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Distributed Bipartite Containment Tracking over Signed Networks with Multiple Leaders

Pelin Şekercioğlu Elena Panteley Ioannis Sarras Antonio Loría Julien Marzat

Abstract—We address the distributed bipartite containment tracking-control problem for second-order systems over multi-leader signed networks. In such systems, the networks' interconnections have signed weights; they are positive if the agents are cooperative with each other and negative otherwise. Moreover, as multiple leaders intervene in the network, it is hardly possible to achieve consensus, unless very stringent conditions are met. Instead, all the agents' states converge to a residual compact set resulting from the agents' initial conditions and the network's topology. In this paper, we propose a bipartite-containment controller for second-order linear systems. For the containment set we establish global exponential (hence, robust) stability, and we compute the specific equilibria to which all agents converge inside the containment set. In addition, we provide strict Lyapunov functions for signed-graph networks. Also, we illustrate our theoretical findings via numerical simulations.

Index Terms—Multiconsensus, bipartite containment tracking, containment, autonomous vehicles, signed graphs.

I. INTRODUCTION

IN the study of coordination of multiagent networks, a large number of problems have been extensively addressed, such as consensus for first-order [1], second-order [2] and linear high-order dynamics [3]. In particular, when there is a leader in the network, all followers converge to the leader's state [4]. However, this so-called leader-follower consensus does not occur when the network contains more than one leader. For this case, in which multiple consensus equilibria may appear, it is more appropriate to speak of *containment* control [5]. This problem consists of making all the followers' states converge to a convex hull that is determined by the leaders' initial conditions and is solvable if for each follower there exists at least one leader that has a directed path to that follower.

There are multiple studies on distributed containment control, e.g., for social networks [6] or for networks of single-integrators [7], [8], double-integrators [9], [10], and general linear autonomous systems [11]. However, most of the current research on the consensus or containment problems for multi-agent systems is on cooperative networks, *i.e.*, the coordination of nodes is achieved only by cooperative interactions. Yet,

P. Şekercioğlu, I. Sarras, and J. Marzat are with DTIS, ONERA, Univ Paris-Saclay, F-91123 Palaiseau, France. E-mail: {pelin.sekercioğlu, ioannis.sarras, julien.marzat}@onera.fr. A. Loría and E. Panteley are with L2S, CNRS, 91192 Gif-sur-Yvette, France. antonio.loria@cnr.fr, elena.panteley@centralesupelec.fr. P. Şekercioğlu is also with L2S-CentraleSupélec, Univ Paris-Saclay, Saclay, France.

there are many scenarios in which agents may be competitive or even disruptive, and containment is significant. For instance, in robotic applications, in the context of herding control [12], in aerospace applications involving the attitude control of multiple rigid bodies [13], and in the context of social networks that include deceiving influencers injecting disinformation [14], to mention a few. In this case, the interconnections may be either positive or negative so, in general, at least two consensus equilibria appear, hence we speak of bipartite consensus [14], [15]. In the case that multiple leaders (cooperative and/or antagonistic) appear, moreover, the analysis of the properties of the Laplacian matrix and the construction of the eigenvectors associated with its zero eigenvalues are more complex [16] and, also in this case, more than two consensus equilibria may appear [17]–[19].

To analyze directed signed networks containing multiple leaders, in [20], the notion of containment control is extended to *bipartite containment tracking-control*. Succeeding [20], bipartite containment has been also studied in [21], [22] and [23]. In general, it consists of having all the followers' states converge to a convex hull determined by the network's topology and the initial conditions of the leaders and the mirror leaders. Moreover, in [20] and [23], limit points for the followers' states are given explicitly. It is also important to mention that in [21]–[23] only structurally balanced networks are considered. Roughly speaking, these are networks whose representing graph contains positive-only cycles or none at all—see Section III and [24] for details. Such networks exclude important cases, such as certain agents capable of being friends with the enemies of their friends. Furthermore, in [21], only cooperative leaders are considered, and in [23], interconnections between the followers are assumed to be only undirected.

As in [20], in this paper, we study the bipartite containment tracking problem over structurally balanced and unbalanced signed networks with multiple cooperative or competitive leaders. Also, as in [20], we allow leaders to have neighbors. In contrast to the latter reference, however, our results apply to second-order systems, which better describe mechanical systems and a variety of (feedback linearizable) autonomous vehicles [25]. In contrast to [21]–[23], our main statements hold for the general case of structurally unbalanced networks, and beyond bipartite containment tracking, we provide explicit estimates of the limit points of the followers.

Furthermore, we give sufficient conditions for exponential stability of the containment set and, in contrast to all references

mentioned previously, our proofs are constructive; we provide a strict Lyapunov function regardless of whether the network is structurally balanced or unbalanced. Exponential stability is important because it covers the much weaker property of mere convergence to the limit points (or to the interior of a convex hull); providing strict Lyapunov functions is significant because they are a basis to establish, in addition, input-to-state stability. Thus, our main results guarantee the robustness of the containment set with respect to additive perturbations.

From a technical viewpoint, our main results are based on the framework introduced in [26]. We extend the method of the latter to general signed graphs containing multiple leaders. We recast the bipartite containment problem into one of stability of a set of the appropriately defined errors. Then, we generalize a statement in [27] on the Lyapunov characterization of exponential stability of sets, for linear systems with one pole at zero and others having negative real parts. The technical result we provide here applies to systems with several poles at the origin. Then, in addition to exponential stability of the containment set, we provide the explicit limit values of the followers by a matrix determined by all eigenvectors associated with the zero eigenvalues. We demonstrate a possible form of these eigenvectors both for structurally balanced and unbalanced networks. In particular, when the considered graph is a traditional cooperative network, the bipartite containment tracking results stay valid for containment tracking.

Notation. $\|\cdot\|$ denotes the Euclidean norm for vectors, absolute value for scalars, and induced norm for matrices.

II. PROBLEM FORMULATION

Consider a group of n second-order dynamical systems modeled by

$$\dot{x}_{1_i} = x_{2_i}, \quad x_{1_i}, x_{2_i} \in \mathbb{R} \quad (1a)$$

$$\dot{x}_{2_i} = u_i, \quad u_i \in \mathbb{R}, \quad i \in \mathcal{I}_{\mathcal{N}} \quad (1b)$$

where $\mathcal{I}_{\mathcal{N}} := \{1, 2, \dots, n\}$.

Remark 1: The system (1) is a simple representation of an autonomous vehicle, in which x_{1_i} represents position and x_{2_i} denotes velocity—cf. [28]. More generally, it represents feedback-linearizable nonlinear systems. It is for notational simplicity, and without loss of generality, that we assume that $x_{1_i} \in \mathbb{R}$, but the contents of this paper apply to systems of higher dimension—see Section V. •

The consensus problem for (1), that is, to ensure that

$$\lim_{t \rightarrow \infty} [x_j(t) - x_i(t)] = 0, \quad \forall i, j \leq n, \quad (2)$$

where $x_i = [x_{1_i} \quad x_{2_i}]^\top$, via distributed control, is completely solved under various conditions on the interconnections and the resulting network's topology. For instance, for static directed networks, it is well-known that under the consensus-control law—cf. [5, Section 8],

$$u_i = -k_1 \sum_{j=1}^n a_{ij}(x_{1_i} - x_{1_j}) - k_2 \sum_{j=1}^n a_{ij}(x_{2_i} - x_{2_j}) - k_3 x_{2_i}, \quad (3)$$

where $a_{ij} \in \mathbb{R}$ is the adjacency weight between nodes i and j , with $k_1, k_2 > 0$ and $k_3 \geq 0$, the expressions in (2) hold if and

only if the underlying graph contains a directed spanning tree [29]. The first two terms in (3) ensure position and velocity consensus respectively, *i.e.*, that (2) holds, but the latter does not necessarily imply that the systems *stabilize* at a common set-point, for which it is required, in addition, that $x_{2_i} \rightarrow 0$. Indeed, we show in Section IV that $x_{2_i} \rightarrow 0$ is possible only if $k_3 > 0$. If $k_3 = 0$, the closed-loop solutions may grow unboundedly, but this is not necessarily nocuous; *e.g.*, the goal may be for a group of vehicles to continue advancing in formation at equal velocity without ever stopping. Thus, the gain k_3 may be freely chosen to be positive or null, depending on whether it is required that $x_{2_i} \rightarrow 0$ or not, respectively—see Proposition 3 on p. 6.

Now, as is well known, if the graph contains a directed spanning tree, the resulting Laplacian matrix, $L := [l_{ij}] \in \mathbb{R}^{n \times n}$, where

$$l_{ij} = \begin{cases} \sum_{k \in \mathcal{I}_{\mathcal{N}}} a_{ik} & i = j \\ -a_{ij} & i \neq j, \end{cases} \quad (4)$$

has exactly one eigenvalue equal to zero. Therefore, the consensus equilibrium is uniquely determined by the left eigenvector v_l corresponding to the eigenvalue, $x_{1_m} := v_l^\top x_1(0)$ [29]. Furthermore, one can construct a strict Lyapunov function to establish exponential stability of the origin in the space of the synchronization errors $e := x_1 - v_r x_{1_m}$ [27], where v_r is the right eigenvector corresponding to zero eigenvalue.

Such is the case, at least, when all nodes in the network are *cooperative*, that is, if $a_{ij} \geq 0$ for all $i, j \leq n$. For networks in which some of the nodes are *competitive*, we have $a_{ij} < 0$ for *some* $i, j \leq n$. In such scenario, the distributed consensus control law (3) may be replaced with

$$u_i = -k_1 \sum_{j=1}^n |a_{ij}| (x_{1_i} - \text{sgn}(a_{ij}) x_{1_j}) - k_2 \sum_{j=1}^n |a_{ij}| (x_{2_i} - \text{sgn}(a_{ij}) x_{2_j}) - k_3 x_{2_i}, \quad (5)$$

where $k_1, k_2 > 0$, and $k_3 \geq 0$. The first two terms result from a natural modification of (3), to take into account the signs of the interconnections—cf. [30]. Under the distributed control law (5), agents on a directed connected signed network containing a directed spanning tree achieve *bipartite consensus* if and only if the underlying graph is structurally balanced [14].

If the signed network is structurally balanced (see Section III for a definition), the associated Laplacian matrix has a simple zero eigenvalue [14] and its associated right eigenvector has all entries equal to ± 1 , which results in agents converging to the same state in modulus but different in signs. In such networks, moreover, it appears natural to encounter several competitive leader nodes that inject disinformation into the network. In this particular case, bipartite consensus can no longer be achieved due to the existence of multiple leaders and antagonistic interactions in the network. Agents can then achieve *bipartite containment* [20], where followers converge to the convex hull spanned by all leaders' trajectories and their mirrored trajectories, in order to avoid competitive leaders in the system.

In this paper, we analyze the behavior of the networked systems (1) in closed loop with the distributed control law (5) and under the assumption that several cooperative or competitive leaders interfere. Since consensus is unattainable, the control goal for general signed graphs is set to achieving *bipartite containment tracking*, that is,

$$\lim_{t \rightarrow \infty} [|x_j(t)| - \max_{i \in \mathcal{L}} |x_i(t)|] \leq 0, \quad j \in \mathcal{F}, \quad (6)$$

where \mathcal{L} and \mathcal{F} are the sets of leaders and followers respectively—see the Standing Assumption below. This is the problem solved, *e.g.*, in [20]–[23]. For a more restrictive case of structurally balanced signed networks, the bipartite containment set in (6) is refined so that the achievable objective is

$$\lim_{t \rightarrow \infty} [x_j(t) - \max_{i \in \mathcal{L}} (\sigma_i x_i(t))] [x_j(t) - \min_{i \in \mathcal{L}} (\sigma_i x_i(t))] \leq 0, \quad (7)$$

where $j \in \mathcal{F}$, $\sigma_i = 1$ if $(i, j) \in \mathcal{V}_p, p \in \{1, 2\}$ or $\sigma_i = -1$ if $i \in \mathcal{V}_p, j \in \mathcal{V}_q$ with $p, q \in \{1, 2\}, p \neq q$. In contrast to the convex hull resulting from (6), that is $x_j(t) \in [-\max_{i \in \mathcal{L}} |x_i(t)|, \max_{i \in \mathcal{L}} |x_i(t)|]$, agents in a structurally balanced signed network converge to a disconnected set composed of two disjoint convex subsets, that is $x_j(t) \in [\min_{i \in \mathcal{L}} (\sigma_i x_i(t)), \max_{i \in \mathcal{L}} (\sigma_i x_i(t))]$ —see Section V-A and V-B. Beyond the inequalities in (6) and (7), we give the explicit limit value of the followers' states and establish exponential stability of the containment set. This is significant because it allows to give a tight bound depending only on the initial conditions of the leaders. This is done under the following.

Standing Assumption:

- 1) The network contains m leaders, which can be organized into k groups of p_i leaders included in a strongly connected subgraph, where $1 \leq k \leq m \leq n$, $i \in \mathcal{I}_k$, and $\sum_{i=1}^k p_i = m$ —cf. [20, Definition 1].
- 2) Given each follower ν_j , *i.e.*, with $j \in \mathcal{F}$ with $\mathcal{F} := \{m+1, m+2, \dots, n\}$, there exists at least one leader ν_i *i.e.*, with $i \in \mathcal{L} := \{1, 2, \dots, m\}$, such that there exists at least one path from ν_i to ν_j —cf. [20, Condition 1].

The Standing Assumption is mild; in the case that there exists no more than one leader group, it boils down to the necessary condition for consensus that imposes the existence of a spanning tree. As the networks considered here contain, *a priori*, multiple leaders, the resulting Laplacian matrix has as many zero eigenvalues and associated eigenvectors as the number of groups of leaders [31]. This also results in multiple convergence points for the agents. Therefore, in contrast to the consensus equilibrium $x_{1_m} = v_l^\top x_1(0)$ for leaderless and single-leader networks, the final states of the agents are determined by all eigenvectors associated with the zero eigenvalues. One of this paper's contributions is to show that under the control law (5) and the Standing Assumption, the limit values of the agents are given by

$$x_m := (\mathbb{V} \otimes I_2)x, \quad (8)$$

where \mathbb{V} is a matrix determined by all the eigenvectors associated with the k null eigenvalues of the Laplacian. More

precisely, the matrix \mathbb{V} is given by,

$$\mathbb{V} := \sum_{i=1}^k \begin{bmatrix} v_{r_{i,1}} \\ v_{r_{i,2}} \\ \vdots \\ v_{r_{i,n}} \end{bmatrix} [v_{l_{i,1}} \quad v_{l_{i,2}} \quad \dots \quad v_{l_{i,n}}], \quad (9)$$

where v_{r_i} and v_{l_i} denote, respectively, the right and left eigenvectors of the matrix L corresponding to the i th 0 eigenvalue, and, for each $j \leq n$, $v_{r_{i,j}}$ and $v_{l_{i,j}}$ denote, respectively, the j th element of the i th right and left eigenvectors. In particular, as we demonstrate further below, a possible form of the right and left eigenvectors associated with the zero eigenvalues is

$$v_{r_1} = \begin{pmatrix} 1_{p_1} \\ 0_{p_2} \\ \vdots \\ 0_{p_k} \\ \xi_1 \end{pmatrix}, \quad v_{r_2} = \begin{pmatrix} 0_{p_1} \\ 1_{p_2} \\ \vdots \\ 0_{p_k} \\ \xi_2 \end{pmatrix}, \quad \dots, \quad v_{r_k} = \begin{pmatrix} 0_{p_1} \\ 0_{p_2} \\ \vdots \\ 1_{p_k} \\ \xi_k \end{pmatrix}, \quad (10a)$$

$$v_{l_1} = \begin{pmatrix} \rho_{p_1} \\ 0_{p_2} \\ \vdots \\ 0_{p_k} \\ 0_{n-m} \end{pmatrix}, \quad v_{l_2} = \begin{pmatrix} 0_{p_1} \\ \rho_{p_2} \\ \vdots \\ 0_{p_k} \\ 0_{n-m} \end{pmatrix}, \quad \dots, \quad v_{l_k} = \begin{pmatrix} 0_{p_1} \\ 0_{p_2} \\ \vdots \\ \rho_{p_k} \\ 0_{n-m} \end{pmatrix}, \quad (10b)$$

where $\xi_i \in \mathbb{R}^{n-m}$ is defined in Lemmas 2 and 3 farther below, $1_{p_i} \in \mathbb{R}^{p_i}$ is a vector of ones, $0_{p_i} \in \mathbb{R}^{p_i}$ and $0_{n-m} \in \mathbb{R}^{n-m}$ are vectors of zeros, and $\rho_{p_i} \in \mathbb{R}^{p_i}$. If $p_i = 1$, where $i \leq k$, we have $\rho_{p_i} = 1$, so the corresponding left eigenvector v_{l_i} has a unique non-zero element equal to 1. If $p_i > 1$, v_{l_i} has p_i elements belonging to $(-1, 1)$, where $\sum_{l=1}^{p_i} |\rho_l| = 1$. The definition of the eigenvectors given in (10) covers that of [31, Corollary 4.2] and [17, Proposition 3], which are restricted to unsigned networks. With this under consideration, we establish bipartite containment of the system (1) and, more significantly, that $x \rightarrow x_m$ —as defined in (8)—exponentially.

III. ANALYSIS APPROACH

Our main results are based on original statements for signed networks with an associated Laplacian having multiple zero eigenvalues. First, following the framework laid in [26] and extending it to multi-leader signed networks, we show how to construct the matrix \mathbb{V} in (8)–(9), to define the average states of the agents. Then, we extend the method of [27], to construct strict Lyapunov functions for linear systems with one zero eigenvalue, to the case of multiple null eigenvalues.

To that end, we first recall certain notations and definitions that will be used later. A signed graph is said to be *structurally balanced* if it may be split into two disjoint sets of vertices \mathcal{V}_1 and \mathcal{V}_2 , where $\mathcal{V}_1 \cup \mathcal{V}_2 = \mathcal{V}$, $\mathcal{V}_1 \cap \mathcal{V}_2 = \emptyset$ such that for every $i, j \in \mathcal{V}_p, p \in [1, 2]$ if $[a_{ij}] \geq 0$ while for every $i \in \mathcal{V}_p, j \in \mathcal{V}_q, p, q \in [1, 2], p \neq q$ if $[a_{ij}] \leq 0$. It is *structurally unbalanced*, otherwise. The following definition is also recalled from [31] to introduce some useful sets of vertices in a graph.

Definition 1: We define a reachable set R_i for any vertex i , as the set containing vertex i and all vertices j such that there exists a directed path from vertex i to vertex j . A reachable set is a maximal reachable set if $R = R_i$ for some i and there is no j such that $R_i \subset R_j$. The reachable set R of vertices is called a *reach* if it is a maximal reachable set, that consists of a leader group and its followers. For each reach \mathcal{R}_i of a graph, we define the *exclusive part* of \mathcal{R}_i as the set $\mathcal{H}_i = \mathcal{R}_i \setminus \bigcup_{j \neq i} \mathcal{R}_j$, i.e., the set of followers influenced only by the leader group i , and the *common part* of \mathcal{R}_i as the set $\mathcal{C}_i = \mathcal{R}_i \setminus \mathcal{H}_i$, i.e., the set of followers influenced by leaders other than the i th leader group.

The following statements, which lead to the construction of the matrix \mathbb{V} , are original contributions of this paper and extend Corollary 4.2 of [31] to the case of signed networks.

Lemma 1: Let \mathcal{G} denote a directed signed graph and let L denote the associated Laplacian matrix. Suppose \mathcal{G} has n vertices and k reaches. Then, the algebraic and geometric multiplicity of the eigenvalue 0 is equal to k . \square

Proof: Let $L_+ := D - |A|$ denote the associated Laplacian matrix of \mathcal{G}_+ , where D is the in-degree matrix and A is the adjacency matrix of \mathcal{G} . \mathcal{G}_+ and \mathcal{G} have identical reaches. Then, the fact that the algebraic and geometric multiplicity of 0 equals k follows from [31, Theorem 3.2]. \square

Lemma 2: Let \mathcal{G} denote a structurally unbalanced directed signed graph. Then, the eigenspace generated by the eigenvectors associated with the null eigenvalues, has a basis defined by the vectors $\gamma_i \in \mathbb{R}^n$, with $i \leq k$, whose elements satisfy the following:

- (i) $\gamma_{i,j} = 0$ for $j \notin \mathcal{R}_i$,
- (ii) $|\gamma_{i,j}| = 1$ for $j \in \mathcal{H}_i$,
- (iii) $|\gamma_{i,j}| \leq 1$ for $j \in \mathcal{C}_i$,
- (iv) $\sum_j |\gamma_i| \leq \mathbf{1}_n$,

where $j \in \mathcal{I}_N$, and $\gamma_{i,j}$ denotes the j th element of γ_i . \square

Proof: For structurally unbalanced graphs, Items (i) and (ii), follow from Definition 1, under the Standing Assumption. Item (iii) follows from [16], while Item (iv) results from computing the null space of L , which is generated by $\gamma_i \in \mathbb{R}^n$ such that $L\gamma_i = 0$ for each $i \leq k$. This gives $L \sum_{i=1}^k \gamma_i = 0$. Then, under the Standing Assumption, the Laplacian matrix is equal to

$$L = \begin{bmatrix} 0 & 0 \\ -A_{lf} & L_f + \Delta_{|A_{lf}|} \end{bmatrix},$$

where $A_{lf} \in \mathbb{R}^{(n-m) \times m}$ and $L_f + \Delta_{|A_{lf}|} \in \mathbb{R}^{(n-m) \times (n-m)}$, we have $-A_{lf} \sum_{i=1}^k \gamma_{i,m} + (L_f + \Delta_{|A_{lf}|}) \sum_{i=1}^k \gamma_{i,n-m} = 0$. This gives us $(L_f + \Delta_{|A_{lf}|}) \sum_{i=1}^k \gamma_{i,n-m} = A_{lf} \sum_{i=1}^k \gamma_{i,m}$, where $\sum_{i=1}^k \gamma_{i,m} = \mathbf{1}_m$ from (10). The sum of the remaining rows of γ_i s gives the following, $\sum_{i=1}^k \gamma_{i,n-m} = (L_{nr} + \Delta_{|A_{rnr}|})^{-1} A_{rnr} \mathbf{1}_m$ and it follows that $\sum_j |\gamma_{i,n-m}| \leq \mathbf{1}_{n-m}$ from Lemma 6 of [20]. Thus, we conclude that $\gamma_{i,j} = 0$ for $j \notin \mathcal{R}_i$, $|\gamma_{i,j}| = 1$ for $j \in \mathcal{H}_i$, $|\gamma_{i,j}| \leq 1$ for $j \in \mathcal{C}_i$, and $\sum_j |\gamma_i| \leq \mathbf{1}_n$. \square

In the more restrictive case that \mathcal{G} is structurally balanced, we have the following.

Lemma 3: Let \mathcal{G} denote a structurally balanced directed signed graph. Then, the eigenspace generated by the eigenvectors associated with the null eigenvalues, has a basis defined by the vectors $\gamma_i \in \mathbb{R}^n$, with $i \leq k$, whose elements satisfy the following:

- (i) $\gamma_{i,j} = 0$ for $j \notin \mathcal{R}_i$
- (ii) $\gamma_{i,j} = \begin{cases} 1, & \text{if } (\nu_j, \nu_i) \in \mathcal{V}_1 \\ -1, & \text{if } \nu_j \in \mathcal{V}_1, \nu_i \in \mathcal{V}_2 \end{cases}$ for $j \in \mathcal{H}_i$
- (iii) $\gamma_{i,j} \in \begin{cases} (0, 1), & \text{if } (\nu_j, \nu_i) \in \mathcal{V}_1 \\ (-1, 0), & \text{if } \nu_j \in \mathcal{V}_1, \nu_i \in \mathcal{V}_2 \end{cases}$ for $j \in \mathcal{C}_i$
- (iv) $\sum_j |\gamma_i| = \mathbf{1}_n$,

where \mathcal{V}_1 and \mathcal{V}_2 are the two disjoint sets of vertices, $i \in \mathcal{I}_K$, $j \in \mathcal{I}_N$, and $\gamma_{i,j}$ denotes the j th element of γ_i . \square

Proof: For a graph that is structurally balanced, we may apply the *gauge transformation*, which consists in a change of coordinates performed by the matrix $D = \text{diag}(\sigma)$, where $\sigma = [\sigma_1, \dots, \sigma_n]$, $\sigma_j \in \{1, -1\}$, $j \in \mathcal{I}_N$ [14]. Let $L_D = DLD$ denote the unsigned Laplacian matrix of the transformed network. Then, we may express the Laplacian L in Jordan canonical form, as $L = DL_D D = DP_D \Lambda P_D^{-1} D$, where $P_D = [v_{D_1}, \dots, v_{D_k}, P_{D_1}] \in \mathbb{C}^{n \times n}$, $P_D^{-1} = [w_{D_1}^\top, \dots, w_{D_k}^\top, P_{D_1}^\dagger]^\top \in \mathbb{C}^{n \times n}$, and $\Lambda \in \mathbb{C}^{n \times n}$, with v_{D_i} and w_{D_i} , $i \leq m$ are the right and left eigenvectors associated to k zero eigenvalues of L_D . From the Jordan decomposition, we can see that the basis of the null space of L is given by $LD\gamma_{D_i} = LDv_{D_i} = 0$, $i \leq k$ and has a basis defined by the columns of $\gamma = D\gamma_D$, where $\gamma_D = [\gamma_{D_1} \ \dots \ \gamma_{D_k}]$ and the columns $\{\gamma_{D_i}\}$ constitute the basis of the associated eigenspace of L_D . Then, using [31, Corollary 4.2], we obtain the following for a structurally balanced signed network: $\gamma_{i,j} = \sigma_j \gamma_{D_i,j} = 0$ for $j \notin \mathcal{R}_i$, $\gamma_{i,j} = \sigma_j \gamma_{D_i,j} = \sigma_j$ for $i \in \mathcal{H}_i$, $\gamma_{i,j} = \sigma_j \gamma_{D_i,j} \in \sigma_j(0, 1)$ for $j \in \mathcal{C}_i$ and $\sum_j \gamma_i = \sum_j D\gamma_{D_i} = D\mathbf{1}_n$, which gives $\sum_j |\gamma_i| = \mathbf{1}_n$. Items (i) to (iv) follow. \square

In general, for signed networks, after Lemma 2 and setting $v_{r_{i,j}} = \gamma_{i,j}$, we obtain the form given in (10a) for the k right eigenvectors associated to the zero eigenvalues, such that for each $j \leq m$, $v_{r_{i,j}}$ is either equal to 1 or to 0, because the j th leader can only be in the exclusive part of its corresponding reach. The remaining rows $\xi_{i,j}$ of v_{r_i} belong, either to $\{-1, 1\}$ or to $(-1, 1)$, depending on the network's topology and signs of the interconnections. Moreover, under the Standing Assumption and the given form in (10a) for right eigenvectors, as the Laplacian matrix has all entries equal to 0 for its first m rows, we obtain (10b) for k left eigenvectors associated to zero eigenvalues. Notice that, because of the form of the left eigenvectors, each column of the matrix \mathbb{V} has the same properties as the basis defined in Lemma 2. Therefore, we may split \mathbb{V} in four blocks, as follows:

$$\mathbb{V} = \sum_{i=1}^k v_{r_i} v_{l_i}^\top = \left[\begin{array}{c|c} V_l & 0_{m \times (n-m)} \\ \hline V_f & 0_{(n-m) \times (n-m)} \end{array} \right], \quad (11)$$

where $V_l \in \mathbb{R}^{m \times m}$ represents leaders' interactions and $V_f \in \mathbb{R}^{(n-m) \times m}$ represents leader-follower interactions.

It is important to remark that the elements of V_f have the properties stated in Lemma 2. This is significant because, owing to the fact that $x \rightarrow x_m$ where x_m is defined by (8), it is clear that V_f is the matrix that defines the limit point for the followers. Such limit points are determined purely by the leaders' initial conditions, as reflected by the columns of zeros in \mathbb{V} —see (11).

Now, akin to the case of networks containing one leader, in which case the error is defined as $e = x_1 - v_r x_{1_m}$, with $x_{1_m} := v_l^\top x_1$, for multi-leader networks we define the consensus errors as

$$e := ([I - \mathbb{V}] \otimes I_2)x, \quad (12)$$

where $e = [e_1 \ e_2]^\top$. Then, to establish beyond the convergence statements that $x_1 \rightarrow x_{1_m}$ and $x_2 \rightarrow x_{2_m}$ and, consequently, the bipartite containment objectives defined by (6), we will prove the stronger property of global exponential stability of the set $\{(e_1, e_2) = (0, 0)\}$. For that, we shall show how to construct strict—in the space of (e_1, e_2) —Lyapunov functions, based on the following proposition, which is another original contribution of this paper and extends Proposition 1 of [27] to the case of signed networks with multiple leaders.

Proposition 1: Let \mathcal{G} be a directed signed network with multiple leaders. Then the following are equivalent:

- (i) the graph has k groups of leaders and m leaders, and given each follower $\nu_j, \forall j \in \mathcal{F}$, there exists at least one leader $\nu_i, \forall i \in \mathcal{L}$, such that there exists at least one path from ν_i to ν_j ,
- (ii) for any $Q \in \mathbb{R}^{n \times n}, Q = Q^\top > 0$ and for any $\{\alpha_1, \alpha_2, \dots, \alpha_k\}$ with $\alpha_i > 0$, there exists a matrix $P(\alpha_i) \in \mathbb{R}^{n \times n}, P = P^\top > 0$ such that

$$PL + L^\top P = Q - \sum_{i=1}^k \alpha_i (P v_{r_i} v_{l_i}^\top + v_{l_i} v_{r_i}^\top P), \quad (13)$$

where $v_{r_i}, v_{l_i} \in \mathbb{R}$ are the right and left eigenvectors of L associated with the i th 0 eigenvalue. \square

Remark 2: Proposition 1 provides a Lyapunov characterization of the second part of the Standing Assumption. \bullet

Proof of Proposition 1: (i) \Rightarrow (ii): By assumption, the graph \mathcal{G} has k leader groups and is connected. Then, from Lemma 1, it follows that L has k zero eigenvalues, and the rest of its eigenvalues have positive real parts: $0 = \lambda_1 = \dots = \lambda_k < \Re e(\lambda_{k+1}) \leq \dots \leq \Re e(\lambda_n)$. Following the lines of proof as for Lemma 2 in [27], we can write the Jordan decomposition of L as $L = U \Lambda U^{-1} = \sum_{i=1}^k \lambda_i(L) v_{r_i} v_{l_i}^\top + U_1 \Lambda_1 U_1^\top$ with $\Lambda_1 \in \mathbb{C}^{n-k \times n-k}, U = [v_{r_1}, \dots, v_{r_k}, U_1] \in \mathbb{C}^{n \times n}$ and $U^{-1} = [v_{l_1}^\top, \dots, v_{l_k}^\top, U_1^\top]^\top \in \mathbb{C}^{n \times n}$. For any $\{\alpha_1, \alpha_2, \dots, \alpha_k\}$ with $\alpha_i > 0$ define $R = L + \sum_{i=1}^k \alpha_i v_{r_i} v_{l_i}^\top$. From this decomposition and the properties of $\Lambda_1, \Re e\{\lambda_j(R)\} > 0$ for all $j \leq n$. $-R$ is Hurwitz, therefore for any $Q = Q^\top > 0$ and $\alpha_i > 0, i \leq m$, there exists $P = P^\top > 0$ such that

$$\begin{aligned} -PR - R^\top P &= -Q, \\ -P(L + \sum_{i=1}^k \alpha_i v_{r_i} v_{l_i}^\top) - (L + \sum_{i=1}^k \alpha_i v_{r_i} v_{l_i}^\top)^\top P &= -Q, \end{aligned}$$

$$PL + L^\top P = Q - \sum_{i=1}^k \alpha_i (P v_{r_i} v_{l_i}^\top + v_{l_i} v_{r_i}^\top P).$$

(ii) \Rightarrow (i): Let statement (ii) hold and assume that the Laplacian matrix has $k + 1$ zero eigenvalues and the rest of its eigenvalues have positive real parts. In view of Lemma 1, the assumption that the system has k groups of leaders does not hold. Now, the Jordan decomposition of L has the form $L = U \Lambda U^{-1} = \sum_{i=1}^{k+1} \lambda_i(L) v_{r_i} v_{l_i}^\top + U_1 \Lambda_1 U_1^\top$ with $U = [v_{r_1}, \dots, v_{r_{k+1}}, U_1]$ and $U^{-1} = [v_{l_1}^\top, \dots, v_{l_{k+1}}^\top, U_1^\top]^\top$. Next let us consider $R(\alpha_i) = L + \sum_{i=1}^k \alpha_i v_{r_i} v_{l_i}^\top$ which admits the Jordan decomposition $R := U \Lambda_R U^{-1}$, where

$$\Lambda_R := \begin{bmatrix} \alpha_1 & & & & \\ & \ddots & & & \\ & & \alpha_k & & \\ & & & 0 & \\ & & & & \Lambda_1 \end{bmatrix}.$$

Clearly, R is not positive definite because one of its eigenvalues is equal to zero. Then, there exists a matrix $Q = Q^\top$ for which there does not exist a matrix $P = P^\top$ such that $-PR - R^\top P = -Q$, which contradicts statement (ii). \square

IV. BIPARTITE CONTAINMENT OF SECOND-ORDER SYSTEMS

In this section, we present our main results. We will consider bipartite containment protocols for second-order systems, with and without absolute velocity damping. Furthermore, we establish robustness of the bipartite containment tracking in the sense of input-to-state stability with respect to external bounded perturbations.

A. Exponential stability

Consider the system (1), interconnected with the bipartite containment control law (5). We analyze the dynamics of the errors in (12). Differentiating the latter on both sides, to obtain

$$\dot{e} = ([I - \mathbb{V}] \otimes I_2) \dot{x}$$

and using (1) and (5), we obtain the closed-loop dynamical equations

$$\dot{e}_1 = e_2 \quad (14a)$$

$$\dot{e}_2 = -k_1 L e_1 - k_2 L e_2 - k_3 e_2. \quad (14b)$$

Guaranteeing the bipartite containment problem is now recast as a problem of stability analysis of the dynamical system (14). Thus, relying on Proposition 1, our next statement provides sufficient conditions on the controller gains to achieve global exponential stability of the set $\{(e_1, e_2) = (0, 0)\}$, which covers the bipartite containment tracking objective (6).

Proposition 2: Consider the system (14) and let P be generated by (13) with $Q = I_n$. Then, under the Standing Assumption, the set $\{(e_1, e_2) = (0, 0)\}$ is exponentially stable if

$$k_1 > 0, \quad (15a)$$

$$k_2 > 2\sqrt{k_1 \bar{\lambda}_P}, \quad (15b)$$

$$\frac{k_2}{k_3} \geq \bar{\lambda}_P, \quad k_3 \geq 0, \quad (15c)$$

where $\bar{\lambda}_P \geq |P|$ is the largest eigenvalue of P . \square

Remark 3: For conciseness, we consider in one statement the two interesting and distinct cases evoked previously, that $k_3 = 0$ or $k_3 > 0$. Note that if k_3 is chosen to be null (15c) trivially holds, but if it is positive (15c) defines a condition on k_2 and k_3 , relative to $\bar{\lambda}_P$, which depends on the Laplacian L —see (13). \bullet

Proof of Proposition 2: Let $Q = Q^\top > 0$ and $\alpha > 0$ be arbitrarily fixed. Since by the Standing Assumption and Proposition 1, $\exists P = P^\top > 0$ such that (13) holds. Then, consider the following Lyapunov function candidate

$$V(e) = \frac{1}{2}|e_1|^2 + \epsilon e_1^\top P e_2 + \mu e_2^\top P e_2, \quad (16)$$

which is positive definite (for all e as in (12)), under the condition $\epsilon \leq \sqrt{\frac{2\mu}{|P|}}$, $\mu > 0$. The total time derivative of V along the trajectories yields

$$\begin{aligned} \dot{V}(e) &= -k_1 \epsilon e_1^\top P L e_1 \\ &\quad - e_2^\top [k_2 \mu (P L + L^\top P) + 2k_3 \mu P - \epsilon P] e_2 \\ &\quad + e_1^\top (I - k_2 \epsilon P L - 2k_1 \mu L^\top P - k_3 \epsilon P) e_2. \end{aligned}$$

Let $\mu > 0$ be such that $2k_1 \mu = k_2 \epsilon = 1$. Using (13) with $Q = I$ and the identity $P \sum_{i=1}^k v_{r_i} v_{l_i}^\top e_1 = P \sum_{i=1}^k v_{r_i} v_{l_i}^\top e_2 = 0$ we obtain the following:

$$\begin{aligned} -k_1 \epsilon e_1^\top P L e_1 &= -k_1 \epsilon e_1^\top (P L + L^\top P) e_1 = -\frac{1}{2} k_1 \epsilon |e_1|^2, \\ -e_2^\top \mu k_2 (P L + L^\top P) e_2 &= -\mu k_2 e_2^\top e_2, \\ e_1^\top [I - (L^\top P + P L)] e_2 &= -e_1^\top [I - I] e_2 = 0. \end{aligned}$$

Hence, in compact form, we have

$$\begin{aligned} \dot{V}(e) &= -\frac{1}{2} e^\top \begin{bmatrix} \frac{1}{2} k_1 \epsilon I & k_3 \epsilon P \\ k_3 \epsilon P & 4k_3 \mu P \end{bmatrix} e \\ &\quad - \frac{1}{4} k_1 \epsilon |e_1|^2 - e_2^\top [k_2 \mu I - \epsilon P] e_2, \quad (17) \end{aligned}$$

so \dot{V} is negative definite if the matrix in (17) is positive semi-definite and $[k_2 \mu I - \epsilon P]$ is positive definite, which, using $2k_1 \mu = k_2 \epsilon = 1$ we see that it is so if and only if

$$k_2 I - 2 \frac{k_1}{k_2} \bar{\lambda}_P I > 0,$$

which, in turn, holds if $k_2 > \sqrt{2k_1 \bar{\lambda}_P}$, that is, under condition (15b). Then, computing the Schur complement, the condition for the matrix in (17) to be positive semi-definite, is $4k_3 \mu P - (k_3 \epsilon P)^\top \frac{2}{k_1 \epsilon} k_3 \epsilon P \geq 0$. If $k_3 = 0$ the latter holds trivially. Otherwise, considering $k_3 > 0$, and using $2 \frac{k_1}{k_2} = \frac{\epsilon}{\mu}$, we see that the latter inequality is equivalent to

$$2 \frac{\mu}{\mu} I - \frac{k_3}{k_1} \frac{\epsilon}{\mu} P = 2 \frac{\mu}{\mu} I - \frac{k_3}{k_1} \frac{2k_1}{k_2} P = 1 - \frac{k_3}{k_2} \bar{\lambda}_P \geq 0,$$

which is satisfied under (15c). We conclude that

$$\dot{V}(e) \leq -\frac{1}{4} \left[\epsilon k_1 |e_1|^2 + [k_2 \mu - \epsilon \bar{\lambda}_P] |e_2|^2 \right], \quad (18)$$

so the statement of the proposition follows. \blacksquare

From the proof of Proposition 2 it is clear the value of $k_3 \geq 0$ is inconsequential to the exponential stability of the containment set. Nevertheless, as mentioned above, it plays a role in the solutions' behavior. This is stated next.

Proposition 3: Consider the system (1) and the bipartite containment control law (5). Under the Standing Assumptions, the bipartite containment objective is achieved, that is, the inequalities (6) hold. Furthermore, if $k_3 > 0$, the final states of the followers satisfy

$$\lim_{t \rightarrow \infty} x_{1_f}(t) = V_f x_{1_l}(0) + \frac{1}{k_3} V_f x_{2_l}(0), \quad (19a)$$

$$\lim_{t \rightarrow \infty} x_{2_f}(t) = 0. \quad (19b)$$

On the other hand, if $k_3 = 0$,

$$\lim_{t \rightarrow \infty} x_{1_f}(t) = V_f x_{1_l}(0) + t V_f x_{2_l}, \quad (20a)$$

$$\lim_{t \rightarrow \infty} x_{2_f}(t) = V_f x_{2_l}, \quad (20b)$$

where x_l and x_f are leaders' and followers' states respectively and $V_f \in \mathbb{R}^{(n-m) \times m}$ is given in (11). \square

Proof: Differentiating the weighted average of the system (8), we obtain the dynamical equations below

$$\dot{x}_{1_m} = \mathbb{V} \dot{x}_1 = \mathbb{V} x_2 = x_{2_m}, \quad (21a)$$

$$\begin{aligned} \dot{x}_{2_m} &= \mathbb{V} \dot{x}_2 \\ &= \mathbb{V} (-k_1 L x_1 - k_2 L x_2 - k_3 x_2) = -k_3 x_{2_m}, \quad (21b) \end{aligned}$$

with $v_{l_i}^\top L = 0$ for $i \leq k$. Their solutions give the following

$$x_{2_m}(t) = x_{2_m}(0) e^{-k_3 t}, \quad (22a)$$

$$x_{1_m}(t) = x_{1_m}(0) + x_{2_m}(0) \int_0^t e^{-k_3 s} ds. \quad (22b)$$

From Proposition 2, we have $\lim_{t \rightarrow \infty} e(t) = 0$, which results in $\lim_{t \rightarrow \infty} x(t) = x_m(t)$. From (22), we obtain $\lim_{t \rightarrow \infty} x_2(t) = 0$ and $\lim_{t \rightarrow \infty} x_1(t) = x_{1_m}(0) + \frac{1}{k_3} x_{2_m}(0)$. Then, using (11), we obtain the relations in (19). Under the Standing Assumption and from Item (iv) of Lemmas 2 and 3,

$$\begin{aligned} \lim_{t \rightarrow \infty} |x_{1_f j}(t)| &= \sum_{i=1}^m |v_{i,m+j} x_{1_{l_i}}(0) + \frac{1}{k_3} v_{i,m+j} x_{2_{l_i}}(0)| \\ &\leq \sum_{i=1}^m |v_{i,m+j}| |x_{1_{l_i}}(0) + \frac{1}{k_3} x_{2_{l_i}}(0)| \\ &\leq \sum_{i=1}^m |v_{i,m+j}| |x_{1_{l_i}}(t)| \leq \max_{1 \leq i \leq m} |x_{1_{l_i}}(t)|, \end{aligned}$$

where $v_{i,j}$ are the elements of the matrix \mathbb{V} in (11). In the case when $k_3 = 0$, (21) becomes

$$\dot{x}_{1_m} = x_{2_m}, \quad \dot{x}_{2_m} = 0,$$

so

$$x_{2_m}(t) = x_{2_m}(0), \quad (23a)$$

$$x_{1_m}(t) = x_{1_m}(0) + t x_{2_m}(0). \quad (23b)$$

From (23), we obtain $\lim_{t \rightarrow \infty} x_2(t) = x_{2_m}(0)$ and $\lim_{t \rightarrow \infty} x_1(t) = x_{1_m}(0) + x_{2_m}(0)t$. Then using (11), we obtain the relations in (20). Under the Standing Assumption and

from Items (iv) of Lemmas 2 and 3, we have

$$\begin{aligned} \lim_{t \rightarrow \infty} |x_{2_{fj}}(t)| &= \sum_{i=1}^m |v_{i,m+j} x_{2_{i1}}| \leq \sum_{i=1}^m |v_{i,m+j}| \max_{1 \leq i \leq m} |x_{2_{i1}}| \\ &\leq \max_{1 \leq i \leq m} |x_{2_{i1}}|, \\ \lim_{t \rightarrow \infty} |x_{1_{fj}}(t)| &= \sum_{i=1}^m |v_{i,m+j} x_{1_{i1}}(0) + t v_{i,m+j} x_{2_{i1}}| \\ &\leq \max_{1 \leq i \leq m} |x_{1_{i1}}(0)| + t \max_{1 \leq i \leq m} |x_{2_{i1}}| \\ &\leq \max_{1 \leq i \leq m} |x_{1_{i1}}(t)|, \end{aligned}$$

so (6) follows. \square

It is worth noting that for unsigned networks, the achievable objective is *containment* [5], that is,

$$\lim_{t \rightarrow \infty} [x_j(t) - \max_{i \in \mathcal{L}} x_i(t)][x_j(t) - \min_{i \in \mathcal{L}} x_i(t)] \leq 0. \quad (24)$$

Then, for such networks, we recover the following statement from Proposition 3.

Corollary 1: Consider the system (1) with the containment control law (5) and let the associated digraph be unsigned. Under the Standing Assumption, the containment objective is achieved, that is the inequality (24) holds. \square

In the next section, we use the strict Lyapunov functions provided in this section in order to conduct a robustness analysis of the control law (5), in the sense of input-to-state stability of the bipartite containment tracking.

B. Robustness Analysis

Consider the perturbed second-order systems

$$\dot{x}_{1_i} = x_{2_i} \quad (25a)$$

$$\dot{x}_{2_i} = u_i + d_i(t), \quad (25b)$$

where the disturbances $d_i : \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}^n$ are assumed to be essentially bounded locally integrable functions, $d_i(t) \leq \bar{d} := \text{ess sup}_{t \geq 0} |d(t)|$. Under the action of the control law (5), the system (25) becomes

$$\dot{x}_1 = x_2 \quad (26a)$$

$$\dot{x}_2 = -k_1 L x_1 - k_2 L x_2 - k_3 x_2 + d(t), \quad (26b)$$

where $d := [d_i] \in \mathbb{R}^n$. Differentiating the errors in (12) on both sides and using (26) we obtain

$$\dot{e}_1 = e_2 \quad (27a)$$

$$\dot{e}_2 = -k_1 L e_1 - k_2 L e_2 - k_3 e_2 + [I - \mathbb{V}]d(t). \quad (27b)$$

Then, we have the following.

Proposition 4: The closed-loop system (27), under the Standing Assumption, is input-to-state stable with respect to essentially bounded, locally integrable external disturbances if the conditions in (15) hold. \square

Proof: Consider the Lyapunov function (16) which is positive definite, under the condition $\epsilon \leq \sqrt{\frac{2\mu}{|P|}}$, $\mu > 0$. The total time derivative of V along the trajectories of (27) yields

$$\dot{V}(e) = \frac{\partial V}{\partial e_1} e_2 + \frac{\partial V}{\partial e_2} (-k_1 L e_1 - k_2 L e_2 - k_3 e_2)$$

$$+ \frac{\partial V}{\partial e_2} [I - \mathbb{V}]d. \quad (28)$$

Then, from (18), we obtain

$$\begin{aligned} \dot{V}(e) &\leq -\frac{1}{4}[\epsilon k_1 |e_1|^2 + (k_2 \mu - \epsilon \bar{\lambda}_P) |e_2|^2] + \frac{\partial V}{\partial e_2} |[I - \mathbb{V}]| |d| \\ &\leq -\frac{1}{4} \epsilon k_1 |e_1|^2 - \frac{1}{4} (k_2 \mu - \epsilon \bar{\lambda}_P) |e_2|^2 \\ &\quad + \epsilon \bar{\lambda}_P e_1^\top |[I - \mathbb{V}]| d + 2\mu \bar{\lambda}_P e_2^\top |[I - \mathbb{V}]| |d|. \end{aligned}$$

We know that $0 \leq |[I - \mathbb{V}]| \leq |I| + |\mathbb{V}| \leq 2$, because all eigenvalues of I are equal to 1 and all eigenvalues of $|\mathbb{V}|$ are either 1 or 0. Let $\delta > 0$ such that $c_1 := \frac{1}{4}(\epsilon k_1 - \frac{4}{\delta} \epsilon \bar{\lambda}_P) > 0$ and $c_2 := \frac{1}{4}(k_2 \mu - \epsilon \bar{\lambda}_P - \frac{8}{\delta} \mu \bar{\lambda}_P) > 0$. Then,

$$\dot{V}(e) \leq -c_1 |e_1|^2 - c_2 |e_2|^2 + c_3 |d|^2,$$

with $c_3 = \bar{\lambda}_P \delta (\epsilon + 2\mu) > 0$. Thus, the system (27) is input-to-state stable with respect to the bounded external input. \square

Corollary 2: The system (27), under the Standing Assumption and over an unsigned network, is input-to-state stable with respect to an essentially bounded, locally integrable external disturbance if the conditions in (15) hold. \square

V. SIMULATION RESULTS

We provide some numerical examples on a system of nonholonomic unicycle mobile robots over both structurally balanced and unbalanced networks. Let $r_i = [r_{x_i} \ r_{y_i}]^\top$ be the inertial position, θ_i the orientation, s_i the linear speed, ω_i the angular speed, m_i the mass, J_i the moment of inertia, F_i the applied force and τ_i the applied torque. Each robot has the dynamical equation

$$\begin{bmatrix} \dot{r}_{x_i} \\ \dot{r}_{y_i} \\ \dot{\theta}_i \end{bmatrix} = \begin{bmatrix} s_i \cos \theta_i \\ s_i \sin \theta_i \\ \omega_i \end{bmatrix}, \quad \begin{bmatrix} \dot{s}_i \\ \dot{\omega}_i \end{bmatrix} = \begin{bmatrix} \frac{1}{m_i} & 0 \\ 0 & \frac{1}{J_i} \end{bmatrix} \eta_i, \quad (29)$$

where $\eta_i := [F_i \ \tau_i]^\top$. We choose a reference point $p_i = r_i + \delta_i \begin{pmatrix} \cos \theta_i \\ \sin \theta_i \end{pmatrix}$ located at a distance $\delta_i = 0.1\text{m}$ along the line that is perpendicular to the wheels' axis and we define

$$\zeta := \begin{bmatrix} r_{x_i} + \delta_i \cos \theta_i \\ r_{y_i} + \delta_i \sin \theta_i \\ s_i \cos \theta_i - \delta_i \omega_i \sin \theta_i \\ s_i \sin \theta_i + \delta_i \omega_i \cos \theta_i \\ \theta_i \end{bmatrix}. \quad (30)$$

In transformed coordinates, with $p_i = [\zeta_{1_i}^\top \ \zeta_{2_i}^\top]^\top$, we have

$$\begin{bmatrix} \dot{\zeta}_{1_i} \\ \dot{\zeta}_{2_i} \end{bmatrix} = \begin{bmatrix} \zeta_{3_i} \\ \zeta_{4_i} \end{bmatrix}, \quad (31a)$$

$$\begin{aligned} \begin{bmatrix} \dot{\zeta}_{3_i} \\ \dot{\zeta}_{4_i} \end{bmatrix} &= \begin{bmatrix} -s_i \omega_i \sin \theta_i - \delta_i \omega_i^2 \cos \theta_i \\ s_i \omega_i \cos \theta_i - \delta_i \omega_i^2 \sin \theta_i \end{bmatrix} \\ &+ \begin{bmatrix} \frac{1}{m_i} \cos \theta_i & -\frac{\delta_i}{J_i} \sin \theta_i \\ \frac{1}{m_i} \sin \theta_i & \frac{\delta_i}{J_i} \cos(\theta_i) \end{bmatrix} \eta_i, \end{aligned} \quad (31b)$$

$$\dot{\zeta}_{5_i} = -\frac{1}{2\delta_i} \zeta_{3_i} \sin \zeta_{5_i} + \frac{1}{2\delta_i} \zeta_{4_i} \cos \zeta_{5_i}. \quad (31c)$$

The feedback linearizing control η_i is given by

$$\eta_i = \begin{bmatrix} \frac{1}{m_i} \cos \theta_i & -\frac{\delta_i}{J_i} \sin \theta_i \\ \frac{1}{m_i} \sin \theta_i & \frac{\delta_i}{J_i} \cos(\theta_i) \end{bmatrix}^{-1} \times \begin{bmatrix} u_i - \left[-s_i \omega_i \sin \theta_i - \delta_i \omega_i^2 \cos \theta_i \right] \\ s_i \omega_i \cos \theta_i - \delta_i \omega_i^2 \sin \theta_i \end{bmatrix}, \quad (32)$$

which gives $[\dot{\zeta}_{1_i}, \dot{\zeta}_{2_i}]^\top = [\zeta_{3_i}, \zeta_{4_i}]^\top$ and $[\dot{\zeta}_{3_i}, \dot{\zeta}_{4_i}]^\top = u_i$. Thus, we implemented (32) with u_i as in (5), $x_{1_i} = [\zeta_{1_i}, \zeta_{2_i}]^\top$, $x_{2_i} = [\zeta_{3_i}, \zeta_{4_i}]^\top$, $m_i = 8$ kg and $J_i = 0.12$ kg/m² for each $i \in \mathcal{I}_{\mathcal{N}}$.

A. Structurally Balanced Networks

Consider a network with five leaders $\nu_i, i \leq 5$, organized in three leader groups $\{\nu_1, \nu_2, \nu_3\}, \{\nu_4\}, \{\nu_5\}$, and four followers $\nu_j, 6 \leq j \leq 9$, communicating over a directed graph as the one depicted in Figure 1, below.

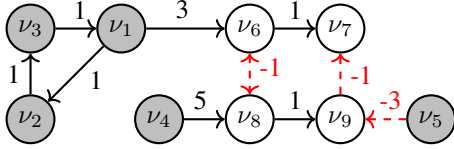


Fig. 1. Network 1: A network of nine mobile robots

The Laplacian matrix corresponding to the graph is

$$L = \begin{bmatrix} 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -3 & 0 & 0 & 0 & 0 & 0 & 4 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -1 & 2 & 0 & 1 \\ 0 & 0 & 0 & -5 & 0 & 1 & 0 & 6 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 & -1 & 0 & 4 & 0 \end{bmatrix}$$

and its eigenvalues are $\lambda_L = 0, 0, 0, 1.5 \pm 0.86i, 2, 3.59, 4, 6.41$. The network may be bipartitioned into two subgroups, $\mathcal{V}_1 = \{\nu_1, \nu_2, \nu_3, \nu_5, \nu_6, \nu_7\}$, $\mathcal{V}_2 = \{\nu_4, \nu_8, \nu_9\}$, so is structurally balanced, and

$$V_l = \begin{bmatrix} 0.33 & 0.33 & 0.33 & 0 & 0 \\ 0.33 & 0.33 & 0.33 & 0 & 0 \\ 0.33 & 0.33 & 0.33 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad (33)$$

$$V_f = \begin{bmatrix} 0.26 & 0.26 & 0.26 & -0.22 & 0 \\ 0.14 & 0.14 & 0.14 & -0.22 & 0.37 \\ -0.04 & -0.04 & -0.04 & 0.87 & 0 \\ -0.01 & -0.01 & -0.01 & 0.22 & -0.75 \end{bmatrix}. \quad (34)$$

We notice that V_l and V_f have the properties stated on Items (i)–(iv) of Lemma 3, as the network is structurally balanced. For V_l , we have two elements equal to one, corresponding to isolated leaders ν_4 and ν_5 , as they are in the exclusive part of the reaches. Leaders ν_1, ν_2 , and ν_3 are in the exclusive part of a reach, so the corresponding elements of the right eigenvector are equal to one. Thus, as they are interconnected within a

strongly-connected graph, the absolute value of the elements of the left eigenvector are less than one. V_f does not have an element equal to ± 1 since all the followers are influenced by more than one leader. Followers ν_6 and ν_8 are not influenced by the leader ν_5 , so the corresponding elements on the fifth column are equal to zero. We also remark that the sum of the absolute value of the terms on each row is equal to 1.

Now, to compute P in (13) we proceed as follows. We set $Q = I_n$ and $\alpha_i = 20$. Then, in Matlab, we use `lyap(-R, Q)` with $Q = I_n$ to obtain the solution of $-PR - R^\top P = -Q$ with $R := L + \sum_{i=1}^k \alpha_i v_{r_i} v_{l_i}^\top$. We obtain $\bar{\lambda}_P = 0.5193$. Consider the system (29) and the bipartite containment law (32) with $k_1 = 0.8, k_2 = 1.5$, and $k_3 = 1.2$, which satisfy the conditions in (15). The respective agents' initial states are $r_x(0) = [3.5 \ 1 \ -0.5 \ -1.6 \ 1 \ -6.5 \ 5.5 \ -3.5 \ 6]^\top$, $r_y(0) = [3 \ 2.5 \ -1.5 \ 1.3 \ -3 \ -1 \ -3 \ -3 \ -2.5]^\top$, $\theta(0) = [0.25 \ 0.61 \ -1.27 \ 0.32 \ 1.42 \ 0.46 \ 0.98 \ 1.19 \ 1.03]^\top$ and $s(0) = [1.2 \ 1.2 \ -1.4 \ -1.6 \ 1.3 \ -2.2 \ 0.4 \ -1.1 \ 1.2]^\top$. The simulation results are shown in Figures 2 and 3. The followers converge to the bipartite containment set spanned by cooperative leaders' final states and competitive leaders' mirrored final states and all agents' velocities converge to zero. Using the relations in (19) and the coordinate transformation, we obtain the following limit values for followers' states, $\lim_{t \rightarrow \infty} r_x(t) = [1.99 \ 1.89 \ -2.68 \ -1.46]^\top$, $\lim_{t \rightarrow \infty} r_y(t) = [1.31 \ -0.15 \ 0.44 \ 1.44]^\top$, and $\lim_{t \rightarrow \infty} s(t) = [0 \ 0 \ 0 \ 0]^\top$.

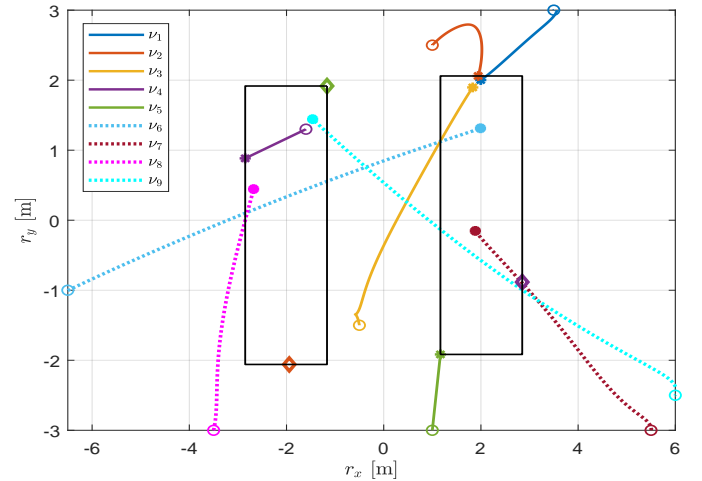


Fig. 2. Bipartite containment tracking of (29) with the control (5) on the plane. The filled dots are the final states of the agents. The diamonds represent the mirrored final states of the leaders. The rectangles represent the containment set.

In a second run of simulations, we tested the bipartite-containment control law (32) on the system (29), using the same initial conditions and controller gains as above. Therefore, in the simulations, we consider that the system is subject to a disturbance $d_i = \sigma_i(t) [1 \ 1]^\top$, where $\sigma_i(t)$ is given by

$$\sigma_i(t) = \begin{cases} \tanh(t-10) - 1 + \frac{1}{(t+10)} & i \in \{7, 9\} \\ -\tanh(t-10) + 1 - \frac{1}{(t+10)} & i = 6 \\ 0 & i \in \{1, 2, 3, 4, 5, 8\}. \end{cases}$$

The simulation results can be appreciated in Figures 4

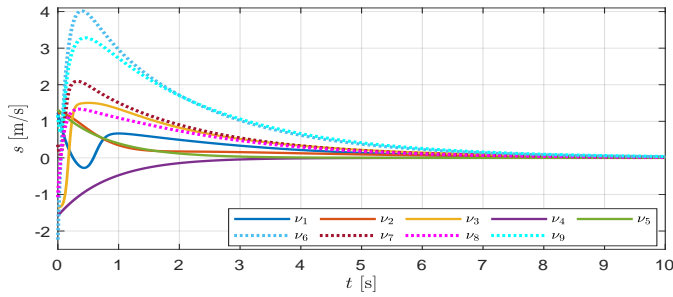


Fig. 3. Bipartite containment tracking of (29) with (5) on velocity.

and 5. During the first 10s, the perturbation $d(t)$ prevents the achievement of bipartite containment tracking, the trajectories of the followers 6, 7, and 9 shift because of the presence of the perturbation, but, after the perturbation vanishes, the trajectories of the followers stop shifting and converge towards the bipartite containment set spanned by cooperative leaders' final states and competitive leaders' mirrored final states and all agents' velocities converge to zero. We obtain the same limit values as before for the followers.

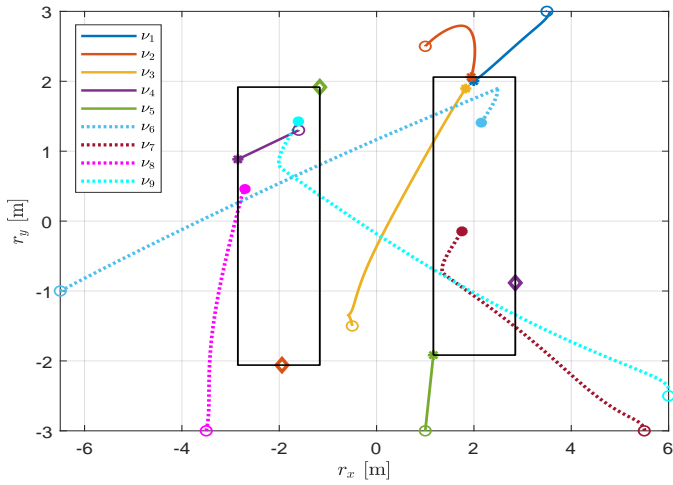


Fig. 4. Bipartite containment tracking of (25) on the plane.

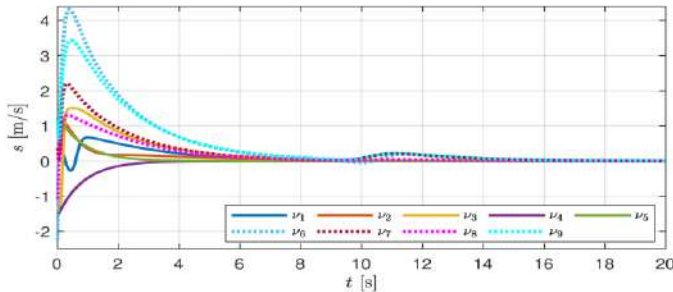


Fig. 5. Bipartite containment tracking of (25) on velocity.

B. Structurally Unbalanced Networks

Consider a network containing five leaders $\nu_i, i \leq 5$, three leader groups $\{\nu_1, \nu_2, \nu_3\}, \{\nu_4\}, \{\nu_5\}$, and four followers $\nu_j, 6 \leq j \leq 9$, provided in Figure 6.

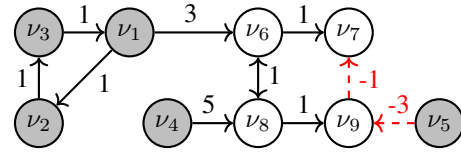


Fig. 6. Network 2: A network of nine mobile robots

The Laplacian matrix corresponding to the graph is

$$L = \begin{bmatrix} 1 & 0 & -1 & 0 & 0 & 0 & 0 & 0 & 0 \\ -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ -3 & 0 & 0 & 0 & 0 & 4 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 0 & -1 & 2 & 0 & 1 \\ 0 & 0 & 0 & -5 & 0 & -1 & 0 & 6 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 & -1 & 0 & 4 \end{bmatrix}$$

and its eigenvalues are $\lambda_L = 0, 0, 0, 1.5 \pm 0.86i, 2, 3.59, 4, 6.41$. The network may not be bipartitioned into two subgroups, so is structurally unbalanced. The matrix V_l is calculated as in (33) and V_f is calculated as

$$V_f = \begin{bmatrix} 0.26 & 0.26 & 0.26 & 0.22 & 0 \\ 0.125 & 0.125 & 0.125 & 0 & 0.375 \\ 0.04 & 0.04 & 0.04 & 0.87 & 0 \\ 0.01 & 0.01 & 0.01 & 0.22 & -0.75 \end{bmatrix}.$$

We notice that V_f has the properties stated on Items (i) – (iv) of Lemma 2, since the network is structurally unbalanced. Since all followers are influenced by more than one leader, there are no agents corresponding to the exclusive part of a reach. As a result V_f does not have an element equal to ± 1 but the absolute value of each element is less than one. We also remark that the sum of the absolute value of the terms on each row is less than 1.

Now, let P be generated by (13) with $Q = I_n$ and $\alpha = 20$, then we obtain $\bar{\lambda}_P = 0.4839$. Consider the system (29) and the bipartite containment law (32) with the same controller gains as before. The respective agents' inertial positions and linear speeds are the same as before, while the orientations are $\theta(0) = [0.25 \ 0.61 \ -1.27 \ 0.32 \ 1.42 \ 0.46 \ 0.98 \ 1.19 \ 1.03]^T$. The simulation results are depicted in Figures 7 and 8.

Note that all followers converge to the convex hull spanned by leaders' final states and mirrored final states and all agents' velocities converge to zero. Using relations in (19) and the coordinate transformation, we obtain the following limit values for followers' states, $\lim_{t \rightarrow \infty} r_x(t) = [1.5 \ 1.1 \ 0.01 \ -0.94]^T$, $\lim_{t \rightarrow \infty} r_y(t) = [1.79 \ -0.01 \ 0.89 \ 1.54]^T$, $\lim_{t \rightarrow \infty} s(t) = [0 \ 0 \ 0 \ 0]^T$.

We remark that for structurally balanced signed networks, the followers' final states converge to the bipartite containment set spanned by cooperative leaders' final states and antagonistic leaders' mirrored states. However, in the case of a structurally unbalanced network, we cannot observe this as we cannot bipartition the agents into two disjoint subsets.

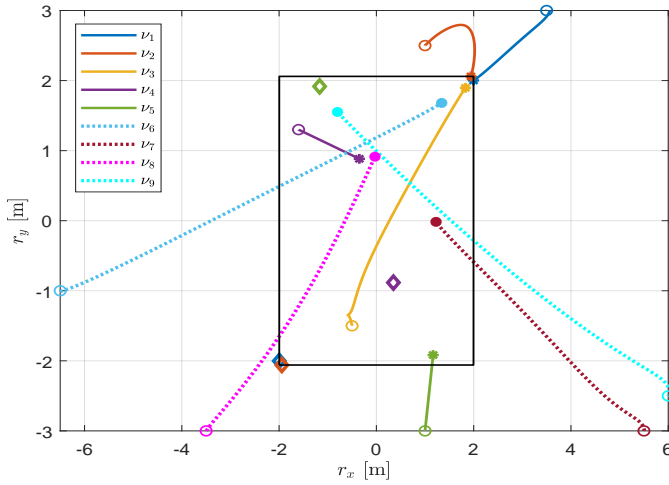


Fig. 7. Bipartite containment tracking of (1) on position. The filled dots are the final states of the agents. The diamonds represent the mirrored final states of the leaders.

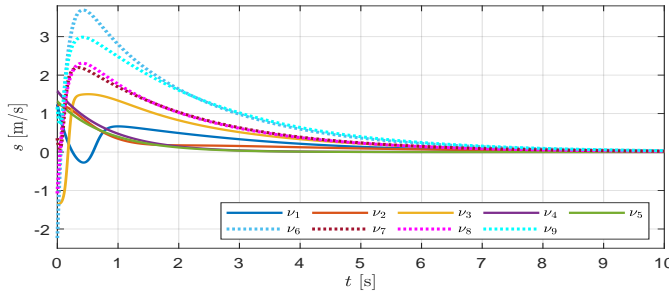


Fig. 8. Bipartite containment tracking of (1) on velocity.

VI. CONCLUSIONS

Our results on bipartite containment tracking control for double-integrators, over multiple-leader signed networks, characterize, via Lyapunov-stability theory, a stability bound for the containment set, as well as the limiting set-points for all the agents. This is significant because the construction of a Lyapunov function may serve to extend our study to cover bipartite containment for complex non-linear systems, such as Lagrangian systems. In order to render our results applicable to more realistic robotic scenarios current/future work will focus on incorporating additional sensor constraints by accounting for the influence of the competitive agents only from a certain distance. Other interesting robot-control problems to consider based on our main results, include that in which the roles of the leaders may change, from cooperative to competitive and vice versa.

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Pelin Şekercioglu obtained her BSc degree in Mechanical Engineering in 2019 and her MSc degree in Advanced Systems and Robotics in 2021, both from Sorbonne University's Faculty of Science & Engineering, Paris, France. She is currently pursuing the PhD degree in Automatic Control at the University Paris-Saclay, France. Her research interest include multi-agent systems and nonlinear control for autonomous robots and aerospace systems.



Antonio Loria obtained his BSc degree on Electronics Engineering from ITESM, Monterrey, Mexico in 1991 and his MSc and PhD degrees in Control Engg. from UTC, France in 1993 and 1996, respectively. He has the honour of holding a researcher position at the French National Centre of Scientific Research (CNRS) since January 1999 (Senior Researcher since 2006). He has co-authored over 300 publications on control systems and stability theory and he served as Associate Editor for *IEEE Trans. Automat. Control*, *IEEE Trans. Control Syst. Techn.*, *IEEE Control Syst. Lett.*, *IEEE Control Syst. Magazine*, *Automatica*, *Systems and Contr. Lett.* and the *Revista Iberoamericana de Automática e Informática industrial* and the *IEEE Conf. Editorial Board*, as well as other journals on Automatic Control.



Elena Panteley is a Senior Researcher at CNRS and a member of the Laboratory of Signals and Systems. She received her PhD. degree in Applied Mathematics from the State University of St. Petersburg, Russia, in 1997. From 1986 to 1998, she held a research position with the Institute for Problem of Mechanical Engineering, Russian Academy of Science, St. Petersburg. She is co-chair of the International Graduate School of Control of the European Embedded Control Institute (EECI-IGSC). Elena

Panteley is the Book-reviews Editor for *Automatica* and Associate Editor for *IEEE Control Systems Letters*. Her research interests include stability and control of nonlinear dynamical systems and networked systems with applications to multi-agent systems.



Ioannis Sarras (M '09) graduated from the Automation Engineering Department of the Technological Education Institute (T.E.I.) of Piraeus, Greece, in 2004. He obtained his MSc in Control Theory from the University of Paul Sabatier in 2006 and the PhD degree on Automatic Control from the University of Paris-Sud in 2010. Between 2010 and 2017 he was a research associate with IFPEN, ULB, MINES ParisTech and ONERA. Since 2017 he has been a Research Engineer at ONERA-The French Aerospace

Lab. He has co-authored over 60 papers in peer-reviewed international journals and conferences. His research activities are in the fields of nonlinear control and observer designs for single- or multi-agent systems with emphasis on aerospace applications.



Julien Marzat graduated as an engineer from ENSEM (INPL Nancy) in 2008 and completed his PhD Thesis in 2011 and Habilitation in 2019, both from University Paris-Saclay. He is currently a Research Scientist at ONERA, where his research interests include guidance, control and fault diagnosis for autonomous robots and aerospace systems.