 1 \\ \| p_k - p_i(t) \|, & \text{otherwise} \end{cases}
\]

In summary, we use the control law \( (8) \) for a follower \( A_i \), following agents \( A_j, A_k \), and the control law \( (8),(9) \) for a co-leader \( A_{ik} \) following an agent \( A_j \). We have tested this control scheme via a number of simulations. In these simulations, it is observed that the control goal of reaching the final positions is achieved, nevertheless the performance is poor compared to the performance seen in Section IV in terms of both the path length and the distance constraints. One reason for this phenomenon is (design-) parametric sensitivity and certain nonlinear characteristics of the “separation-separation” control law \( (8) \), particularly the denominator term whose magnitude may become very small from time to time. Another reason is that the control laws for the co-leaders are not derived based directly on their specific duties but rather adapted from the “separation-separation” idea which is mainly for an agent following two other agents. The addressing of the above issues will be discussed in an extended version of this paper.

Design of an enhanced control scheme to obtain a performance level that is comparable to the results in Sections III and IV is currently being investigated by the authors. Nevertheless, the simulation results demonstrate the feasibility of cohesive motion control with agent kinematics models that are more complex than the velocity integrator model.

A closer look at \( (8) \) reveals that due to the sine function in the denominator, the angular and translational velocity inputs may become unbounded. In our work, this problem is eliminated in the implementation of the controller using a velocity limiter.

VI. CONCLUSION

In this paper, we have formulated and presented “a” solution for the problem of controlling the cohesive motion of rigid and constraint-consistent autonomous formations, where the rigidity of the formation is maintained via a set of constraints on the agents to keep their distances from certain other agents at some predefined values. For both of the two main hierarchical (underlying directed graph) structures for such 2-dimensional formations, we have designed decentralized control laws for cohesive motion of the formation. The designs have been initially performed assuming a simple integrator agent kinematics, and later extended for a nonholonomic unicycle agent model. Directed graph notions, basic vector analysis, and switching are used in system modeling and control design. The effectiveness of the designed control schemes have been demonstrated via a set of simulation results.

There exist a number of topics for future work. A formal stability and convergence analysis for the proposed control designs is underway for an extended version of this paper. Beside that, the proposed control laws and strategies can be enhanced to make the paths of the agents smoother and/or more optimal in the sense of total displacement of all agents, etc. The control schemes can be re-designed for agent kinematics other than the velocity integrator and nonholonomic unicycle models. Consideration of obstacles in the region and addition of obstacle avoidance to the cohesive motion problem is another future research aspect.

REFERENCES


