





A Continuous-Time Violation-Free Multiagent Optimization Algorithm and Its Applications to Safe Distributed Control

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Abstract—In this work, we propose a continuous-time distributed optimization algorithm with guaranteed zero coupling constraint violation and apply it to safe distributed control in the presence of multiple control barrier functions (CBFs). The optimization problem is defined over a network that collectively minimizes a separable cost function with coupled linear constraints. An equivalent optimization problem with auxiliary decision variables and a decoupling structure is proposed. A sensitivity analysis demonstrates that the subgradient information can be computed using local information. This then leads to a subgradient algorithm for updating the auxiliary variables. A case with sparse coupling constraints is further considered, and it is shown to have better memory and communication efficiency. For the specific case of a CBF-induced time-varying quadratic program (QP), an update law is proposed that achieves finite-time convergence. Numerical results involving a static resource allocation problem and a safe coordination problem for a multiagent system demonstrate the efficiency and effectiveness of our proposed algorithms.

Index Terms—Control barrier functions, constrained control, decentralized control, optimization algorithms.

I. INTRODUCTION

DISTRIBUTED optimization has received increasing attention in the last few decades thanks to increasing computational power availability. Depending on how the problem is formulated, distributed optimization can be categorized into the *cost-coupled* and *constraint-coupled* optimization [1]. In the former case, the cost function to be minimized is a summation of local cost functions, each of which depends on a common decision variable \mathbf{x} subject to a common constraint, that is

$$\min_{\mathbf{x} \in X} \sum_{i \in \{1, 2, \dots, N\}} f_i(\mathbf{x}) \quad (1)$$

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where the local cost function f_i and global constraint set X are known to agent i . One such example is the training process of learning algorithms, where the decision variables are the parameters in the learning model and the local cost function is associated with data accessible only to local computational units. Much attention has been focused on this case in the distributed optimization community (see [2] and [3] for overviews).

In the constraint-coupled case, each node has its own local decision variable, and the cost function is a summation of local cost functions that depend on the local decision variables only. The constraints in this case are coupled and involve all or parts of the local variables. The problem setup is then given by

$$\min_{(\mathbf{x}_1, \dots, \mathbf{x}_N) \in X} \sum_{i \in \{1, 2, \dots, N\}} f_i(\mathbf{x}_i) \quad (2)$$

where the local cost function f_i and parts of the constraint set X are known to agent i . Conceptually, we can refer to the stack of all local variables as the global variable. One example of this setup is the economic dispatch problem in power systems, where the local decision variables are constrained by the shared resource limit, and the size of the global decision variable increases with the size of the power grid.

Albeit its wide outreach in real-time decision-making and profound practical implications, the constraint-coupled optimization problem (2) was less attended to compared to the vast literature on the cost-coupled optimization problem (1). One viable approach to (2) involves solving its dual problem. Assuming that the optimization problem (2) has zero duality gap and the constraint functions are separable, then the dual problem of (2) has a separable objective function with a common decision variable (the dual variable), aligning the problem with the formulation of (1). Thanks to this observation, many distributed optimization algorithms for (1) can be readily applied to solve (2) by tackling its dual problem [4], [5], [6], [7]. One major drawback of these duality-based approaches is that, primal convergence is not easily retrieved from dual solutions, known as the primal recovery problem [8]. The remedy usually involves a running average scheme, which leads to a slow convergence rate. Recent works in [9] and [10] have proposed various methods to avoid the recovery procedure. Another issue is that, in order to solve for the local primal variable, each node has to solve for a consensus on the dual variable, causing efficiency concerns.

In order to avoid the primal recovery problem as well as enhance efficiency, recently, primal decomposition approach has been pursued as a general distributed solution to the constraint-coupled problem [1]. Instead of looking at the dual problem, primal decomposition approach splits the coupling but separable constraints into local ones using auxiliary variables. The algorithm usually comprises two parts: 1) solving/updating the local primal variables based on local problems; and 2) updating the auxiliary variables. This approach has its roots in large-scale optimization, where the global variable is too large for one computational node to process and a central coordinating node is required for updating the auxiliary variables. See, for example, [11] for more details. It is only until recently that [1] proposes a distributed auxiliary update and provides an asymptotic convergence guarantee. Wang et al. [12] further extended this approach and provided a convergence rate analysis.

One issue that has been largely overlooked in the existing distributed optimization literature is primal feasibility throughout solution iterations. Most algorithms mentioned above or surveyed in [2] and [3] at best provide an asymptotic convergence guarantee and asymptotic primal feasibility guarantee. This might not be desirable when applying optimization-based algorithms in real-time safe-critical scenarios, i.e., when transient behavior becomes a crucial safety concern and constraint violation could lead to catastrophic consequences. Conceptually, the problem is challenging since the feasible set is defined over the global decision variable and cannot be evaluated for satisfaction using only local information, which voids the usual practice of projecting the solution onto the feasible set [13].

There are only a few distributed violation-free algorithms for constraint-coupled optimization problems. Recently, Wu et al. [14] proposed a right-hand primal decomposition scheme, yet it only achieved an approximate optimal solution. Abeynanda et al. [15] considered primal feasibility in dual decomposition methods, where the solution still only converged to a neighborhood of the optimal solution. Tan and Dimarogonas [16] proposed a violation-free algorithm with optimality guarantee, but only for a single constraint. A highly relevant work [17] adopted a similar primal decomposition scheme as in this article, and used a cascaded law based on projected saddle-point dynamics and safe gradient flow for updating the auxiliary and primal variables. However, only practical convergence can be established due to a regularization step. The violation-free Laplacian-based gradient algorithm in [18] instead focuses on the special case of the economic dispatch problem. In summary, the existing violation-free results either give inexact solutions or are tailored to specific problems. One exception is our recent work [19], where the focus is on designing a discrete-time, violation-free, distributed and accelerated optimization algorithm. We note that technicality concerns differ significantly depending on whether the dynamics is continuous-time or discrete-time.

In this work, we propose a distributed, continuous-time optimization algorithm for problem (2) with coupling linear constraints. Our contributions are summarized as follows.

- 1) The coupling constraints hold during the solution evolution, and the iterated variable is shown to converge to the optimal solution under a few mild assumptions.
- 2) The proposed algorithm is more efficient in memory and communication compared to existing results. Each node only needs to store a variable of size $d_i + M$ and transmit a variable of size $2M$ to its neighbors, where d_i is the size of the local primal variable and M the number of coupling constraints. This is notably smaller compared to, e.g., primal decomposition algorithms [1] and dual decomposition algorithms [4].
- 3) We apply the distributed optimization algorithm to the control barrier function (CBF)-induced quadratic program (QP) as feedback in safe distributed control. To accommodate the slowly time-varying parameters in QP, we further strengthen our proposed algorithm such that finite-time convergence is achieved.

The rest of this article is organized as follows. We first present problem formulation in Section II as well as some leading assumptions. The proposed primal decomposition scheme and the corresponding updates of auxiliary variables are detailed in Sections III and IV, respectively. The overall algorithm and the convergence analysis are discussed in Section V. Two special cases are further considered in the following sections, focusing on the sparsely coupled case and the CBF-induced QP case. Numerical results are shown in Section VIII to demonstrate the effectiveness and the favorable properties of our proposed algorithms. Finally, Section IX concludes this article.

II. PRELIMINARIES AND PROBLEM SETUP

Notations: \mathbb{R} is the set of real numbers, and $\overline{\mathbb{R}} = \mathbb{R} \cup \{-\infty, \infty\}$. \mathbb{R}^n denotes the n dimensional Euclidean vector space. Each vector $\mathbf{a} = (a_1, a_2, \dots, a_n) \in \mathbb{R}^n$ is interpreted as a column vector if not stated otherwise. $\text{diag}(\cdot)$ is a function that only keeps the diagonal entries and sets the off-diagonal entries to zero. $\text{blkdiag}(\mathbf{g}_1, \mathbf{g}_2, \dots, \mathbf{g}_n)$ denotes a block diagonal matrix with diagonal blocks $\mathbf{g}_1, \mathbf{g}_2, \dots, \mathbf{g}_n$, where $\mathbf{g}_i, i = 1, \dots, n$, can be either a vector or a matrix. For $x \in \mathbb{R}$, $\text{sign}(x) := \begin{cases} 1, & x > 0; \\ 0, & x = 0; \\ -1, & x < 0. \end{cases}$ For any $\mathbf{x} = (x_1, \dots, x_n) \in \mathbb{R}^n$, $\text{sign}(\mathbf{x}) := (\text{sign}(x_1), \text{sign}(x_2), \dots, \text{sign}(x_n))$. Vector inequalities are to be interpreted elementwise. $\mathbf{0}$ and $\mathbf{1}$ refer to vectors of proper dimensions with all entries to be 0 or 1, respectively. Given a function $f : \mathbb{R}^n \rightarrow \overline{\mathbb{R}}$, $\partial f(\mathbf{x})$, the subdifferential of f at \mathbf{x} , is defined as the set of vectors \mathbf{s} such that $f(\mathbf{x}') \geq f(\mathbf{x}) + \mathbf{s}^\top (\mathbf{x}' - \mathbf{x})$ for all $\mathbf{x}' \in \mathbb{R}^n$. Such a vector \mathbf{s} is called a subgradient of f at \mathbf{x} . When $f(\mathbf{x})$ is differentiable, the gradient of f is denoted ∇f and the partial derivative $\frac{\partial f}{\partial x_i}$. For two matrices A and B of proper dimensions, we use the convention that $[A, B]$ denotes the horizontal stacking, and $\begin{bmatrix} A \\ B \end{bmatrix}$ the vertical stacking. Let $A \in \mathbb{R}^{m \times n}$ be a matrix and $\mathbf{I} \subseteq \{1, 2, \dots, m\}$ be an index set. Then, $A^{\mathbf{I}}$ denotes a matrix composed of the rows indexed in \mathbf{I} . Note that $A^{\mathbf{I}} = I^{\mathbf{I}} A$ where I is an identity matrix of proper dimension.

A. Problem Setup

Consider the following multiagent optimization problem:

$$\begin{aligned} \min_{\mathbf{x}_1, \dots, \mathbf{x}_N} \quad & \sum_{i \in \mathcal{I}} f_i(\mathbf{x}_i) \\ \text{s.t.} \quad & \begin{cases} \sum_{i \in \mathcal{I}} \mathbf{a}_i^{\top} \mathbf{x}_i + b_i^1 \leq 0 \\ \vdots \\ \sum_{i \in \mathcal{I}} \mathbf{a}_i^{\top} \mathbf{x}_i + b_i^m \leq 0 \\ \vdots \\ \sum_{i \in \mathcal{I}} \mathbf{a}_i^{\top} \mathbf{x}_i + b_i^M \leq 0 \end{cases} \end{aligned} \quad (3)$$

where $\mathcal{I} = \{1, 2, \dots, N\}$, and there are M linear coupling constraints indexed by $\mathcal{M} = \{1, 2, \dots, M\}$. Here, $\mathbf{a}_i^m, \mathbf{x}_i \in \mathbb{R}^{d_i}, d_i \in \mathbb{N}, b_i^m \in \mathbb{R} \quad \forall i \in \mathcal{I}, m \in \mathcal{M}$. For brevity, denote $\mathbf{x} = [\mathbf{x}_1; \mathbf{x}_2; \dots; \mathbf{x}_N]$, $\mathbf{a}^m = [\mathbf{a}_1^m; \mathbf{a}_2^m; \dots; \mathbf{a}_N^m]$, $\mathbf{b}^m = (b_1^m, \dots, b_N^m)$, $m \in \mathcal{M}$, $\mathbf{a}_i = [\mathbf{a}_i^1; \mathbf{a}_i^2; \dots; \mathbf{a}_i^M]$, $\mathbf{b}_i = (b_i^1, \dots, b_i^M), i \in \mathcal{I}$. Only $\mathbf{a}_i, \mathbf{b}_i, f_i$ are known to agent i .

The N computational nodes communicate over a connected and undirected graph $\mathcal{G} = (\mathcal{I}, E)$. $(i, j) \in E$ represents that the agents i, j can communicate with each other. The associated Laplacian matrix [20] is denoted L , and \mathbf{l}_i is its i th row. We make the following assumptions.

Assumption 1: For all $i \in \mathcal{I}$, each function $f_i(\mathbf{x}_i)$ is convex.

Assumption 2: The optimal value of (3) is finite.

Stacking $\{\mathbf{a}_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ and $\{\mathbf{b}_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ by the order of the agents, we obtain $\mathbf{a}_A = [\mathbf{a}_1; \mathbf{a}_2; \dots; \mathbf{a}_N]$, $\mathbf{b}_A = [\mathbf{b}_1; \mathbf{b}_2; \dots; \mathbf{b}_N]$. Similarly, stacking $\{\mathbf{a}_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ and $\{\mathbf{b}_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ by the order of the constraints, we obtain $\mathbf{a}_C = [\mathbf{a}^1; \mathbf{a}^2; \dots; \mathbf{a}^M]$, $\mathbf{b}_C = [\mathbf{b}^1; \mathbf{b}^2; \dots; \mathbf{b}^M]$. There exists a constant permutation matrix¹ J such that $\mathbf{b}_C = J\mathbf{b}_A$. Note that J only depends on N and M and is independent of the communication graph \mathcal{G} .

In this work, we aim to find a continuous-time distributed algorithm that solves (3) while satisfying all coupling constraints for all time. In [16], a special case of (3) with quadratic cost and a single coupling constraint is investigated. However, the approach in [16] is difficult to generalize to convex programs with multiple coupling constraints, as studied in this work.

Our proposed approach is based on two key observations.

1) By introducing a set of auxiliary variables as decision variables, an equivalent optimization problem can be constructed with separable costs and constraints. 2) When viewing these auxiliary variables as independent variables, the subgradient of the optimal value with respect to these variables can be computed using local information. The first fact motivates the primal decomposition scheme. The second fact motivates the distributed updated law for these variables leveraging subgradient algorithms. The convergence and optimality of this approach are later shown using tools from nonsmooth analysis. Two special cases with sparse coupling constraints or quadratic cost functions are also discussed in the sequel.

¹ A permutation matrix J is a square binary matrix that has exactly one entry of 1 in each row and each column and zeros elsewhere. A permutation matrix is orthogonal, i.e., $JJ^{\top} = J^{\top}J = I$.

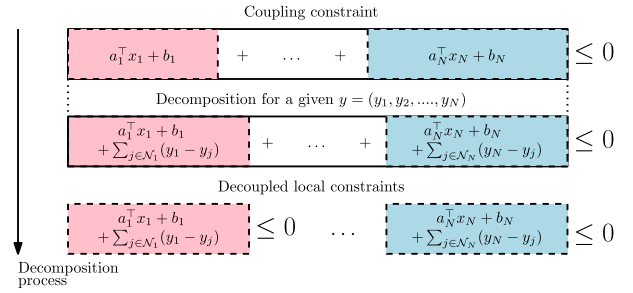


Fig. 1. Illustration of the constraint decomposition scheme. Here, only one coupling constraint is considered and the superscript is neglected for simplicity. By introducing an auxiliary variable \mathbf{y} , one coupling constraint becomes N local constraints. Proposition 1 shows that when \mathbf{y} is a decision variable, the two class of constraints represent the same feasible region in \mathbf{x} . Our proposed algorithm locally updates y_i to obtain an “optimal” constraint decomposition in the sense that $\mathbf{a}_i^{\top} \mathbf{x}_i^* + b_i + \sum_{j \in \mathcal{N}_i} (y_i - y_j) \leq 0$ for all $i \in \mathcal{I}$, where \mathbf{x}_i^* is the optimal solution to the original optimization problem.

III. EQUIVALENT PROBLEM

In this section, we present a new optimization problem that is equivalent to (3) but with a separable structure. Similar decomposition schemes were also discussed in [16, Proposition 1] and [17, Proposition 4.1]. Introduce auxiliary decision variables $\{y_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ where $y_i^m \in \mathbb{R}$. Denote $\mathbf{y}^m = (y_1^m, \dots, y_N^m) \in \mathbb{R}^N, m \in \mathcal{M}$, and $\mathbf{y} = [\mathbf{y}^1; \mathbf{y}^2; \dots; \mathbf{y}^M]$. Consider

$$\begin{aligned} \min_{\mathbf{x}, \mathbf{y}^1, \dots, \mathbf{y}^M} \quad & \sum_{i \in \mathcal{I}} f_i(\mathbf{x}_i) \\ \text{s.t.} \quad & \begin{cases} A^{\top} \mathbf{x} + L\mathbf{y}^1 + \mathbf{b}^1 \leq 0 \\ \vdots \\ A^M \mathbf{x} + L\mathbf{y}^M + \mathbf{b}^M \leq 0 \end{cases} \end{aligned} \quad (4)$$

where recall that L is the graph Laplacian matrix, $A^m = \text{blkdiag}(\mathbf{a}_1^m, \dots, \mathbf{a}_N^m) \in \mathbb{R}^{(\sum_i d_i) \times N}$.

When organizing the constraints by the order of agents, the problem can be rewritten as

$$\begin{aligned} \min_{\mathbf{x}, \mathbf{y}^1, \dots, \mathbf{y}^M} \quad & \sum_{i \in \mathcal{I}} f_i(\mathbf{x}_i) \\ \text{s.t.} \quad & \begin{cases} A_1^{\top} \mathbf{x}_1 + (I_M \otimes \mathbf{l}_1) \mathbf{y} + \mathbf{b}_1 \leq 0 \\ \vdots \\ A_i^{\top} \mathbf{x}_i + (I_M \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i \leq 0 \\ \vdots \\ A_N^{\top} \mathbf{x}_N + (I_M \otimes \mathbf{l}_N) \mathbf{y} + \mathbf{b}_N \leq 0 \end{cases} \end{aligned} \quad (5)$$

where recall that \mathbf{l}_i is the i th row of the graph Laplacian, $A_i = [\mathbf{a}_i^1, \mathbf{a}_i^2, \dots, \mathbf{a}_i^M] \in \mathbb{R}^{d_i \times M}$. One verifies that the optimization problems in (4) and (5) are the same up to a permutation of constraints. An illustration of the decomposition approach is shown in Fig. 1.

Proposition 1 (Equivalence): The two optimization problems in (3) and (4) are equivalent, in the sense that

- 1) for any feasible solution $(\mathbf{x}', \mathbf{y}')$ to (4), \mathbf{x}' is a feasible solution to (3);

- 2) for any feasible solution \mathbf{x}' to (3), there exists a $\mathbf{y}' \in \mathbb{R}^{NM}$ such that $(\mathbf{x}', \mathbf{y}')$ is a feasible solution to (4);
- 3) the two problems have the same cost function.

Proof: See Appendix. \square

If $\mathbf{y}^m, m \in \mathcal{M}$, are viewed as independent variables instead of decision variables, then the problem (5) has a natural separable structure for a given \mathbf{y} . In the following, we consider a distributed solution to (3), composed of the local optimization problems for agent $i \in \mathcal{I}$:

$$\begin{aligned} & \min_{\mathbf{x}_i} f_i(\mathbf{x}_i) \\ & \text{s.t.} \quad \begin{cases} \mathbf{a}_i^{1\top} \mathbf{x}_i + \sum_{j \in \mathcal{N}_i} (y_i^1 - y_j^1) + b_i^1 \leq 0 \\ \vdots \\ \mathbf{a}_i^{M\top} \mathbf{x}_i + \sum_{j \in \mathcal{N}_i} (y_i^M - y_j^M) + b_i^M \leq 0 \end{cases} \end{aligned} \quad (6)$$

and some local update law for the variable $y_i^m, i \in \mathcal{I}, m \in \mathcal{M}$, that will be detailed in the next section. We note that this local optimization problem will give an optimal \mathbf{x}_i if and only if $\mathbf{y}^m, m \in \mathcal{M}$ is optimal to the problem in (4) in view of Proposition 1. Nevertheless, for any given \mathbf{y} , we have the following result.

Proposition 2 (Constraint satisfaction): For a given \mathbf{y} , if $\mathbf{x}_i, i \in \mathcal{I}$, is feasible to the local optimization problem in (6), then the stacked vector $[\mathbf{x}_1; \mathbf{x}_2; \dots; \mathbf{x}_N]$ is a feasible solution to (3).

Proof: Consider the m th constraint in (3). By summing up the m th constraint of (6) for each agent, we have $\sum_{i \in \mathcal{I}} \mathbf{a}_i^{m\top} \mathbf{x}_i + \sum_{i \in \mathcal{I}} \mathbf{l}_i \mathbf{y}^m + \sum_{i \in \mathcal{I}} b_i^m = \sum_{i \in \mathcal{I}} \mathbf{a}_i^{m\top} \mathbf{x}_i + b_i^m \leq 0$, considering that $\sum_{i \in \mathcal{I}} \mathbf{l}_i \mathbf{y}^m = \mathbf{1}^\top L \mathbf{y}^m = 0$. \square

IV. SENSITIVITY ANALYSIS OF LOCAL AND GLOBAL OPTIMIZATION PROBLEMS

In this section, we will investigate how \mathbf{y} affects the optimal value of the local optimization problems. We will propose an updating scheme for \mathbf{y} such that the sum of the optimal values of the local problems always decreases until reaching the optimal value of the centralized problem.

Assumption 3: For any $\mathbf{y} \in \mathbb{R}^{NM}$, Slater's conditions hold for all local optimization problems, i.e., there exists \mathbf{x}_i that is strictly feasible to (6).

One sufficient condition for this assumption to hold is that $\text{Rank}(A_i) = M, \forall i \in \mathcal{I}$. In the following, we assume Assumption 3 holds. For a given \mathbf{y} , consider the local problem (6)

$$\begin{aligned} \phi_i(\mathbf{y}) & := \min f_i(\mathbf{x}_i) \\ & \text{s.t.} \quad A_i^\top \mathbf{x}_i + (I_M \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i \leq 0. \end{aligned} \quad (7)$$

Under Assumption 3, $\phi_i(\mathbf{y})$ is well defined for all $\mathbf{y} \in \mathbb{R}^{NM}$. Given $\mathbf{y} \in \mathbb{R}^{NM}$, define

$$\phi(\mathbf{y}) = \sum_{i \in \mathcal{I}} \phi_i(\mathbf{y}). \quad (8)$$

In general, $\phi(\mathbf{y})$ is not differentiable. In the following, we use tools from nonsmooth analysis [21]. Let the subdifferential, i.e., the set of all subgradients, of $\phi(\mathbf{y})$ be $\partial\phi(\mathbf{y})$. We have the following results characterizing the subdifferential of $\phi(\mathbf{y})$.

Proposition 3 (Subdifferential): Let Assumptions 1–3 hold. Denote by $\mathbf{c}_i = (c_i^1, \dots, c_i^M) \in \mathbb{R}^M$ a Lagrange multiplier to (6) for $i \in \mathcal{I}$. Define $\zeta_i^m = \sum_{j \in \mathcal{N}_i} (c_i^m - c_j^m)$, $\zeta^m = (\zeta_1^m, \zeta_2^m, \dots, \zeta_N^m)$, $\zeta = [\zeta^1; \zeta^2; \dots; \zeta^M]$. Then

- 1) $\mathbf{c}_i \in \mathbb{R}^M$, not necessarily unique, always exist;
- 2) $\phi(\cdot)$ is convex, but not strongly convex;
- 3) $\zeta \in \partial\phi(\mathbf{y})$.

Proof: From Assumptions 1–3, the strong duality theorem for convex inequality constraints [22, Proposition 3.5.1] applies, and thus, the strong duality holds and at least one Lagrange multiplier exists. This proves Point 1).

We show the convexity of $\phi_i(\mathbf{y})$ by definition. For any $\mathbf{y}', \mathbf{y}''$, denote $\mathbf{x}', \mathbf{x}''$ the corresponding optimal solution of (7). It is clear that $\phi_i(\lambda \mathbf{y}' + (1-\lambda)\mathbf{y}'') \leq f_i(\lambda \mathbf{x}' + (1-\lambda)\mathbf{x}'') \leq \lambda f_i(\mathbf{x}') + (1-\lambda)f_i(\mathbf{x}'') = \lambda \phi_i(\mathbf{y}') + (1-\lambda)\phi_i(\mathbf{y}'')$, where the inequalities hold thanks to the linearity of the constraints and the convexity of $f_i(\cdot)$, respectively. Thus, $\phi(\mathbf{y})$ is also convex. $\phi(\mathbf{y})$ not being strongly convex is evident since $\phi(\mathbf{y} + s\mathbf{1}) = \phi(\mathbf{y})$ for any $s \in \mathbb{R}$.

Now consider a perturbed version of (7) with \mathbf{y}' and denote its optimal value $\phi_i(\mathbf{y}')$. From sensitivity analysis [23, Eq. 5.57], we know

$$\phi_i(\mathbf{y}') \geq \phi_i(\mathbf{y}) + \mathbf{c}_i^\top (I_M \otimes \mathbf{l}_i) (\mathbf{y}' - \mathbf{y}) \quad (9)$$

for all \mathbf{y}' . This means $(I_M \otimes \mathbf{l}_i^\top) \mathbf{c}_i$ is a subgradient of $\phi_i(\mathbf{y})$. Since $\phi(\mathbf{y})$ is convex, $\partial\phi$ is nonempty and takes compact and convex values [24, Proposition 9]. Based on the calculus of subdifferentials: $\partial(f_1 + f_2)(\mathbf{x}) \supseteq \partial f_1(\mathbf{x}) + \partial f_2(\mathbf{x})$, we know

$$\sum_{i \in \mathcal{I}} (I_M \otimes \mathbf{l}_i^\top) \mathbf{c}_i \in \partial\phi(\mathbf{y}). \quad (10)$$

Note that

$$(I_M \otimes \mathbf{l}_i^\top) \mathbf{c}_i = \begin{bmatrix} \mathbf{l}_i^\top & 0 & 0 \\ 0 & \mathbf{l}_i^\top & 0 \\ 0 & 0 & \ddots \\ 0 & 0 & 0 & \mathbf{l}_i^\top \end{bmatrix} \begin{bmatrix} c_i^1 \\ c_i^2 \\ \dots \\ c_i^M \end{bmatrix} = \begin{bmatrix} c_i^1 \mathbf{l}_i^\top \\ c_i^2 \mathbf{l}_i^\top \\ \dots \\ c_i^M \mathbf{l}_i^\top \end{bmatrix}$$

and that

$$\sum_{i \in \mathcal{I}} c_i^m \mathbf{l}_i^\top = \begin{bmatrix} \mathbf{l}_1^\top & \mathbf{l}_2^\top & \dots & \mathbf{l}_N^\top \end{bmatrix} \mathbf{c}^m = L^\top \mathbf{c}^m = L \mathbf{c}^m$$

with $\mathbf{c}^m = (c_1^m, c_2^m, \dots, c_N^m)$. We thus obtain

$$\begin{aligned} \sum_{i \in \mathcal{I}} (I_M \otimes \mathbf{l}_i^\top) \mathbf{c}_i & = [L \mathbf{c}^1; L \mathbf{c}^2; \dots; L \mathbf{c}^M] \\ & = (I_M \otimes L) \mathbf{c}_C \in \partial\phi(\mathbf{y}) \end{aligned} \quad (11)$$

where $\mathbf{c}_C = [\mathbf{c}^1; \mathbf{c}^2; \dots; \mathbf{c}^M]$ (ordered by constraints). Equivalently, we have $\zeta \in \partial\phi(\mathbf{y})$. This proves Point 3). \square

Remark 1: Recall that \mathbf{c}_i can be calculated solely based on the local problem at node i . Proposition 3 reveals that although each computational node does not have the full information about the subgradient of $\phi(\mathbf{y})$, each computational node has access to the subgradient of $\phi(\mathbf{y})$ with respect to the local auxiliary variable \mathbf{y}_i by communicating local Lagrange multipliers to its neighbors.

Algorithm 1: Distributed Optimization Algorithm.

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- 1: **Locally stored state:** $\mathbf{x}_i, \mathbf{y}_i$
 - 2: **Initialization:** choose arbitrary \mathbf{y}_i .
 - 3: **loop**
 - 4: Send \mathbf{y}_i to and gather \mathbf{y}_j from neighbors $j \in N_i$
 - 5: Compute $(\mathbf{x}_i, \mathbf{c}_i)$ as the primal-dual optimizer of (6)
 - 6: Send \mathbf{c}_i to and gather \mathbf{c}_j from neighbors $j \in N_i$
 - 7: Update \mathbf{y}_i according to (13)
 - 8: **end loop**
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Specifically, we have that

$$\frac{\partial \phi(\mathbf{y})}{\partial \mathbf{y}_i^m} = \zeta_i^m = \sum_{j \in N_i} (c_i^m - c_j^m) \quad \forall m \in \mathcal{M} \quad (12)$$

whenever $\phi(\mathbf{y})$ is differentiable.

V. PROPOSED ALGORITHM

In this section, we give details about the proposed continuous-time distributed optimization algorithm. A pseudocode for computational node i is given in Algorithm 1. Note that since the analysis is done in continuous time, we are assuming that the four steps in the loop block are executed at the same time instant, i.e., $\mathbf{y}_i, \mathbf{y}_j, \mathbf{c}_i, \mathbf{c}_j$ in Steps 4 and 6 are computed and transmitted simultaneously. For digital implementation, all agents synchronously communicate \mathbf{y}_i and \mathbf{c}_i in Steps 4 and 6. We also choose a small sampling time to approximate the continuous-time update of \mathbf{y}_i in Step 7.

Theorem 1: Let Assumptions 1–3 hold. Denote by $\mathbf{c}_i(\mathbf{y})$ the Lagrange multiplier of (6) given \mathbf{y} . If \mathbf{y}_i is updated according to

$$\dot{\mathbf{y}}_i = -k_0 \sum_{j \in N_i} (\mathbf{c}_i(\mathbf{y}) - \mathbf{c}_j(\mathbf{y})) \text{ for almost all } t \quad (13)$$

where $k_0 > 0$ is a constant gain and a Caratheodory solution² exists, then the following holds:

- 1) the Caratheodory solution is unique and converges to the set of optimal \mathbf{y} of the equivalent problem (4);
- 2) the solution to the local problem (6) asymptotically converges to (one of) the optimal solution(s) of the centralized problem in (3);
- 3) and the coupling constraints in (3) hold during the solution evolution.

Proof: From Proposition 3, \mathbf{c}_i is well defined for all \mathbf{y} , but it is not necessarily unique. From the right-hand side of (13), one derives

$$\dot{\mathbf{y}}_i = -k_0 \begin{bmatrix} \sum_{j \in N_i} (c_i^1 - c_j^1) \\ \sum_{j \in N_i} (c_i^2 - c_j^2) \\ \dots \\ \sum_{j \in N_i} (c_i^M - c_j^M) \end{bmatrix} = -k_0 \begin{bmatrix} l_i \mathbf{c}^1 \\ l_i \mathbf{c}^2 \\ \dots \\ l_i \mathbf{c}^M \end{bmatrix} \quad (14)$$

² A Caratheodory solution of a differential equation $\dot{\mathbf{x}}(t) = X(\mathbf{x}(t))$ or a differential inclusion $\dot{\mathbf{x}}(t) \in X(\mathbf{x}(t))$ is an absolutely continuous function $\mathbf{x}(t) : [0, \infty) \rightarrow \mathbb{R}^n$ that satisfies the differential equation or the differential inclusion for almost all t , respectively [24].

for almost all t . Reorder $\{-k_0 l_i \mathbf{c}^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ by the order of constraints, we obtain $\dot{\mathbf{y}} = [\dot{\mathbf{y}}^1; \dot{\mathbf{y}}^2; \dots; \dot{\mathbf{y}}^M]$ where

$$\dot{\mathbf{y}}^m = -k_0 [l_1 \mathbf{c}^m; l_2 \mathbf{c}^m; \dots; l_N \mathbf{c}^m] = -k_0 L \mathbf{c}^m.$$

Thus, $\dot{\mathbf{y}} = -k_0 (I_M \otimes L) \mathbf{c}_C$ for almost all t , where we recall $\mathbf{c}_C = [\mathbf{c}^1; \mathbf{c}^2; \dots; \mathbf{c}^M]$ (ordered by constraints). Denote the Caratheodory solution of this differential equation to be $\mathbf{y}(t)$.

Now consider Caratheodory solutions of the differential inclusion $\dot{\mathbf{y}} \in -k_0 \partial \phi(\mathbf{y}) = -\partial k_0 \phi(\mathbf{y})$ in view of Proposition 3, where $\phi(\mathbf{y})$ is defined in (8). From [24, gradient differential inclusion of a convex function], we know such a solution exists and is unique. Recall that $\dot{\mathbf{y}}(t) \in -\partial k_0 \phi(\mathbf{y}(t))$ for almost all t , thus $\mathbf{y}(t)$ is also unique.

In order to investigate how $\phi(\mathbf{y}(t))$ evolves with respect to time, we check the set-valued lower Lie derivative along the differential inclusion

$$\underline{L}_{-\partial k_0 \phi(\mathbf{y})} \phi(\mathbf{y}) = \{a \in \mathbb{R} : \text{there exists } \boldsymbol{\xi} \in \partial \phi(\mathbf{y}) \text{ such that } a = \min_{\mathbf{v} \in -\partial k_0 \phi(\mathbf{y})} \boldsymbol{\xi}^\top \mathbf{v}\}. \quad (15)$$

For any $\boldsymbol{\xi} \in \partial \phi(\mathbf{y})$, there exists $\mathbf{v} = -k_0 \boldsymbol{\xi} \in -\partial k_0 \phi(\mathbf{y})$ such that $\boldsymbol{\xi}^\top \mathbf{v} = -k_0 \|\boldsymbol{\xi}\|^2 \leq 0$. Hence, $\sup \underline{L}_{-\partial k_0 \phi(\mathbf{y})} \phi(\mathbf{y}) \leq 0$ for all \mathbf{y} , and the equality holds if and only if $\mathbf{0} \in \partial \phi(\mathbf{y})$. Following [24, Proposition 13] and the uniqueness of the solutions, we know $\phi(\mathbf{y}(t))$ is nonincreasing. In particular, when $\mathbf{0} \notin \partial \phi(\mathbf{y})$, $\sup \underline{L}_{-\partial k_0 \phi(\mathbf{y}(t))} \phi(\mathbf{y}(t)) < 0$, and thus $\phi(\mathbf{y}(t))$ is strictly decreasing.

Denote $h(t) = \sup \underline{L}_{-\partial k_0 \phi(\mathbf{y}(t))} \phi(\mathbf{y}(t))$, $\alpha = \limsup_{t \rightarrow \infty} h(t)$. Such a limit exists and is bounded since $h(t)$ is upper bounded by 0. Assume $\alpha < 0$, then, $\exists T > 0$ and $\epsilon = -\alpha/2$ such that $h(t) < \alpha + \epsilon = \alpha/2 < 0$ for all $t \geq T$. This implies that $\phi(\mathbf{y}(t)) < \phi(\mathbf{y}(T)) + \alpha(t - T)/2$ for all $t \geq T$, which contradicts with Assumption 2. Thus, we have $\limsup_{t \rightarrow \infty} h(t) = 0$. This means that a subsequence of $h(t)$ converges to 0 asymptotically, which leads to the conclusion that a subsequence of $\mathbf{y}(t)$ converges to the set $\{\mathbf{y} : \mathbf{0} \in \partial \phi(\mathbf{y})\}$. This proves Point 1).

Since $\mathbf{y}(t)$ converges to the optimal set $\{\mathbf{y} : \mathbf{0} \in \partial \phi(\mathbf{y})\}$ asymptotically, and in view of the equivalence between (3) and (4) from Proposition 1, we know the optimal solution to (3) is obtained asymptotically. This shows Point 2). Point 3) follows from Assumption 3 and Proposition 2. \square

Remark 2: Convergence of the subgradient differential inclusion of a convex function was investigated in [21] and [24, Gradient differential inclusion of a convex function], where the convergence property has been established. However, we note that here $\phi(\mathbf{y})$ has infinitely many local minima and they may not be bounded. Proofs in [21] and [24] rely on nonsmooth Lyapunov function analysis (with an assumption on the uniqueness of the local minima) or LaSalle's principle (with an assumption on the boundedness of the local minima), both of which are not applicable here. Instead, we did not prove the convergence of $\mathbf{y}(t)$ to a particular optimal point, but to an optimal set $\{\mathbf{y} : \mathbf{0} \in \partial \phi(\mathbf{y})\}$.

Remark 3 (Caratheodory solution): One may wonder why a Caratheodory solution is considered in Theorem 1 and how to guarantee/verify its existence. In Proposition 3, we have

established that, for a given \mathbf{y} , the Lagrange multiplier c_i always exists but may not be unique under Assumptions 1–3. If $c_i(\mathbf{y})$, as a function of \mathbf{y} , is continuous, then classic solutions to the ODE in (13) exist, and of course a Caratheodory solution exists. We introduce the Caratheodory solution so that we can neglect discontinuities of $c_i(\mathbf{y}(t))$ for a duration of measure zero. Theoretically, for the local optimization problem (7) parameterized by \mathbf{y} , when the cost function is smooth and the strong second order sufficient condition (SSOSC) holds at \mathbf{y}' , there exists a neighborhood of \mathbf{y}' such that a unique primal-dual optimizer $(\mathbf{x}_i(\mathbf{y}), \mathbf{c}_i(\mathbf{y}))$, when viewed as a function of \mathbf{y} , exists and is locally Lipschitz continuous in \mathbf{y} [25]. Other conditions exist for ensuring continuous primal-dual pairs of perturbed optimization problems. See a recent survey [26] and references therein. Numerically, if there are multiple eligible local Lagrange multipliers, one can choose \mathbf{c}_i that is close to \mathbf{c}_i^- , where \mathbf{c}_i^- denotes the variable \mathbf{c}_i calculated one step before.

Remark 4 (Differentiability): [27, Corollary 7.3.1] states that the perturbed optimal value function is locally differentiable if and only if the Lagrange multiplier is unique. Thus, one sufficient condition for local differentiability of $\phi_i(\mathbf{y})$ is that the optimization problem in (7) fulfills the linearly independent constraint qualification (LICQ), which ensures the existence and uniqueness of the Lagrange multiplier [28]. When $\phi_i(\mathbf{y})$'s are differentiable, the subgradient then becomes the usual gradient, i.e., $\partial\phi_i(\mathbf{y}) = \{\nabla\phi_i(\mathbf{y})\}$. In this case, the adaptive law in (13) becomes the well-established gradient flow. This will be discussed in detail for one special case, namely, the control barrier function-induced QPs, in Section VII.

Remark 5 (Memory, computation, and communication efficiency): In Algorithm 1, each computational node i stores variables \mathbf{x}_i and \mathbf{y}_i of dimension $d_i + M$, while broadcasting \mathbf{y}_i and \mathbf{c}_i of dimension $2M$ to neighbors. Compared to the primal decomposition scheme in [1], our approach requires smaller storage ($d_i + M$ versus $d_i + D_i M$) and communication ($2M$ versus $2D_i M$) variables, where D_i is the degree of the communication graph at node i [20]. Mestres and Cortes [17] adopted the same decomposition scheme as in this work, but requires each local node to store $2d_i + 2M$ variables. Additionally, the proposed algorithm requires less computation for local nodes at each iteration, as they only need to solve a single optimization problem with the size of decision variable d_i , unlike the dual decomposition scheme in [4], which involves solving two optimizations with sizes d_i and M .

VI. SPARSE CASE

What has been discussed so far deals with the most general case, and is applicable in a densely coupled scenario, i.e., every computational node is involved in every coupling constraint. In many cases, the constraint coupling is sparse and, usually, is consistent with the communication topology. For example, in multirobot applications [29], [30], [31], collision avoidance is a pairwise constraint between two robots, and they need to have some information exchange between them in order to work out a safe path. Exploiting the sparsity of the constraint coupling would help us relax conservative conditions, reduce the size

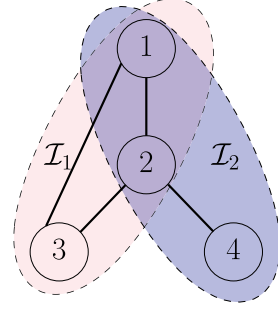


Fig. 2. Illustration of a communication graph satisfying Assumption 4. In this scenario, the agent index sets for each constraint are $\mathcal{I}_1 = \{1, 2, 3\}$, $\mathcal{I}_2 = \{1, 2, 4\}$, the constraint index sets for each agent are $\mathcal{M}_1 = \mathcal{M}_2 = \{1, 2\}$, $\mathcal{M}_3 = \{1\}$, $\mathcal{M}_4 = \{2\}$, and the sets of neighboring nodes with relevant constraint involvement are $N_1^1 = \{2, 3\}$, $N_1^2 = \{2\}$, $N_2^1 = \{1, 3\}$, $N_2^2 = \{1, 4\}$, $N_3^1 = \{1, 2\}$, $N_4^2 = \{2\}$, respectively.

of optimization problems on each computational node, and improve communication efficiency with the neighbors. To formally characterize sparsity, we first define the following notations.

Define $\mathcal{I}_m \subseteq \mathcal{I}$ as the index set of the computational nodes involved in the m th constraint, i.e., $i \in \mathcal{I}_m$ if and only if $\mathbf{a}_i^m \neq \mathbf{0}$ or $b_i^m \neq 0$. Similarly, define $\mathcal{M}_i \subseteq \mathcal{M}$ as the index set of the coupling constraints involving node i , i.e., $m \in \mathcal{M}_i$ if and only if $\mathbf{a}_i^m \neq \mathbf{0}$ or $b_i^m \neq 0$. Define the set of neighboring nodes of node i involved in the m th constraint as $N_i^m = \{j \in \mathcal{I} : j \in N_i \text{ and } j \in \mathcal{I}_m\}$. In the sparse setting, we assume that each agent knows which neighbors are involved in which relevant constraints, i.e., $N_i^m \forall m \in \mathcal{M}_i$ is known to agent i .

We call the communication graph $\mathcal{G} = (\mathcal{I}, E)$ is consistent with the m th constraint if the induced subgraph [20] $\mathcal{G}_m := (\mathcal{I}_m, E_m)$ is connected, where $(i, j) \in E_m$ if and only if $i, j \in \mathcal{I}_m$ and $(i, j) \in E$. Define $\mathcal{G}'_m := (\mathcal{I}, E_m)$.

Assumption 4: The communication graph \mathcal{G} is consistent with all constraints.

Fig. 2 illustrates a scenario where there are 4 computational nodes and 2 coupling constraints. Note that both \mathcal{G}_1 (the subgraph in pink) and \mathcal{G}_2 (the subgraph in blue) are connected, then \mathcal{G} is consistent with these two constraints.

Under Assumption 4, we know at most $|\mathcal{M}_i|$ columns of A_i are nonzero. One sufficient condition that fulfills Assumption 3 in this case is thus $\text{Rank}(A_i) = |\mathcal{M}_i|$ for all i .

A. Equivalent Optimization Problems

Now we show that the original problem in (3) is equivalent to the following optimization problems in a sparse setting:

$$\begin{aligned} & \min_{\mathbf{x}_i, \mathbf{y}_i, i \in \mathcal{I}} \sum_{i \in \mathcal{I}} f_i(\mathbf{x}_i) \\ & \text{s.t. } \mathbf{a}_i^m \top \mathbf{x}_i + \sum_{j \in N_i^m} (y_i^m - y_j^m) + b_i^m \leq 0 \\ & \quad \forall i \in \mathcal{I}, m \in \mathcal{M}_i. \end{aligned} \quad (16)$$

Proposition 4 (Equivalence in a sparse setting): Under Assumptions 3 and 4, the two problems in (3) and (16) are equivalent, in the sense that

- 1) for any feasible solution $(\mathbf{x}', \mathbf{y}')$ to (16), \mathbf{x}' is a feasible solution to (3);
- 2) for any feasible solution \mathbf{x}' to (3), there exists a variable \mathbf{y}' such that $(\mathbf{x}', \mathbf{y}')$ is a feasible solution to (16);
- 3) the two problems have the same cost function.

The proof follows similar steps as in that of Proposition 1 except that now we need to use the Laplacian matrices of the induced subgraphs $\mathcal{G}_m, m \in \mathcal{M}$, which are assumed to be connected under Assumption 4. Details are omitted here for brevity. Similar to Section III, the reformulated problem in (16) has a separable structure, and only local information $y_j^m, j \in N_i^m$ is needed to determine the constraints concerning each node. It is obvious from (16) that $y_i^m, m \in \mathcal{M} \setminus \mathcal{M}_i$ is not involved in the local optimization problem. Thus, we can preset those components in \mathbf{y} to be constant zero. The sparse formulation in (16) also accounts for local constraints that involve only one node. Denoting the node by i , we have $a_j^m, b_j^m = 0$ for any $j \neq i$ and we preset $y_k^m = 0$ for any $k \in \mathcal{I}$.

B. Local Optimization Problems

Following a similar analysis procedure, in the following, we will treat \mathbf{y}_i as an independent variable and design a distributed updating law so that \mathbf{y}_i converges to the optimal \mathbf{y}_i^* to (16). For node i and a given \mathbf{y} , a local optimization problem is given by

$$\phi_i(\mathbf{y}) := \min_{\mathbf{x}_i} f_i(\mathbf{x}_i)$$

$$\text{s.t. } \mathbf{a}_i^{m\top} \mathbf{x}_i + \sum_{j \in N_i^m} (y_i^m - y_j^m) + b_i^m \leq 0 \quad \forall m \in \mathcal{M}_i. \quad (17)$$

Define $\mathbf{c}_i = (c_i^1, \dots, c_i^m, \dots, c_i^M)$, where c_i^m is the Lagrange multiplier of (17) if $m \in \mathcal{M}_i$, and is equal to 0 otherwise.

Similar to previous discussions, we have the constraint satisfaction property as follows. The proof is omitted for brevity.

Proposition 5 (Constraint satisfaction): For any given \mathbf{y} , if $\mathbf{x}_i, i \in \mathcal{I}$ is feasible to the local optimization problem in (17), then $[\mathbf{x}_1; \mathbf{x}_2; \dots; \mathbf{x}_N]$ is a feasible solution to (3).

Define the summation of the optimal values of the local optimization problems as

$$\phi(\mathbf{y}) = \sum_{i \in \mathcal{I}} \phi_i(\mathbf{y}). \quad (18)$$

Proposition 6 (Subdifferential): Let Assumptions 1–4 hold. Let $\mathbf{c}_i = (c_i^1, \dots, c_i^M) \in \mathbb{R}^m$ be defined below (17). Define $\zeta_i^m = \sum_{j \in N_i^m} (c_i^m - c_j^m)$ if $m \in \mathcal{M}_i$ and $\zeta_i^m = 0$ if $m \notin \mathcal{M}_i$.

Let $\zeta^m = (\zeta_1^m, \zeta_2^m, \dots, \zeta_N^m), \zeta = [\zeta^1; \zeta^2; \dots; \zeta^M]$. Then

- 1) $\mathbf{c}_i \in \mathbb{R}^m$, not necessarily unique, always exists;
- 2) $\phi(\mathbf{y})$ is convex;

Algorithm 2: Sparse Distributed Optimization Algorithm.

- 1: **Local stored state:** $\mathbf{x}_i, \mathbf{y}_i$
 - 2: **Initialization:** Choose arbitrary \mathbf{y}_i , and let $y_i^m = 0$ if $m \notin \mathcal{M}_i$.
 - 3: **loop**
 - 4: Send y_i^m to and gather y_j^m from $j \in N_i^m \quad \forall m \in \mathcal{M}_i$
 - 5: Compute $(\mathbf{x}_i, \mathbf{c}_i)$ from (17)
 - 6: Send c_i^m to and gather c_j^m from $j \in N_i^m \quad \forall m \in \mathcal{M}_i$
 - 7: Update \mathbf{y}_i according to (21)
 - 8: **end loop**
-

- 3) $\zeta \in \partial\phi(\mathbf{y})$.

Proof: The first two claims follow from a similar argument to that of Proposition 3 and are omitted here. We will show Point 3) in the following. From sensitivity analysis, for any \mathbf{y}, \mathbf{y}' , we know (19), shown at the bottom of this page, holds, where $\tilde{\mathbf{l}}_{i, \mathcal{G}_m}$ is the i th row of the Laplacian matrix of $\mathcal{G}'_m = (\mathcal{I}, E_m)$. The first inequality in (19) is from [23, Equation 5.57], and the last two equalities follow from the definition of graph Laplacian matrices and noting that when $m \notin \mathcal{M}_i, \tilde{\mathbf{l}}_{i, \mathcal{G}_m} = \mathbf{0}$. Equation (19) implies that $\tilde{\mathbf{L}}_i^\top \mathbf{c}_i$ is a subgradient of $\phi_i(\mathbf{y})$.

Following the calculus rule for subdifferential, $\sum_i \tilde{\mathbf{L}}_i^\top \mathbf{c}_i$ is a subgradient of $\phi(\mathbf{y})$. With a few linear algebraic operations, we know:

$$\tilde{\mathbf{L}}_i^\top \mathbf{c}_i = \begin{bmatrix} \tilde{\mathbf{l}}_{i, \mathcal{G}_1}^\top & 0 & \dots & 0 \\ 0 & \tilde{\mathbf{l}}_{i, \mathcal{G}_2}^\top & \dots & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & \tilde{\mathbf{l}}_{i, \mathcal{G}_M}^\top \end{bmatrix} \begin{bmatrix} c_i^1 \\ c_i^2 \\ \dots \\ c_i^M \end{bmatrix} = \begin{bmatrix} c_i^1 \tilde{\mathbf{l}}_{i, \mathcal{G}_1}^\top \\ c_i^2 \tilde{\mathbf{l}}_{i, \mathcal{G}_2}^\top \\ \dots \\ c_i^M \tilde{\mathbf{l}}_{i, \mathcal{G}_M}^\top \end{bmatrix}.$$

Thus, the entry in $\sum_i \tilde{\mathbf{L}}_i^\top \mathbf{c}_i$ that corresponds to y_i^m is

$$\begin{aligned} \left[\sum_{k \in \mathcal{I}} c_k^m \tilde{\mathbf{l}}_{k, \mathcal{G}_m}^\top \right]_i &= \sum_{k \in \mathcal{I}} [\tilde{\mathbf{l}}_{k, \mathcal{G}_m}^\top]_i c_k^m \\ &= \begin{cases} \sum_{j \in N_i^m} (c_i^m - c_j^m) & \text{if } m \in \mathcal{M}_i \\ 0 & \text{if } m \notin \mathcal{M}_i \end{cases}. \end{aligned} \quad (20)$$

The second equality comes from the fact that $[\tilde{\mathbf{l}}_{k, \mathcal{G}_m}^\top]_i = [L_{\mathcal{G}_m}]_{k, i}$, the (k, i) th element of the Laplacian of the graph $\mathcal{G}'_m = (\mathcal{I}, E_m)$. Thus $[\tilde{\mathbf{l}}_{k, \mathcal{G}_m}^\top]_i$ is equal to 0 if $m \notin \mathcal{M}_i$, or $k \neq i \wedge k \notin N_i^m$; -1 if $k \in N_i^m$; and $|N_i^m|$ if $k = i$. Thus we conclude ζ is a subgradient of $\phi(\mathbf{y})$. \square

The distributed optimization algorithm for node i in the sparse case is given as follows.

The main difference compared to Algorithm 1 is that 1) now node i receives $\mathbf{y}_j, \mathbf{c}_j$ from and send $\mathbf{y}_i, \mathbf{c}_i$ to neighboring nodes

$$\begin{aligned} \phi_i(\mathbf{y}') &\geq \phi_i(\mathbf{y}) + \sum_{m \in \mathcal{M}_i} c_i^m \sum_{j \in N_i^m} ((y_i'^m - y_j'^m) - (y_i^m - y_j^m)) \\ &= \phi_i(\mathbf{y}) + \sum_{m \in \mathcal{M}_i} c_i^m \tilde{\mathbf{l}}_{i, \mathcal{G}_m} (\mathbf{y}'^m - \mathbf{y}^m) \\ &\quad + \sum_{m \notin \mathcal{M}_i} c_i^m \tilde{\mathbf{l}}_{i, \mathcal{G}_m} (\mathbf{y}'^m - \mathbf{y}^m) \\ &= \phi_i(\mathbf{y}) + \mathbf{c}_i^\top \tilde{\mathbf{L}}_i (\mathbf{y}' - \mathbf{y}). \end{aligned} \quad \text{, where } \tilde{\mathbf{L}}_i := \begin{bmatrix} \tilde{\mathbf{l}}_{i, \mathcal{G}_1}^\top & 0 & \dots & 0 \\ 0 & \tilde{\mathbf{l}}_{i, \mathcal{G}_2}^\top & \dots & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & \dots & \tilde{\mathbf{l}}_{i, \mathcal{G}_M}^\top \end{bmatrix} \quad (19)$$

that are relevant, as in set N_i^m in Steps 4 and 7; and 2) only relevant components in \mathbf{y}_j and \mathbf{c}_j are taken into account, as in (17) and (21) in Steps 5 and 6. This leads to fewer variables to communicate among the network and smaller size local optimization problems to solve.

The following theorem states the convergence property.

Theorem 2: Let Assumptions 1–4 hold and \mathbf{c}_i as defined below (17). If $\mathbf{y}_i(t)$ is updated according to

$$\dot{\mathbf{y}}_i^m = \begin{cases} -k_0 \sum_{j \in N_i^m} (\mathbf{c}_i^m - \mathbf{c}_j^m), & \text{if } m \in \mathcal{M}_i \\ 0 & \text{if } m \notin \mathcal{M}_i \end{cases} \quad (21)$$

for almost all t , where $k_0 > 0$ is a constant gain and a Caratheodory solution exists, then the properties in Theorem 1 hold.

Proof: In view of (20), we observe that $\dot{\mathbf{y}}_i^m(t)$ given in (21) is exactly the product of (20) together with a constant negative gain. Stacking $\dot{\mathbf{y}}_i^m$ by the order of constraints, we obtain that $\dot{\mathbf{y}} \in -\partial k_0 \phi(\mathbf{y})$ for almost all t from Proposition 6. Thus, the analyses in the proof of Theorem 1 are also applicable here and are neglected. \square

VII. SPECIAL CASE: CONTROL BARRIER FUNCTIONS-INDUCED QUADRATIC PROGRAMS

A. Control Barrier Functions and Safe Distributed Control

In this section, we consider the application of our proposed algorithms in the context of control barrier function-induced safe distributed control. CBF approaches [29], [30], [31] have already been applied to multirobot safe coordination with pairwise constraints, for example, collision avoidance and connectivity maintenance. In the following, we introduce a more general formulation that further includes collective constraints.

Consider a multiagent system with \mathbf{p}_i the state vector of agent $i, i \in \mathcal{I}$. The dynamics of each agent is given by

$$\dot{\mathbf{p}}_i = \mathbf{f}_i(\mathbf{p}_i) + \mathbf{g}_i(\mathbf{p}_i)\mathbf{x}_i$$

where $\mathbf{f}_i, \mathbf{g}_i$ are locally Lipschitz vector fields, \mathbf{x}_i is the control input to agent i that is yet to be designed. Suppose that this multiagent system is subject to M coupling state constraints, that is, along the system trajectory, it has to maintain

$$h^m(\mathbf{p}_1, \dots, \mathbf{p}_N) \geq 0, m \in \mathcal{M}$$

and h^m is a smooth function. The constraint h^m is a collective constraint since it restricts the states of all agents. We call the following inequality a CBF condition associated with the m th constraint

$$\sum_{i \in \mathcal{I}} \mathbf{a}_i^{m\top} \mathbf{x}_i + b_i^m \leq 0 \quad (22)$$

where $\mathbf{a}_i^{m\top} = -\nabla_{\mathbf{p}_i} h^m \mathbf{g}(\mathbf{p}_i)$, $b_i^m, i \in \mathcal{I}$ are such that $\sum_{i \in \mathcal{I}} b_i^m = -k h^m(\mathbf{p}_1, \dots, \mathbf{p}_N) - \sum_{i \in \mathcal{I}} \nabla_{\mathbf{p}_i} h^m \mathbf{f}_i(\mathbf{p}_i)$, and constant $k > 0$. Here, we use linear functions instead of the extended class \mathcal{K} functions for simplicity. Results from CBF literature [32] state that, if a locally Lipschitz control input $\mathbf{x}_i, i \in \mathcal{I}$, is chosen such that (22) holds for all time, then the set $\{(\mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_N) : h^m(\mathbf{p}_1, \dots, \mathbf{p}_N) \geq 0, m \in \mathcal{M}\}$

is forward invariant and the m th state constraint is always satisfied, provided that it is initially satisfied. In the following analysis, we will neglect the explicit state constraints $h^m(\mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_N) \geq 0$ and instead focus on enforcing the CBF conditions for all time.

In CBF literature [16], [32], a commonly used formulation to enforce the CBF conditions is expressed as a QP as follows:

$$\begin{aligned} \min_{\mathbf{x}_1, \dots, \mathbf{x}_N} \quad & \sum_{i \in \mathcal{I}} \frac{1}{2} \|\mathbf{x}_i - \mathbf{x}_{\text{nom}, i}\|^2 \\ \text{s.t.} \quad & \begin{cases} \sum_{i \in \mathcal{I}} \mathbf{a}_i^{1\top} \mathbf{x}_i + b_i^1 \leq 0 \\ \vdots \\ \sum_{i \in \mathcal{I}} \mathbf{a}_i^{M\top} \mathbf{x}_i + b_i^M \leq 0 \end{cases} \end{aligned} \quad (23)$$

The quadratic program in (23) aims at minimally modifying nominal local controllers $\mathbf{x}_{\text{nom}, i}$, which relate to the underlying system tasks, while always respecting M CBF conditions, hereafter referred to as coupling constraints, which relate to system safety.

One challenging problem that naturally arises from this formulation is, for multiagent systems where agents only have local information, how to solve this optimization problem in a distributed way with guaranteed safety assurance.

We assume that $\mathbf{a}_i, b_i, \mathbf{x}_{\text{nom}, i}$ only depend on locally obtainable information from the neighbors of the i th agent, and that the quadratic program is always feasible. These are referred to as the local obtainability and compatibility properties of the CBF conditions as discussed in [16] and [33]. One illustrative application of coordinating a multiagent system with multiple state constraints is shown later in the simulation section.

What sets apart the CBF-induced QP in (23) from the previously discussed distributed optimization formulation is that, since the solution to (23) is applied as feedback to a dynamical system and $\mathbf{x}_{\text{nom}, i}, \mathbf{a}_i^m, b_i^m$ are state-dependent, they are time-varying in nature rather than static and evolve along the closed-loop system trajectory. In the following, we will first take a look at a time-invariant instance of (23), i.e., when $\mathbf{x}_{\text{nom}, i}, \mathbf{a}_i^m$ and b_i^m are constant, and then analyze the performance of our proposed algorithm in a time-varying setting. We note that the results in this section are also applicable to the sparsely coupled case. This extension is straightforward and neglected for notation simplicity.

Following the previous analysis, with the help of an auxiliary variable $\mathbf{y} \in \mathbb{R}^{N \times M}$, we have $\phi(\mathbf{y}) = \sum_{i \in \mathcal{I}} \phi_i(\mathbf{y})$ with $\phi_i(\mathbf{y})$ given by the local optimization problems:

$$\begin{aligned} \phi_i(\mathbf{y}) = \min_{\mathbf{x}_i} \quad & \frac{1}{2} \|\mathbf{x}_i - \mathbf{x}_{\text{nom}, i}\|^2 \\ \text{s.t.} \quad & A_i^\top \mathbf{x}_i + (I_M \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i \leq 0. \end{aligned} \quad (24)$$

Proposition 7: Consider the local QP in (24) with constant $\mathbf{x}_{\text{nom}, i}, A_i, \mathbf{y}, \mathbf{b}_i$. Assume that Assumption 3 holds. Then the Lagrange multiplier $\mathbf{c}_i = (c_i^1, c_i^2, \dots, c_i^M)$ exists and satisfies the algebraic equation

$$\begin{aligned} \Lambda_i \mathbf{c}_i = \max \quad & (A_i^\top \mathbf{x}_{\text{nom}, i} + (I_M \otimes \mathbf{l}_i) \mathbf{y} \\ & + \mathbf{b}_i + (\Lambda_i - A_i^\top A_i) \mathbf{c}_i, \mathbf{0}) \end{aligned} \quad (25)$$

where $\Lambda_i = \text{diag}(A_i^\top A_i)$, and the primal-dual optimizer to (24) is $(\mathbf{x}_{nom,i} - A_i \mathbf{c}_i, \mathbf{c}_i)$. The optimal cost is $\frac{1}{2} \|A_i \mathbf{c}_i\|^2$.

The proof follows from analyzing the Karush–Kuhn–Tucker (KKT) condition of the Lagrangian and is given in Appendix for the sake of completeness. A similar result was reported in [34, Thm. 5]. There, however, A_i, Λ_i are assumed to be nonsingular.

For the time-invariant optimization problem, if the local optimization problem in (24) always fulfills the LICQ³ by, for example, A_i being full column rank, then [27, Corollary 7.3.1] states that $\phi_i(\mathbf{y})$ in (24) is differentiable as discussed in Remark 4. In this case, the subgradient reduces to the gradient in the normal sense, and the adaptive law in (13) becomes a gradient flow. Under Assumptions 2 and 3 and the convexity of $\phi(\mathbf{y})$, the convergence guarantee of $\phi(\mathbf{y}(t))$ is well established in view that it is lower bounded and monotonically decreasing.

B. Finite-Time Convergence for Time-Varying Optimizations

In this section, we will strengthen our proposed algorithms of the previous sections to compensate for the time-varying parameters in the QP. Under LICQ, since the update law in (13) is a gradient flow, one could modify it to a scaled normalized gradient flow as in [35, (6b)], that is

$$\dot{\mathbf{y}}_i = -k_0 \text{sign} \frac{\partial}{\partial \mathbf{y}_i} \phi(\mathbf{y}) = -k_0 \text{sign} \sum_{j \in N_i} (\mathbf{c}_i - \mathbf{c}_j). \quad (26)$$

Cortes [35] showed that the normalized gradient flow achieved finite-time convergence for static strongly convex functions. However, this result is not directly applicable here since $\phi(\mathbf{y})$ is not strongly convex. Moreover, for the CBF-induced QP in (23), $\mathbf{x}_{nom,i}, \mathbf{a}_i^m, b_i^m$ depend on the states of the multiagent system and are time-varying. Before presenting the main result, we introduce the following Lemma that will simplify the analysis later on.

Lemma 1: Let \mathbf{w}_C be the vector of $\{w_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}, w_i^m \in \mathbb{R}$ ordered by constraints. Define $\mathbf{v}_C := I_M \otimes L \mathbf{w}_C, \mathbf{v}_A := [I_M \otimes \mathbf{l}_1; I_M \otimes \mathbf{l}_2; \dots; I_M \otimes \mathbf{l}_N] \mathbf{w}_C$, where \mathbf{l}_i is the i th row of the Laplacian L . Then, $\mathbf{v}_C = J \mathbf{v}_A$, where J is the permutation matrix defined in Section II-A.

Proof: Define $\mathbf{w}^m = (w_1^m, \dots, w_N^m)$. Let $v_i^m = [L \mathbf{w}^m]_i$. Then it is clear that \mathbf{v}_C is the vector of $\{v_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ ordered by constraints, and \mathbf{v}_A is the vector of $\{v_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ ordered by agents. Thus $\mathbf{v}_C = J \mathbf{v}_A$. \square

The main result is summarized in the theorem below with slowly time-varying $\mathbf{x}_{nom,i}(t), \mathbf{a}_i^m(t), b_i^m(t)$. Here, we note that LICQ is imposed as an easy-to-check sufficient condition for guaranteeing the differentiability of $\phi_i(\mathbf{y})$. Depending on the problem at hand, other conditions may also be applicable.

Theorem 3: Consider the centralized QP in (23). Assume the LICQ holds for every local optimization problem in (24) at every time instant. Let \mathbf{c}_i be the Lagrange multiplier of the local QP for agent i . Assume further that $\mathbf{x}_{nom,i}(t), \mathbf{a}_i^m(t), b_i^m(t)$ are slowly

³ We say that the LICQ is satisfied at \mathbf{x}^* for an optimization problem, if the gradients of all active constraints are linearly independent.

time-varying in the sense that there exists a constant $D > 0$ such that $\|\mathbf{d}_i^{\mathbf{I}_i}(t)\| \leq D$ for all $i \in \mathcal{I}$ and all index sets $\mathbf{I}_i \subseteq \mathcal{M}$ with

$$\mathbf{d}_i^{\mathbf{I}_i}(t) = -\frac{dA_i^{\top, \mathbf{I}_i} A_i^{\top, \mathbf{I}_i, \top}}{dt} \mathbf{c}_i^{\mathbf{I}_i} + \frac{d}{dt} (A_i^{\top, \mathbf{I}_i} \mathbf{x}_{nom,i} + \mathbf{b}_i^{\mathbf{I}_i}). \quad (27)$$

Denote $\underline{\lambda} = \min_{\mathbf{I}_i, i \in \mathcal{I}} \lambda_{\min}((A_i^{\top, \mathbf{I}_i} A_i^{\top, \mathbf{I}_i, \top})^{-1})$, $\bar{\lambda} = \max_{\mathbf{I}_i, i \in \mathcal{I}} \lambda_{\max}((A_i^{\top, \mathbf{I}_i} A_i^{\top, \mathbf{I}_i, \top})^{-1})$. If k_0 is chosen such that

$$k_0 \underline{\lambda} - ND\sqrt{M\bar{\lambda}}\|L\| - \epsilon \geq 0 \quad (28)$$

for some $\epsilon > 0$, then the Filippov solution of the scaled normalized gradient flow in (26) converges to a critical point of $\phi(\mathbf{y})$ in finite time $t_r \leq \sum_{m \in \mathcal{M}} \|L \mathbf{c}^m(0)\|_1 / \epsilon$. Moreover, the coupling constraints in (23) are always satisfied.

Proof: Consider the nonsmooth Lyapunov function

$$V(\mathbf{y}) = \left\| \frac{\partial \phi(t, \mathbf{y})}{\partial \mathbf{y}} \right\|_1 = \|(I_M \otimes L) \mathbf{c}_C\|_1 = \sum_{m \in \mathcal{M}} \|L \mathbf{c}^m\|_1.$$

Denote at the time t the index set of strictly active constraints of agent i to be $\mathbf{I}_i(t)$ and its complement $\bar{\mathbf{I}}_i(t) = \mathcal{M} \setminus \mathbf{I}_i(t)$.

In the following, we will show that for any constant $\mathbf{I}_i(t), i \in \mathcal{I}$, $V(\mathbf{y})$ decreases monotonically for a system $\Sigma_{\mathbf{I}_i, i \in \mathcal{I}}$ given by (26) together with the algebraic equation

$$\begin{aligned} A_i^{\top, \mathbf{I}_i} A_i^{\top, \mathbf{I}_i, \top} \mathbf{c}_i^{\mathbf{I}_i} &= A_i^{\top, \mathbf{I}_i} \mathbf{x}_{nom,i} + (I^{\mathbf{I}_i} \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i^{\mathbf{I}_i} \\ \mathbf{c}_i^{\bar{\mathbf{I}}_i} &= \mathbf{0}. \end{aligned} \quad (29)$$

for all $i \in \mathcal{I}$. This equation is obtained by considering only the constraints indexed in \mathbf{I}_i in (25) and noting $\mathbf{c}_i^{\mathbf{I}_i} > \mathbf{0}$. When viewing $\mathbf{I}_i, i \in \mathcal{I}$ as the index of such systems, since $V(\mathbf{y})$ decreases monotonically for all $\Sigma_{\mathbf{I}_i, i \in \mathcal{I}}$ as will be shown later, $V(\mathbf{y})$ effectively acts as a common Lyapunov function [36]. Thus, it suffices to consider a system $\Sigma_{\mathbf{I}_i, i \in \mathcal{I}}$, and the time index is dropped to ease the notation.

For arbitrary constant $\mathbf{I}_i, i \in \mathcal{I}$, from (29), we know

$$\begin{aligned} d\mathbf{c}_i^{\mathbf{I}_i}/dt &= (A_i^{\top, \mathbf{I}_i} A_i^{\top, \mathbf{I}_i, \top})^{-1} (I^{\mathbf{I}_i} \otimes \mathbf{l}_i d\mathbf{y}/dt + \mathbf{d}_i^{\mathbf{I}_i}) \\ d\mathbf{c}_i^{\bar{\mathbf{I}}_i}/dt &= \mathbf{0}. \end{aligned}$$

Here $\mathbf{d}_i^{\mathbf{I}_i}$ is defined in (27). $A_i^{\top, \mathbf{I}_i} A_i^{\top, \mathbf{I}_i, \top}$ is invertible since LICQ is assumed. Denote by $\Gamma_i' = \begin{pmatrix} (A_i^{\top, \mathbf{I}_i} A_i^{\top, \mathbf{I}_i, \top})^{-1} & 0 \\ 0 & 0 \end{pmatrix}$ and $J_{\mathbf{I}_i}$ the permutation matrix such that $[\mathbf{c}_i^{\mathbf{I}_i}; \mathbf{c}_i^{\bar{\mathbf{I}}_i}] = J_{\mathbf{I}_i} \mathbf{c}_i$. Thus $[I^{\mathbf{I}_i}; I^{\bar{\mathbf{I}}_i}] = J_{\mathbf{I}_i} I_M$. We can write the time derivative of \mathbf{c}_i in a compact form as

$$\begin{aligned} \dot{\mathbf{c}}_i &= J_{\mathbf{I}_i}^\top [d\mathbf{c}_i^{\mathbf{I}_i}/dt; d\mathbf{c}_i^{\bar{\mathbf{I}}_i}/dt] \\ &= J_{\mathbf{I}_i}^\top (\Gamma_i') J_{\mathbf{I}_i} (I_M \otimes \mathbf{l}_i \dot{\mathbf{y}} + J_{\mathbf{I}_i}^\top [\mathbf{d}_i^{\mathbf{I}_i}; \mathbf{0}]) \\ &= \Gamma_i (I_M \otimes \mathbf{l}_i \dot{\mathbf{y}} + \mathbf{d}_i^{\mathbf{I}_i, \prime}) \end{aligned} \quad (30)$$

where $\Gamma_i = J_{\mathbf{I}_i}^\top \Gamma_i' J_{\mathbf{I}_i}, \mathbf{d}_i^{\mathbf{I}_i, \prime} := J_{\mathbf{I}_i}^\top [\mathbf{d}_i^{\mathbf{I}_i}; \mathbf{0}]$.

Let $\mathbf{z} = I_M \otimes Lc_C$. Then $V(\mathbf{y}) = \|\mathbf{z}\|_1$. The generalized time derivative is given by

$$\frac{d}{dt}V(\mathbf{y}) \in \sum_{i \in \mathcal{I}^\neq} \text{sign}(z_i)\dot{z}_i + \sum_{i \in \mathcal{I}^=} \text{SIGN}(z_i)\dot{z}_i \quad (31)$$

where $\mathcal{I}^= = \{i \in \mathcal{I} : z_i = 0\}$, $\mathcal{I}^\neq = \{i \in \mathcal{I} : z_i \neq 0\}$,
 $\text{SIGN}(z) := \begin{cases} 1, & z > 0; \\ [-1, 1], & z = 0; \\ -1, & z < 0. \end{cases}$ Since we are dealing with

Filippov solutions, we can disregard the case which $z_i = 0$ holds for isolated time instants of measure zero. If $z_i = 0$ holds along an interval of time of positive measure, then, in the sense of Filippov, \dot{z}_i exists at those time instants and $\dot{z}_i = 0$. Based on this fact, we have that for almost all t , $\frac{d}{dt}V(\mathbf{z}) = \sum_{i \in \mathcal{I}^\neq} \text{sign}(z_i)\dot{z}_i + \sum_{i \in \mathcal{I}^=} \text{sign}(z_i)\dot{z}_i$, that is

$$\frac{d}{dt}V(\mathbf{y}) = \text{sign}\mathbf{z}^\top \dot{\mathbf{z}} = \text{sign}\mathbf{z}^\top (I_M \otimes L)J\dot{c}_A. \quad (32)$$

Define $\boldsymbol{\sigma} = (I_M \otimes L)\text{sign}\mathbf{z}$. After some calculations, one finds $\boldsymbol{\sigma} = [L\text{sign}Lc^1; L\text{sign}Lc^2; \dots; L\text{sign}Lc^M]$. Denote by $\sigma_i^m = [L\text{sign}Lc^m]_i$. Then $\boldsymbol{\sigma}$ can be seen as $\{\sigma_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ ordered by constraints. Let $\boldsymbol{\sigma}_i = (\sigma_i^1, \sigma_i^2, \dots, \sigma_i^M)$, and $\boldsymbol{\sigma}_A = J^\top \boldsymbol{\sigma} = [\boldsymbol{\sigma}_1; \boldsymbol{\sigma}_2; \dots; \boldsymbol{\sigma}_N]$ be the vector of $\{\sigma_i^m\}_{i \in \mathcal{I}, m \in \mathcal{M}}$ ordered by agents. From Lemma 1, we have

$$\boldsymbol{\sigma}_A = [I_M \otimes \mathbf{l}_1; I_M \otimes \mathbf{l}_2; \dots; I_M \otimes \mathbf{l}_N]\text{sign}\mathbf{z}. \quad (33)$$

Furthermore, from (26), $\dot{\mathbf{y}}_A = -k_0\text{sign}([I_M \otimes \mathbf{l}_1; I_M \otimes \mathbf{l}_2; \dots; I_M \otimes \mathbf{l}_N]c_C)$, thus $\dot{\mathbf{y}} = -k_0\text{sign}(I_M \otimes Lc_C) = -k_0\text{sign}(\mathbf{z})$ in view of Lemma 1 and the definition of \mathbf{z} . Further considering (33), we have $[I_M \otimes \mathbf{l}_1; I_M \otimes \mathbf{l}_2; \dots; I_M \otimes \mathbf{l}_N]\dot{\mathbf{y}} = -k_0\boldsymbol{\sigma}_A$. Following (30), we thus obtain:

$$\begin{aligned} \dot{c}_A &= [\dot{c}_1; \dot{c}_2; \dots; \dot{c}_N] \\ &= \text{blkdiag}(\Gamma_1, \dots, \Gamma_N)(-k_0\boldsymbol{\sigma}_A + [d_1^{I_1'}; \dots; d_N^{I_N'}]). \end{aligned} \quad (34)$$

From (32), the generalized time derivative is

$$\begin{aligned} \frac{d}{dt}V(\mathbf{y}) &= \boldsymbol{\sigma}_A^\top \dot{c}_A \\ &= \sum_{i \in \mathcal{I}} \boldsymbol{\sigma}_i^\top \Gamma_i (-k_0\boldsymbol{\sigma}_i + d_i^{I_i'}). \end{aligned} \quad (35)$$

Consider the following two cases.

- 1) $Lc^m = \mathbf{0}$ for all $m \in \mathcal{M}$. In this case, $V(\mathbf{y}) = 0$, and thus from the first-order optimality condition one critical point of $\phi(\mathbf{y})$ has been reached.
- 2) $Lc^m \neq \mathbf{0}$ for some $m \in \mathcal{M}$. This implies that $\|L\text{sign}Lc^m\| \geq 1$ [37, Proposition 2.1]. Without loss of generality, assume that $|\sigma_1^1| \geq 1$ and $\mathbf{I}_1 = \{1, 2, \dots, M'\}$. These assumptions are not restrictive as they can be fulfilled by permuting the numbering of the agents and constraints. This leads to

$$\Gamma_1 = \begin{pmatrix} (A_1^{\top, \mathbf{I}_1} A_1^{\top, \mathbf{I}_1, \top})^{-1} & 0 \\ 0 & 0 \end{pmatrix} \quad (36)$$

and $\|\boldsymbol{\sigma}_1^{I_1}\| \geq 1$. The generalized time derivative becomes

$$\begin{aligned} \frac{d}{dt}V(\mathbf{y}) &\leq -k_0\boldsymbol{\sigma}_1^\top \Gamma_1 \boldsymbol{\sigma}_1 + \sum_{i \in \mathcal{I}} \boldsymbol{\sigma}_i^\top \Gamma_i d_i^{I_i'} \\ &\leq -k_0\lambda_{\min}((A_1^{\top, \mathbf{I}_1} A_1^{\top, \mathbf{I}_1, \top})^{-1}) \\ &\quad + \sum_{i \in \mathcal{I}} \|\boldsymbol{\sigma}_i\| \|\Gamma_i\| \|d_i^{I_i'}\| \end{aligned} \quad (37)$$

for almost all t . The first inequality comes from the positive semidefiniteness of Γ_i , and the second inequality follows from the positive definiteness of $(A_1^{\top, \mathbf{I}_1} A_1^{\top, \mathbf{I}_1, \top})^{-1}$ and $\|\boldsymbol{\sigma}_1^{I_1}\| \geq 1$. Note that $\boldsymbol{\sigma}_i \in \mathbb{R}^M$, $[\boldsymbol{\sigma}_i]_m = [L\text{sign}Lc^m]_i$, then $\|\boldsymbol{\sigma}_i\| \leq \sqrt{M}\|L\|$, $\|d_i^{I_i'}\| = \|d_i^{I_i}\| \leq D$. Thus, from (28)

$$\frac{d}{dt}V(\mathbf{y}) \leq -k_0\underline{\lambda} + ND\sqrt{M}\bar{\lambda}\|L\| \leq -\epsilon. \quad (38)$$

Based on these discussions, we know $\frac{d}{dt}V \leq -\epsilon$ for almost all t as long as $Lc^m \neq \mathbf{0}$ for some $m \in \mathcal{M}$ for arbitrary systems $\Sigma_{\mathbf{I}_i, i \in \mathcal{I}}$. Hence, leveraging the theory of common Lyapunov functions, it gives a trivial upper estimate of the convergence time as $\sum_{m \in \mathcal{M}} \|Lc^m(0)\|_1/\epsilon$. From Proposition 2, we further conclude that the coupling constraints are fulfilled for all time. \square

Theorem 3 shows that the solution optimal to the slowly time-varying QP (23) is obtained in a violation-free, finite-time, and distributed manner. These properties are favorable for implementing the CBF-induced QPs as in (23) in a safe, (pointwise) optimal, and distributed way.

One could easily recognize that the update law in (26) and the analysis in Theorem 3 are similar to those in [16], where a simple case with a single coupling constraint is considered. We note that this extension is not trivial due to the nonlinear relations between c_i and \mathbf{y} in (25). Compared to [16], here we distinguish active constraints from inactive ones in order to obtain an analytical relation between changes in c_i and \mathbf{y} , and show that the Lyapunov function monotonically decreases for any active constraints, i.e., it is a common Lyapunov function.

VIII. SIMULATIONS

In this section, we demonstrate the effectiveness of the proposed algorithms in a static optimization problem and a multiagent safe coordination application. All the simulations are conducted in Matlab R2022b on an Intel Core i7-1365 U Windows laptop, and the primal-dual pairs are solved by the built-in `quadprog` function with default parameters. We apply forward Euler integration for simulating the continuous-time dynamics with a sampling time 0.01 s.

A. Static Online Optimization Problem

In this section, we consider an optimization problem that involves $N = 9$ agents indexed in $\mathcal{I} = \{1, 2, \dots, 9\}$ with the communication graph shown in Fig. 3. Here each agent i has 6 decision variables $\mathbf{x}_i = (x_{i,1}, \dots, x_{i,6})$, where $(x_{i,1}, x_{i,2}, x_{i,3})$ represents the demands of 3 products, and $(x_{i,4}, x_{i,5}, x_{i,6})$ the

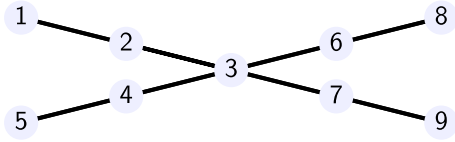


Fig. 3. Communication graph.

supplies of 3 resources. The optimization problem is given by

$$\begin{aligned} & \min_{\mathbf{x}_1, \dots, \mathbf{x}_9} \sum_{i \in \mathcal{I}} (\mathbf{x}_i^\top Q \mathbf{x}_i + \sum_{j=4,5,6} h_{i,j} x_{i,j}) \\ & \text{s.t.} \quad \begin{cases} \sum_{i \in \mathcal{I}} 2x_{i,2} + x_{i,3} - x_{i,4} \leq 0 \\ \sum_{i \in \mathcal{I}} 2x_{i,1} + x_{i,3} - x_{i,5} \leq 0 \\ \sum_{i \in \mathcal{I}} x_{i,1} + x_{i,2} - x_{i,6} \leq 0 \\ x_{i,1} \geq h_{i,1}, x_{i,2} \geq h_{i,2}, x_{i,1} \geq h_{i,3} \quad \forall i \in \mathcal{I} \end{cases} \quad (39) \end{aligned}$$

where $h_{i,j} = \text{ceil}(10 \sin(ij) + 20)$, $i \in \mathcal{I}$, $j = 1, 2, \dots, 6$, Q is symmetric and $\mathbf{x}_i^\top Q \mathbf{x}_i = (2x_{i,2} + x_{i,3} - x_{i,4})^2 + (2x_{i,1} + x_{i,3} - x_{i,5})^2 + (x_{i,1} + x_{i,2} - x_{i,6})^2$. The first three inequality constraints represent that the total supply for the resources needs to exceed the total demand of producing three different products; the last three inequality constraints represent the local production output requirements. In the cost function, we penalize the derivation between the local supply and local demand, which can be interpreted as the cost of transporting or storing the deficient or surplus resources, and take into account the local cost of obtaining those resources. We assume that the local production output requirement $h_{i,j}$, $j = 1, 2, 3$ and the local cost coefficient $h_{i,j}$, $j = 4, 5, 6$ are only known to agent i .

It is clear that the local cost function $f_i(\mathbf{x}_i) = \mathbf{x}_i^\top Q \mathbf{x}_i + \sum_{j=4,5,6} h_{i,j} x_{i,j}$ is convex but not strongly convex, and the local coefficient matrix per the definition in (6)

$$A_i^\top = \begin{pmatrix} 0 & 2 & 1 & -1 & 0 & 0 \\ 2 & 0 & 1 & 0 & -1 & 0 \\ 1 & 1 & 0 & 0 & 0 & -1 \\ -1 & 0 & 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \end{pmatrix}$$

is of full rank. This fulfills Assumption 3 on Slater's condition.

From the structure of the problem, since the last three constraints only involve its own decision variable, the algorithms for the sparse case apply here and that the related \mathbf{y}^m equals zero. Our proposed approach introduces 27 auxiliary scalar variables, with each node needing to communicate 6 scalar variables with its neighbors. In comparison, the primal decomposition approach in [1] requires 48 auxiliary scalar variables and 24 scalar variables to be communicated by node 3. By choosing $y_i^m(0) = 0$, $\forall i \in \mathcal{I}$, $m \in \mathcal{M}$, $k_0 = 1$ with sampling-time 0.01s, we obtain the results shown in Fig. 4. One observes that 1) the total cost error is monotonically decreasing; 2) the local Lagrange multipliers corresponding to each coupling constraint converge to a common value; 3) the three coupling constraints are always fulfilled during the solution iterations. This violation-free behavior could be desirable in this scenario because one does not need to wait for the convergence of the optimization algorithm before applying the solutions, and the intermediate solution,

though suboptimal, still guarantees that the supply-demand requirement is respected.

B. Application to Safe Distributed Control for MAS

In the second example, we show one application of the proposed algorithm for safe distributed control of a multiagent system. Denote by $\mathbf{p}_i = (p_{i,1}, p_{i,2}) \in \mathbb{R}^2$ the state and $\mathbf{p}_{i,d} \in \mathbb{R}^2$ the desired state of agent i . We assume that the dynamics of each agent is given by $\dot{\mathbf{p}}_i = \mathbf{x}_i$, where \mathbf{x}_i is the velocity command to agent i . The coordination task is to transform the formation of the multiagent system from the initial formation $\mathbf{p}_{\text{initial}} = [\mathbf{p}_1(0); \mathbf{p}_2(0); \dots; \mathbf{p}_9(0)] = (4, 6, 2, 8, 0, 10, -2, 8, -4, 6, 2, 12, -2, 12, 4, 14, -4, 14)$ (shown in red in Fig. 5) to the target formation $\mathbf{p}_{\text{final}} = [\mathbf{p}_{1,d}; \mathbf{p}_{2,d}; \dots; \mathbf{p}_{9,d}] = (60, 16, 60, 13, 60, 10, 60, 7, 60, 4, 63, 13, 63, 7, 66, 16, 66, 4)$. The communication graph is in Fig. 3. Assume that agent i , $i \in \mathcal{I}$ has access to the desired relative position $\mathbf{p}_{ij,d} = \mathbf{p}_{j,d} - \mathbf{p}_{i,d}$, $j \in N_i$ and its absolute position \mathbf{p}_i , and agent 3, referred to as the leader, knows its target position $\mathbf{p}_{3,d}$. An intuitive distributed protocol for fulfilling this task is given by

$$\mathbf{x}_{\text{nom},i}(\mathbf{p}_i, \{\mathbf{p}_j\}_{j \in N_i}) = \sum_{j \in N_i} \mathbf{p}_{ij,d} - \mathbf{p}_j + \delta_i(\mathbf{p}_{i,d} - \mathbf{p}_i)$$

where $\mathbf{p}_{ij} = \mathbf{p}_j - \mathbf{p}_i$, $\delta_i = 1$ if agent i is the leader and $\delta_i = 0$ otherwise.

Suppose that the multiagent team needs to satisfy 2 coupling state constraints during the formation transition, given by

$$h_1(t, \mathbf{p}_1, \dots, \mathbf{p}_9) = 30 + t - 0.1 \sum_{i \in \mathcal{I}} (p_{i,1} + p_{i,2}) \geq 0 \quad (40a)$$

$$h_2(t, \mathbf{p}_1, \dots, \mathbf{p}_9) = 10 + t - 0.1 \sum_{i \in \mathcal{I}} (p_{i,1} - p_{i,2}) \geq 0. \quad (40b)$$

These two inequalities impose time-varying upper bounds on the collective summation of all coordinates as in (40a) and the collective difference between the first and the second coordinates as in (40b), respectively. When viewing the two coordinates of \mathbf{p}_i as two different local sources and the overall task as transitioning from one resource allocation scheme to another, one may interpret the first constraint as a gradual relaxation on the source limit, and the second one as the gradual relaxation on the difference limit between the resources.

Following the control barrier function-induced control design procedures [38], the centralized safety-assuring controller is given by

$$\begin{aligned} & \min_{\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_9} \sum_{i \in \mathcal{I}} \frac{1}{2} \|\mathbf{x}_i - \mathbf{x}_{\text{nom},i}\|^2 \\ & \text{s.t.} \quad \sum_{i \in \mathcal{I}} [0.1 \ 0.1] \mathbf{x}_i - h_1(t, \mathbf{p}_1, \dots, \mathbf{p}_9) - 1 \leq 0 \\ & \quad \sum_{i \in \mathcal{I}} [0.1 \ -0.1] \mathbf{x}_i - h_2(t, \mathbf{p}_1, \dots, \mathbf{p}_9) - 1 \leq 0. \quad (41) \end{aligned}$$

Here, we choose the extended class \mathcal{K} function to be an identity function for simplicity. It is clear that (41) is a special case of (23) with 2 coupling inequality constraints. Denote the corresponding

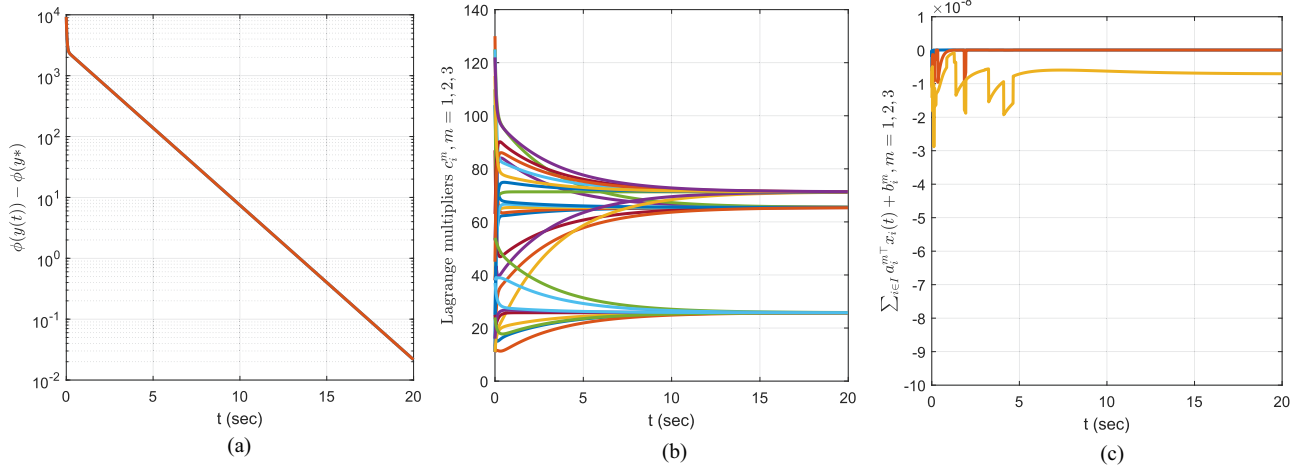


Fig. 4. Numerical results involving nine agents solving a static optimization problem. (a) Time evolution of the total cost minus the optimal cost. (b) Time evolution of the local Lagrange multipliers corresponding to the three coupling constraints. (c) Time evolution of the value of the first three coupling constraints.

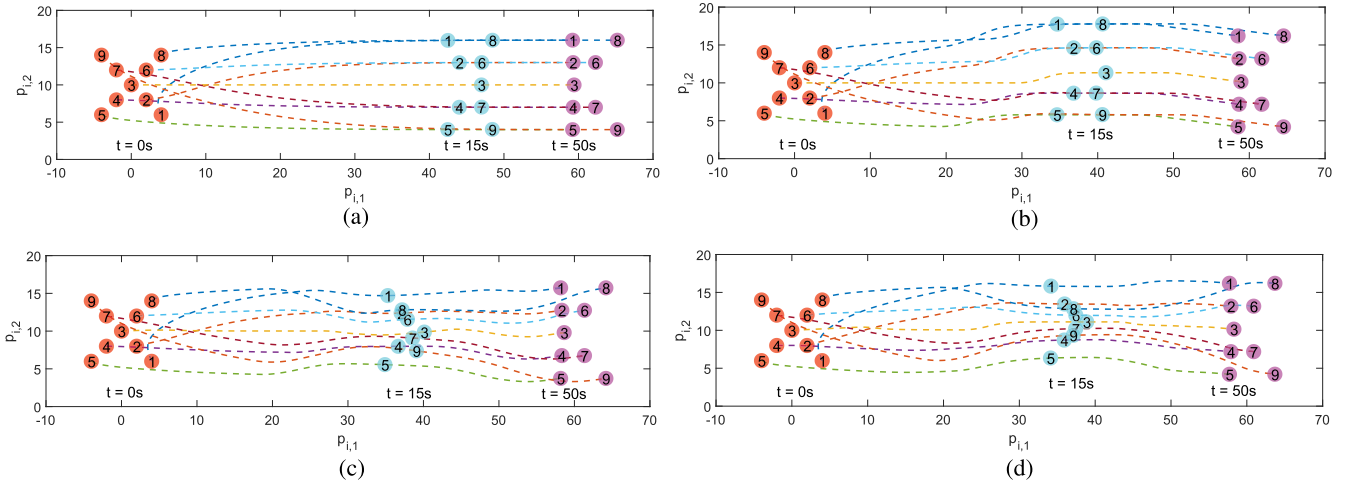


Fig. 5. Trajectories for different control schemes when coordinating nine agents. (a) Nominal case. (b) Centralized case. (c) Distributed case. (d) Naive distributed case.

auxiliary variables by $\mathbf{y}^1, \mathbf{y}^2$. Based on previous analysis, the local QP-based controller is given by

$$\begin{aligned} & \min_{\mathbf{x}_i} \frac{1}{2} \|\mathbf{x}_i - \mathbf{x}_{\text{nom},i}\|^2 \\ & \text{s. t. } [0.1 \ 0.1] \mathbf{x}_i + p_{i,1} + p_{i,2} + \mathbf{l}_i \mathbf{y}^1 - 31/9 \leq 0 \\ & [0.1 \ -0.1] \mathbf{x}_i + p_{i,1} - p_{i,2} + \mathbf{l}_i \mathbf{y}^2 - 11/9 \leq 0. \end{aligned} \quad (42)$$

where \mathbf{l}_i is the i th row of the Laplacian matrix. These auxiliary variables are updated locally according to (26). In this case we know $A_i^\top = 0.1 \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$ is of full column rank and the LICQ of the local optimization problem is always fulfilled. Moreover, recall that $\mathbf{x}_{\text{nom},i}(\mathbf{p}(t))$ and $\mathbf{y}^m(t), m = 1, 2$ are locally Lipschitz in time, we know the control input from this local optimization problem is also locally Lipschitz in time [39,

Theorem 3.1]. Together with the violation-free property from Theorem 3, our proposed algorithm guarantees system safety.

In Fig. 5, we present the trajectories of four different cases: 1) the nominal case, where the controller $\mathbf{x}_{\text{nom},i}$ is applied; 2) the centralized case, where we assume a central node exists that computes the safe controller from (41) and sends the control signal to each agent; 3) the distributed case, where our proposed safe controller in (42) is implemented; 4) the naive distributed case, where the controller from (42) is used with all $\mathbf{y}^1, \mathbf{y}^2$ zero. The last case is often used in CBF literature when system designers focus on guaranteeing safety and would sacrifice pointwise optimality.

In the simulation, we choose $k_0 = 1$ and replace $\text{sign}(\cdot)$ with a saturation function $\text{sat}(v) = 1, \text{ if } v > 0.1; 10v, \text{ if } -0.1 \leq v \leq 0.1; -1, \text{ if } v < -0.1$ for eliminating the numerical chattering. One observes that the formation task is fulfilled by all four control schemes. In Fig. 6, it becomes clear that the two coupling

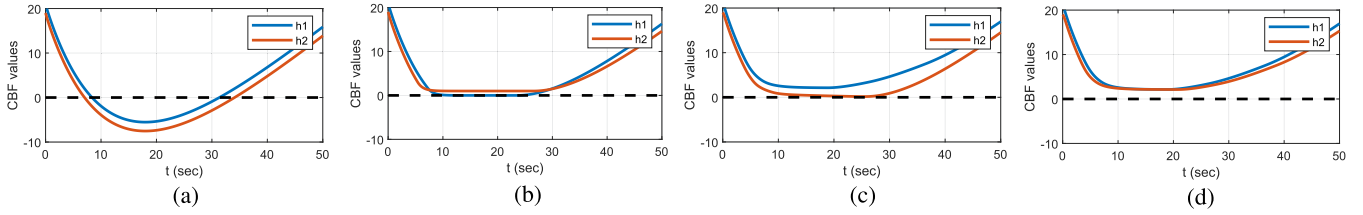


Fig. 6. Time evolution of the CBF values when coordinating nine agents. (a) Nominal case. (b) Centralized case. (c) Distributed case. (d) Naive distributed case.

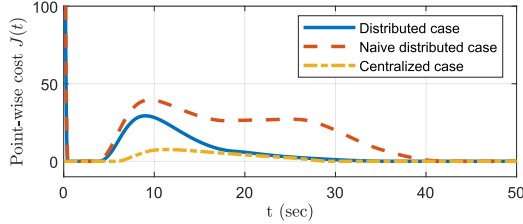


Fig. 7. Time evolution of the cost $\sum_{i \in \mathcal{I}} \frac{1}{2} \|\mathbf{x}_i - \mathbf{x}_{nom,i}\|^2$ along the state trajectory when the proposed algorithm is applied.

state constraints are violated in the nominal case, and respected in the other three cases. Moreover, the distributed case with the proposed algorithm shows to be less conservative compared to the naive distributed scheme as the trajectory approaches closer to the safety boundary. To better quantify the performance of the proposed algorithm, we further compare the pointwise cost $\sum_{i \in \mathcal{I}} \frac{1}{2} \|\mathbf{x}_i - \mathbf{x}_{nom,i}\|^2$ in Fig. 7 along the state trajectory when our proposed algorithm is applied, i.e., the trajectory in Fig. 5(c). At any time t , one could view the curves corresponding to the naive distributed case and the centralized case in Fig. 7 as the initial cost and the optimal cost of the frozen-time optimization problem, respectively. Compared to the naive implementation, our proposed algorithm achieves safe distributed control with much less pointwise cost.

One key prerequisite that can restrict applicability of the proposed approach is Assumption 3. Even though we provide sufficient conditions for it to hold in dense and sparse cases, it can still be limiting. We will explore how to online monitor local feasibility and adapt the local parameter y_i with feasibility guarantees in our future work.

IX. CONCLUSION

In this work, we propose a continuous-time violation-free, distributed algorithm for constraint-coupled optimization problems and demonstrate its applicability for CBF-induced safe distributed control design. To decompose the global constraint coupled optimization problem into equivalent local ones, auxiliary variables are introduced, whose differences indicate the allocation of the constraints among all agents. Moreover, the subgradient information with respect to the auxiliary variables can be obtained using local information, which leads to a subgradient algorithmlike update law design with asymptotic optimality and all-time constraint satisfaction guarantee. For safe distributed control design, we further strengthen our algorithms to achieve

finite-time convergence to cope with slowly time-varying parameters, leading to a safety-assured and pointwise optimal controller. Two numerical examples are provided to illustrate the favorable properties of the proposed algorithms: a static resource allocation optimization example and a multiagent coordination example with two coupling state constraints.

APPENDIX

Proof of Proposition 1: To prove Point 1), given any feasible solution $(\mathbf{x}', \mathbf{y}')$ to (4), for an arbitrary m th constraint in (3), we know $\mathbf{1}^\top (A^m \mathbf{x}' + L \mathbf{y}' + \mathbf{b}^m) = \sum_{i \in \mathcal{I}} \mathbf{a}_i^{m \top} \mathbf{x}'_i + b_i^m \leq 0$ thanks to the fact that $\mathbf{1}^\top L = \mathbf{0}$ for L being the Laplacian matrix of any connected and undirected graph \mathcal{G} [20]. Thus, \mathbf{x}' also satisfies the m th constraint in (3).

For Point 2), given any feasible solution \mathbf{x}' to (3), for an arbitrary m th constraint in (3), define $\mathbf{v}^m = A^m \mathbf{x}' + \mathbf{b}^m$, $\mathbf{w}^m = \frac{\mathbf{1}_N^\top \mathbf{v}^m}{N} \mathbf{1}_N$. Thus, $\mathbf{w}^m \leq \mathbf{0}$ is obtained from the fact that \mathbf{w}^m has the same value in each entry and $\mathbf{1}_N^\top \mathbf{w}^m = \mathbf{1}_N^\top \mathbf{v}^m = \sum_{i \in \mathcal{I}} \mathbf{a}_i^{m \top} \mathbf{x}'_i + b_i^m \leq 0$. We further know that there exists a $\mathbf{y}^m \in \mathbb{R}^N$ such that $L \mathbf{y}^m + \mathbf{v}^m = \mathbf{w}^m$ thanks to the fact that $\text{Range}(L) = \{\mathbf{z} \in \mathbb{R}^N : \mathbf{1}_N^\top \mathbf{z} = 0\}$ for a connected undirected graph [20]. Thus, such a $(\mathbf{x}', \mathbf{y}^1, \dots, \mathbf{y}^M)$ is also feasible to the problem in (4).

Point 3) is obvious in view of the two problems. Based on the previous analysis, (3) and (4) share the same set of feasible solutions with respect to \mathbf{x} . Noting that they also share the same cost function, we conclude that the two problems are equivalent. \square

Proof of Proposition 7: For problem (24), we consider its Lagrangian

$$\mathcal{L}(\mathbf{x}_i, \mathbf{c}_i) = \frac{1}{2} \|\mathbf{x}_i - \mathbf{x}_{nom,i}\|^2 + \mathbf{c}_i^\top (A_i^\top \mathbf{x}_i + (I_M \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i)$$

where $\mathbf{c}_i = (c_i^1, c_i^2, \dots, c_i^M) \in \mathbb{R}^M$ is the Lagrange multiplier. Since Slater's condition holds and the problem (24) is a linearly constrained convex optimization problem, \mathbf{x}_i is an optimal solution if and only if \mathbf{c}_i exists and satisfies the following Karush–Kuhn–Tucker (KKT) conditions [40, Theorem 10.6]:

$$\mathbf{x}_i - \mathbf{x}_{nom,i} + A_i \mathbf{c}_i = \mathbf{0} \quad (43a)$$

$$A_i^\top \mathbf{x}_i + (I_M \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i \leq \mathbf{0} \quad (43b)$$

$$\mathbf{c}_i \geq \mathbf{0} \quad (43c)$$

$$\mathbf{c}_i \circ (A_i^\top \mathbf{x}_i + (I_M \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i) = \mathbf{0} \quad (43d)$$

where \circ denotes Hadamard Product, i.e., pointwise multiplication. To solve the KKT system, we obtain from (43a) that

$$\mathbf{x}_i = \mathbf{x}_{\text{nom},i} - A_i \mathbf{c}_i = \mathbf{x}_{\text{nom},i} - \sum_{m=1}^M c_i^m \mathbf{a}_i^m. \quad (44)$$

Substituting it to (43b) and (43d), we know

$$A_i^\top \mathbf{x}_{\text{nom},i} - A_i^\top A_i \mathbf{c}_i + (I_M \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i \leq 0 \quad (45a)$$

$$\mathbf{c}_i \circ (A_i^\top \mathbf{x}_{\text{nom},i} - A_i^\top A_i \mathbf{c}_i + (I_M \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i) = 0. \quad (45b)$$

Next, we consider two disjoint cases for the m th coupled inequality. Before proceeding, we denote $\mathcal{C}_m := \{1, \dots, m-1, m+1, \dots, M\}$. We assume that the Lagrangian variables corresponding to the index set \mathcal{C}_m are known, i.e., $c_i^p, p \in \mathcal{C}_m$ are known. Define $\mathbf{x}_{\text{nom},i}^{m'} = \mathbf{x}_{\text{nom},i} - \sum_{p \in \mathcal{C}_m} c_i^p \mathbf{a}_i^p$, $\mathbf{b}_i^{m'} = (I_M \otimes \mathbf{l}_i) \mathbf{y} + \mathbf{b}_i$. Then $\mathbf{x}_i = \mathbf{x}_{\text{nom},i}^{m'} - c_i^m \mathbf{a}_i^m$ from (44). Define $\Lambda_i = \text{Diag}(A_i^\top A_i) \in \mathbb{R}^{M \times M}$. Consider the following cases.

1) $[A_i^{m\top} \mathbf{x}_{\text{nom},i}^{m'} + \mathbf{b}_i^{m'}]_m \leq 0$. It is clear from (43d) that

$$c_i^m = 0. \quad (46)$$

Then $c_i^m = 0$ together with $c_i^p, p \in \mathcal{C}_m$ is the Lagrange multiplier.

2) $[A_i^{m\top} \mathbf{x}_{\text{nom},i}^{m'} + \mathbf{b}_i^{m'}]_m > 0$. Suppose $c_i^m = 0$ in this case, then $\mathbf{x}_i = \mathbf{x}_{\text{nom},i}^{m'}$ yet it fails the constraint $A_i^{m\top} \mathbf{x}_i + \mathbf{b}_i^m \leq 0$. By contradiction, we have $c_i^m > 0$. Therefore, to satisfy (43d), there must hold

$$[A_i^\top \mathbf{x}_{\text{nom},i}^{m'} + \mathbf{b}_i^{m'} - c_i^m A_i^\top \mathbf{a}_i^m]_m = 0. \quad (47)$$

Thus

$$\mathbf{a}_i^{m\top} \mathbf{a}_i^m c_i^m = [A_i^{m\top} \mathbf{x}_{\text{nom},i}^{m'} + \mathbf{b}_i^{m'}]_m. \quad (48)$$

Recall $[\Lambda_i]_{m,m} = \mathbf{a}_i^{m\top} \mathbf{a}_i^m$, $\mathbf{x}_{\text{nom},i}^{m'} = \mathbf{u}_{\text{nom},i} - A_i \mathbf{c}_i + c_i^m \mathbf{a}_i^m$. Thus

$$[\Lambda_i]_{m,m} c_i^m = [A_i^\top (\mathbf{u}_{\text{nom},i} - A_i \mathbf{c}_i) + \mathbf{b}_i^m + \Lambda_i \mathbf{c}_i]_m. \quad (49)$$

Summarizing the two cases in (46) and (49), we obtain $c_i^m, m \in \mathcal{M}$ satisfies

$$[\Lambda_i]_{m,m} c_i^m = \max([A_i^\top (\mathbf{x}_{\text{nom},i} - A_i \mathbf{c}_i) + \mathbf{b}_i^m + \Lambda_i \mathbf{c}_i]_m, 0).$$

Stacking it together, we conclude that

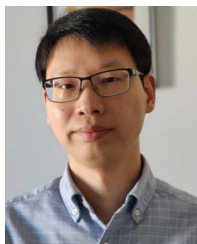
$$\Lambda_i \mathbf{c}_i = \max(A_i^\top \mathbf{x}_{\text{nom},i} + \mathbf{b}_i^m + (\Lambda_i - A_i^\top A_i) \mathbf{c}_i, \mathbf{0}). \quad (50)$$

Up to now, we have shown that if $(\mathbf{x}_i, \mathbf{c}_i)$ satisfies the KKT condition, then \mathbf{c}_i satisfies (50). In the following we show that whenever \mathbf{c}_i solves (50), the pair $(\mathbf{x}_i, \mathbf{c}_i)$ with $\mathbf{x}_i = \mathbf{x}_{\text{nom},i} - A_i \mathbf{c}_i$ fulfills the KKT conditions. One verifies that (43a) and (43c) are trivially satisfied. What remains to show is (43b) and (43d). Denote by $c_i^p, p \in \mathcal{C}_m$ as part of the solution to (50). Now $c_i^p, p \in \mathcal{C}_m$ are not assumed to be the correct multipliers but will be proved so later. Recall $\mathbf{x}_{\text{nom},i}^{m'} = \mathbf{x}_{\text{nom},i} - \sum_{p \in \mathcal{C}_m} c_i^p \mathbf{a}_i^p$. If $[A_i^{m\top} \mathbf{x}_{\text{nom},i}^{m'} + \mathbf{b}_i^{m'}]_m \leq 0$, we know (50) dictates $c_i^m = 0$. If $[A_i^{m\top} \mathbf{x}_{\text{nom},i}^{m'} + \mathbf{b}_i^{m'}]_m > 0$, then (50) dictates $\mathbf{a}_i^{m\top} \mathbf{a}_i^m c_i^m = [A_i^{m\top} \mathbf{x}_{\text{nom},i}^{m'} + \mathbf{b}_i^{m'}]_m$. In both cases, the parts in (43b) and (43d) corresponding to the m th constraint are fulfilled. This analysis holds for all $m \in \mathcal{M}$. This concludes the proof. \square

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