Multi-Robot Data Gathering Under Buffer Constraints and Intermittent Communication

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Abstract—We consider a team of heterogeneous robots which are deployed within a common workspace to gather different types of data. The robots have different roles due to different capabilities: some gather data from the workspace (source robots) and others receive data from source robots and upload them to a data center (relay robots). The data-gathering tasks are specified locally to each source robot as high-level Linear Temporal Logic (LTL) formulas, that capture the different types of data that need to be gathered at different regions of interest. All robots have a limited buffer to store the data. Thus the data gathered by source robots should be transferred to relay robots before their buffers overflow, respecting at the same time limited communication range for all robots. The main contribution of this work is a distributed motion coordination and intermittent communication scheme that guarantees the satisfaction of all local tasks, while obeying the above constraints. The robot motion and inter-robot communication are closely coupled and coordinated during run time by scheduling intermittent meeting events to facilitate the local plan execution. We present both numerical simulations and experimental studies to demonstrate the advantages of the proposed method over existing approaches that predominantly require all-time network connectivity.

Index Terms—Networked Robots, Linear Temporal Logic, Motion and Task Planning, Intermittent Communication.

I. INTRODUCTION

ANY applications involve robots that are deployed in a workspace to gather different types of data and upload them to a data center for processing. For instance, teams of autonomous ground vehicles (AGV) can monitor the temperature, humidity, and stand density in large forests or teams of autonomous aerial vehicles (AAV) can monitor the behavior of animal flocks and growth of the crops in farmlands [1]. Due to heterogeneous sensing and motion capabilities, the robots in these applications can gather different types of data in different regions within the workspace. Thus the robots can be assigned local data-gathering tasks that vary across the team [1]. In this work, we employ Linear Temporal Logic (LTL) as the formal language to describe complex high-level tasks beyond the classic point-to-point navigation. A LTL task formula is usually specified with respect to an abstraction of the robot motion [2], [3]. Then a high-level discrete plan is found using off-the-shelf model-checking algorithms [4], and is executed through low-level continuous controllers [5]. This framework can be extended to allow for both robot motion and actions in the task specification [6].

The above framework has also been applied to multi-robot systems either in a top-down approach where a global LTL task formula is assigned to the whole team of robots [6], [7]–[9], or in a bottom-up manner where an individual LTL task formula is assigned locally to each robot [10], [11]. Here, we favor the latter formalism as it provides a more natural framework to model independent temporal tasks within large teams of robots that have heterogeneous capabilities. Specifically, we consider two types of robots: source robots that are assigned local tasks to gather different types of data in different regions in the workspace, and relay robots that receive data from source robots and upload them directly to a data center. All robots have a limited buffer to store the data. Thus the data gathered by source robots should be transferred to relay robots before the buffers overflow. Moreover, all robots have a limited communication range, so that they can only communicate when they are sufficiently close to each other. Therefore, to monitor the workspace and achieve their local tasks, the robots may need to temporarily disconnect from the network provided that they intermittently meet with each other to transfer their gathered data. In this paper, we propose a distributed data-gathering and intermittent communication framework that relies on introducing meeting events in the discrete motion plans of the robots during run-time, so that their local data-gathering tasks are satisfied while respecting buffer size and limited communication range constraints. The great challenge in deciding meeting events between robots in a distributed fashion is that this requires communication, which in the proposed intermittent communication framework is only available when the robots meet.

Communication in the field of mobile robotics has typically relied on constructs from graph theory, with line-of-sight models [12], [13] and proximity graphs [14]–[19] gaining the most popularity. In most of these problems, the property of interest is connectivity of the communication network as this allows reliable delivery of information between any pair of robots. Approaches that ensure connectivity for all time either maintain all initial communication links between the robots provided that the initial communication network is connected [14], [19]–[21], or allow for addition and removal of communication links while ensuring that the connectivity requirement is not violated [6], [15]–[18], [22]. In practice, the above graph-based communication models can be rather conservative, since proximity does not necessarily imply tangible and reliable communication. Therefore, more realistic communication models have recently been proposed in [23]–[25] that take into account path loss, shadowing, and multi-path fading as well as optimal routing decisions for desired information rates. The above approaches that enforce all-time connectivity are rather restrictive as they do not allow the robots to move freely to accomplish their tasks but, instead, impose on the robots all-time proximity constraints that may be in conflict with their assigned local tasks. Intermittent communication frameworks, on the other hand, allow the robots to occasionally disconnect from the team and accomplish their tasks free of communication constraints. Intermittent communication in multi-agent systems has been studied in consensus problems [26], coverage problems [27], and in delay-tolerant networks [28], [29]. The common assumption in these works is that the communication network is intermittently connected infinitely often. In our recent work [30]–[32], we proposed an intermittent connectivity control strategy that determines a sequence of meeting events for subgroups of robots so that the whole team is connected infinitely often, for coverage and path optimization problems. However, local high-level temporal tasks are not considered there nor is a model of inter-robot data transfer. Additionally, the resulting communication schedules in [31] are determined offline so that any changes in the priorities of the data-gathering tasks can not be easily handled.

The constraint of limited buffer size is of practical importance for the data-gathering applications considered in this paper, especially...
when the local temporal tasks require an infinite sequence of data-gathering actions. In this case, source robots cannot gather data indefinitely without transferring them to relay robots as this may cause buffer overflow. Consequently, the fulfillment of source robot’s local tasks depends not only on collecting data at regions of interest in the workspace, but also on transferring these data to relay robots during run-time. The work in [33] considers a single robot transferring data from data-gathering locations to data-uploading locations. The proposed approach minimizes the time interval between two consecutive time instants when the robot visits any data-uploading location. But it does not explicitly model the evolution of the robot’s buffer or the inter-robot communication. Similar buffer constraints are considered in [34] for multi-robot frontier-based exploration. However locally-assigned data-gathering tasks described by LTL formulas are not considered there, nor are communication constraints.

Another related area is temporal logic motion and task planning under resource constraints. Particularly, different from the nominal planning problem under temporal tasks [2], [9], [35], additional constraints on various resources (such as battery and fuel) are imposed on the robot model. The work in [36] considers a global surveillance task performed by multiple aerial vehicles subject to battery charging constraints, where each robot’s state is augmented by its battery status during the model-checking process. The multi-vehicle routing problem considered in [37] proposes a solution based on Mixed-Integer Linear Programming (MILP) over the complete system model, which can potentially be extended to include resource constraints.

Reactive control approaches are proposed in [38], [39] to handle dynamic constraints imposed by the environment. The main contribution of this work lies in the development of an online distributed framework that jointly controls local data-gathering tasks and data transfer communication events between the robots, so that the buffers at every robot never overflow. The proposed framework guarantees the satisfaction of all local tasks specified as LTL formulas, without imposing all-time connectivity requirements on the communication network. Instead, by controlling intermittent communication the robots have much more flexibility in accomplishing their assigned tasks. The efficiency of the proposed framework compared to a centralized approach and two static approaches is demonstrated via numerical simulations and experimental studies. To the best of our knowledge, this is the first distributed data-gathering framework under intermittent communication that is also online.

This work is built on preliminary results presented in [40]. Compared to [40], the real-time control and coordination algorithm presented here is more efficient as it allows the relay robots to swap meeting events in order to faster service the source robots, while it also accounts for robot failures, dynamic robot membership, and fixed data centers. Furthermore, we present extensive numerical simulations illustrating the capabilities of our method, as well as experimental results showing that it can be seamlessly applied to solve real-world problems. Finally, we compare our on-line control approach to two standard techniques that require all-time communication and show that we significantly outperform these methods in terms of the amount of data gathered and transmitted to the data center.

The rest of the paper is organized as follows: Section IV introduces some preliminaries on LTL and Büchi Automaton. Section III formulates the problem. Section IV discusses the proposed dynamic approach to joint data-gathering and intermittent communication control. Numerical simulations and experimental studies are shown in Sections VI and VII respectively. We conclude in Section VIII.

II. PRELIMINARIES ON LTL

Atomic propositions are Boolean variables that can be either true or false. The ingredients of an LTL formula are a set of atomic propositions $AP$ and several boolean and temporal operators, which are specified according to the following syntax [4]:

$$\varphi ::= T \mid p \mid \varphi_1 \land \varphi_2 \mid \neg \varphi \mid \bigcirc \varphi \mid \varphi_1 U \varphi_2,$$

where $T \triangleq True$, $p \in AP$ and $\bigcirc$ (next), $U$ (until), $\bot \triangleq \neg T$. For brevity, we omit the derivations of other useful operators like $\diamond$ (always), $\triangleright$ (eventually), $\Rightarrow$ (implication). The semantics of LTL is defined over the infinite words over $2^{AP}$. Intuitively, $\sigma \in AP$ is satisfied on a word $w = w(1)w(2)w(3)\ldots \in (2^{AP})^*$ if it holds at $w(1)$, i.e., if $\sigma \in w(1)$. The classical semantics is defined over the word suffix that begins in the next position $w(2)$, whereas $\varphi_1 U \varphi_2$ states that $\varphi_1$ has to remain true until $\varphi_2$ becomes true. Finally, $\diamond \varphi$ and $\Box \varphi$ are true if $\varphi$ holds on $w$ eventually and always, respectively. We refer the readers to Chapter 5 of [4] for the full definition of LTL syntax and semantics.

The language of words that satisfy an LTL formula $\varphi$ over $AP$ can be fully captured through $\mathcal{A}_\varphi$ a Nondeterministic Büchi automaton (NBA) $\mathcal{A}_\varphi$, defined as $\mathcal{A}_\varphi = (Q, 2^{AP}, \delta, Q_0, F)$, where $Q$ is a set of states; $2^{AP}$ is the set of all allowed alphabets; $\delta \subseteq Q \times 2^{AP} \times Q$ is a transition relation; $Q_0, F \subseteq Q$ are the set of initial and accepting states, respectively. The process of constructing $\mathcal{A}_\varphi$ can be done in time and space $O(|\varphi|^2)$, where $|\varphi|$ is the length of $\varphi$ [4]. There are fast translation tools [41], [42] to obtain $\mathcal{A}_\varphi$ given $\varphi$.

III. PROBLEM FORMULATION

In this section, we present the robot motion and action model, communication model, task specification and the problem formulation.

A. Robot Model

Consider a team of $N$ dynamical robots where each robot $i \in N = \{1, 2, \ldots, N\}$ satisfies the unicycle dynamics:

$$\dot{x}_i = v_i \cos(\theta_i), \quad \dot{y}_i = v_i \sin(\theta_i), \quad \dot{\theta}_i = \omega_i,$$

where $p_i(t) = (x_i(t), y_i(t)) \in \mathbb{R}^2$, $\theta_i(t) \in (-\pi, \pi]$ is robot $i$’s position and orientation at time $t > 0$. The control inputs are given by $u_i(t) = (v_i(t), \omega_i(t))$ as the linear and angular velocities. Each robot has a reference linear and angular velocities denoted by $v_i^{ref}$ and $\omega_i^{ref}$. The workspace is a bounded 2D area $W \subset \mathbb{R}^2$, within which there are clusters of obstacles $O \subset W$. The free space is denoted by $F = W \setminus O$. Note that all robots are assumed to be point masses and robot collision is not considered here.

As mentioned in Section I, the robots are categorized into two subgroups, denoted by $N^s, N^f \subset N$ so that $N^s \cup N^f = N$. Every robot $i \in N^f$ is equipped with short-range wireless units and can only send and receive data from other robots $j$ such that $\|p_i(t) - p_j(t)\| \leq r_i$, where $r_i > 0$ is the communication range, $\forall j \in N^f$. On the other hand, robots in $N^s$ are equipped with long-range wireless units and have the extra function to upload their stored data to a remote data center. In other words, robots in $N^s$ are responsible for gathering data about the workspace while robots in $N^f$ are in charge of uploading these data to the data center. In the sequel, we simply refer to robots in $N^f$ as source robots and robots in $N^s$ as relay robots. Note that there are more than one source and relay robots, i.e., it holds that $|N^f|, |N^s| \geq 1$.

Remark 1. The fact that the relay robots can upload their stored data immediately to the data center is due to their long-range communication capabilities. This assumption can be relaxed by choosing one or several fixed data centers within the workspace and assuming that relay robots have only short communication ranges so that they need to visit the data center to upload their data. More details are provided in Section VA.
B. Data-gathering Tasks

Each source robot $i \in \mathcal{N}^f$ has a local data-gathering task associated with different regions in the freespace. Denote by $\Pi_i = \{\pi_{i,1}, \pi_{i,2}, \ldots, \pi_{i,M_i}\}$ the collection of these regions, where $\pi_{i,\ell} \subseteq \mathcal{F}$, $\forall \ell = 1, 2, \cdots, M_i$ and $M_i > 0$. They contain information of interest. Moreover, there is a set of data-gathering actions that robot $i$ can perform at these regions, denoted by $G_i = \{g_{i,0}, g_{i,1}, g_{i,2}, \ldots, g_{i,\ell}\}$, where $g_{i,k}$ means that “type-$k$ data is gathered”, $\forall k = 1, 2, \cdots, K_i$ and $K_i \geq 1$. By default, $g_{i,0}$ means doing nothing. The time needed to perform each action by robot $i \in \mathcal{N}^f$ is given by function $Z_i : G_i \rightarrow \mathbb{R}^+$. 

With a slight abuse of notation, we denote the set of robot $i$’s atomic propositions by $AP_i = \{\pi_{i,\ell} \land g_{i,k}, \forall \pi_{i,\ell} \in \Pi_i, \forall g_{i,k} \in G_i\}$, where each proposition $\pi_{i,\ell} \land g_{i,k}$ stands for “robot $i$ gathers type-$k$ data at region $\pi_{i,\ell}$”. Over these atomic propositions, we can specify a high-level data-gathering task, denoted by $\varphi_i$, following the LTL semantics in Section III. Simply speaking, $\varphi_i$ specifies the desired sequence of data-gathering actions to be performed at certain regions of interest within the workspace. Note that LTL formulas allow us to specify data-gathering tasks of finite or infinite executions. For instance, $\varphi_i = \varphi((\pi_{i,1} \land g_{i,3}) \lor \varphi((\pi_{i,3} \land g_{i,4}))$ means that “robot $i$ should gather type-$2$ data at region $1$ first, then type-$4$ data at region $3$”, or $\varphi_i = \varphi_1 \land \varphi_2 \land \varphi_3$ means that “robot $i$ should infinitely often gather type-$7$ data at region $6$ and type-$2$ data at region $7$”.

Remark 2. It is worth mentioning that relay robots $j \in \mathcal{N}^r$ do not have local tasks as their goal is to communicate with source robots and upload data to the data center. This assumption can be relaxed and is part of our future work.

C. Buffer Size and Communication Constraints

Each robot $i \in \mathcal{N}$ has a limited buffer to store data. To simplify the problem formulation, we quantify the data size into units, i.e., robot $i$ has a buffer to store a maximum number $\overline{B}_i > 0$ units of data, $\forall i \in \mathcal{N}$. Furthermore, denote by $b_i(t) \in \mathbb{N}_{\geq 0}$ the number of data units stored in the buffer of any robot $i \in \mathcal{N}$ at time $t \geq 0$. Note that $b_i(0) = 0$, $\forall i \in \mathcal{N}$. It should hold that $b_i(t) \leq \overline{B}_i, \forall t > 0$ such that the buffer of robot $i$ does not overflow. Whenever robot $i \in \mathcal{N}^f$ performs a data-gathering action $g_{i,k} \in G_i$ at time $t$, $b_i(t)$ changes as follows:

$$b_i(t^+) = b_i(t^-) + D_i(g_{i,k}),$$

where $D_i : G_i \rightarrow \mathbb{Z}^+$ specifies the number of data units gathered by performing action $g_{i,k} \in G_i$; $b_i(t^-)$ and $b_i(t^+)$ are the number of data units stored at robot $i$’s buffer before and after the action $g_{i,k}$ is performed at time $t > 0$. If $b_i(t^+) > \overline{B}_i$, then this action $g_{i,k}$ can not be performed as it would lead to buffer overflow. We assume that $D_i(g_{i,k}) \leq \overline{B}_i, \forall g_{i,k} \in G_i$, meaning that any action in $G_i$ can be performed when the current buffer is zero.

Moreover, any two robots can send and receive data when they are within each other’s communication range. In particular, denote by $c_{ij} : \mathbb{R} \rightarrow \mathbb{Z}^+$ the data transfer function from robot $i$ to robot $j$ at time $t > 0$. When robot $i$ transfers $c_{ij}(t)$ units of data to robot $j$, their stored data units change by:

$$b_i(t^+) = b_i(t^-) - c_{ij}(t),$$

where $b_i(t^-)$ and $b_i(t^+)$ are the stored data units of robot $i$ (or robot $j$) before and after the data transfer. To allow this transfer, two conditions should hold: (i) $c_{ij}(t) \leq b_i(t^-)$ so that robot $i$ has enough data to transfer; and (ii) $b_j(t^+) \leq \overline{B}_j$ so that robot $j$’s buffer does not overflow.

D. Problem Statement

Given the limited communication range and limited buffer size constraints, our goal is to jointly design discrete motion plans for the robots that satisfy the local data-gathering tasks as well as sequences of communication events that ensure data delivery to the data center without allowing the buffers to overflow. Moreover, we seek a solution that is distributed and online, meaning that there is no central coordinator that collects all information and determines the robot actions, and that all robot actions are determined in run-time.

Remark 3. Note that different from “top-down” approaches [7, 8, 9], here the data-gathering tasks are assigned locally to each source robot, not to the whole team. Each source robot does not need to know the number of the other source robots or their local tasks.

IV. DYNAMIC DATA-GATHERING AND INTERMITTENT COMMUNICATION CONTROL

The proposed solution, as shown in Figure II, consists of three main parts: (i) the workspace abstraction and the synthesis of local discrete plans; (ii) the coordination of meeting events between source and relay robots, including the initial coordination and the real-time coordination; and (iii) the execution of local discrete plans and the data transfer protocol.

A. Local Discrete Plan Synthesis

Initially at time $t = 0$, each source robot $i \in \mathcal{N}^f$ synthesizes its local discrete plan to satisfy its local task $\varphi_i$. This plan is given as an infinite sequence of regions to visit and the data-gathering actions to perform at each region.
1) Road Map Construction: First, an abstraction of the freespace $\mathcal{F}$ is constructed as a roadmap on which all robots in $\mathcal{N}$ can move. In this work, we rely on the triangulation algorithm for polygons with holes, see Chapter 6 of [43] and software “poly2tri” from [44]. One approach is to decompose the freespace into triangular areas that have either one, two, or three facets, depending on how much of each triangle’s boundary is shared with the obstacles. Different optimization objectives are discussed in [45] to choose the reference path over these triangular partitions. Given the triangular decomposition above, we can find the middle points of each facet and the center point of each triangular cell (also called waypoints).

Then we can connect the center point to the middle point of each facet, and also connect any two middle points. An example is shown in Figure 2. Due to their unicycle dynamics and point mass model, the robots can navigate among the waypoints by following the roadmap, without crossing the obstacles.

**Definition 1.** The roadmap over the freespace $\mathcal{F}$ is a weighted and undirected graph $\mathcal{M} = (\mathcal{M}, H, W)$, where $\mathcal{M}$ is the set of waypoints $m \in \mathbb{R}^2$. $\forall m \in \mathcal{M}, H \subseteq \mathcal{M} \times \mathcal{M}$ indicates whether two waypoints are connected, and $W : H \rightarrow \mathbb{R}^+$ is the Euclidean distance between two waypoints.

Using the roadmap $\mathcal{M}$, we can construct a finite transition system (FTS) to abstract the motion of each source robot $i \in \mathcal{N}^I$ among its regions of interest within the freespace. Denote this motion model by $T_i = (\Pi_i, \rightarrow_i, I_i, P_i)$, where $\Pi_i$ is the set of regions of interest, $\rightarrow_i \subseteq \Pi_i \times \Pi_i$ denotes the transition relation, $I_i, 0 \in \Pi_i$ is the region robot $i$ starts from initially, $T_i \hookrightarrow \mathbb{R}^+$ approximates the time each transition takes. Particularly, consider two regions of interest of robot $i$ denoted by $\pi_{i,s}, \pi_{i,f} \in \Pi_i$. Denote by $m_{i,s}, m_{i,f} \in \mathcal{M}$ the closest waypoints to the center points of $\pi_{i,s}$ and $\pi_{i,f}$, respectively. Then, $(\pi_{i,s}, \pi_{i,f}) \rightarrow_i$ is a path in $\mathcal{M}$ starting from $m_{i,s}$ to $m_{i,f}$ without crossing any other waypoint $m_{i,k} \in \mathcal{M}$ that belongs to any other region $\pi_{e,f} \in \Pi_i$ with $e \neq s, f$. Denote the shortest of those paths by $T_{i,sf} = m_{i,s}m_{i,s+1} \cdots m_{i,f}$, which can be obtained from a graph search over $\mathcal{M}$ between $m_{i,s}$ and $m_{i,f}$. Furthermore, the time for robot $i$ to traverse $T_{i,sf}$ can be approximated given its reference linear and angular velocities introduced in Section III.

Specifically, for each transition $(\pi_{i,s}, \pi_{i,f}) \rightarrow_i$, the time for robot $i$ to traverse the associated path $T_{i,sf}$ is computed by

$$T_i(\pi_{i,s}, \pi_{i,f}) = \left( \frac{\sum_{k=1}^{f-1} ||m_{i,k} - m_{i,k+1}||}{v_{i,s}^\text{ref}} \right) + \left( \frac{\sum_{k=s}^{f-2} \theta(m_{i,s+k+1} - m_{i,s+k+2} - m_{i,s+k+1})}{\omega_{i,f}^\text{ref}} \right),$$

where $v_{i,s}^\text{ref}$, $\omega_{i,f}^\text{ref}$ are the reference linear and angular velocities of robot $i \in \mathcal{N}^I$ as defined in Section III and the function $\theta : \mathbb{R}^2 \rightarrow \mathbb{R}^2 \mapsto [-\pi, \pi]$ computes the angle between two 2D vectors. Note that $T_i(\cdot)$ is only an estimate of the time it takes for robot $i$ to traverse each edge.

The complete robot model that integrates the motion abstraction $T_i$ with the data-gathering actions in $G_i$ can be constructed as in [5].

**Definition 2.** The complete robot model given by the FTS $\mathcal{R}_i = (\Pi_i, \rightarrow_i, I_i, P_i, \mathcal{A}P_i, \mathcal{L}_i, \Gamma_i, \Pi_i, \Gamma_i, \mathcal{N}_i, \mathcal{C}_i, \Pi_i, \mathcal{G}_i)$, where $\Pi_i \subseteq \Pi_i \times \Pi_i$ is the set of transitions via robot motion or actions such that $T_i$ and $T_i$ are mutually exclusive if (i) $(\pi_{i,s}, \pi_{i,f}) \rightarrow_i$ and $g_i,k = g_i,0$, or (ii) $\pi_{i,s} = \pi_{i,f}$ and $g_i,k,1, g_i,1,1, g_i,1, l, g_i,1, G_i, \mathcal{A}P_i$ are the atomic propositions from Section III-B the labeling function is defined as $L_i((\pi_{i,s}, g_i, l)) = \{\pi_{i,s}, g_i, l\}, \forall (\pi_{i,s}, g_i, l) \in \Pi_i; \Pi_i, 0, g_i, 0 = (\Pi_i, 0, g_i, 0)$ is the initial state; and $T_i(\pi_{i,s}, g_i, l) = T_i(\pi_{i,s}, \pi_{i,f}) + Z_i(g_i,k)$. $\pi_{i,s}, g_i, l \in \pi_{i,f}$ is the time measure, where $Z_i(\cdot)$ is the time needed to accomplish action $g_i,k$.\[\Box\]

In other words, $\mathcal{R}_i$ encapsulates the motion and actions that robot $i \in \mathcal{N}^I$ can perform within the workspace.

2) Local Plan Synthesis: The local plan of robot $i$, denoted by $\tau_i^0, R_i$, is an infinite path of $\mathcal{R}_i$, whose trace satisfies its local task $\varphi_i$.

We rely on the automaton-based model checking algorithm [4], [10] to synthesize $\tau_i^0, R_i$ in the following four steps: (i) we derive the Büchi automaton $\mathcal{A}_{\varphi_i}$ associated with $\varphi_i$ via the translation tools [10], which is denoted by $\mathcal{A}_{\varphi_i} = (Q_{\varphi_i}, 2^K_{\varphi_i}, \delta_{\varphi_i}, Q_{\varphi_i}, 0, F_{\varphi_i})$, where the notations are defined similarly to Section II; (ii) we construct the product automaton $P_i = \mathcal{R}_i \otimes \mathcal{A}_{\varphi_i}$ defined as $P_i = (Q_i, \Pi_i, \delta_i, Q_i, 0, F_i, 0, P_i, 0)$, where $Q_i = \Pi_i \otimes Q_{\varphi_i}$; (iii) we search for the optimal plan $\tau_i^0, R_i$; (iv) we search for the optimal accepting path $\tau_i^0, R_i$ of $P_i$ with the prefix-suffix structure, denoted by

$$\delta_i^{(k)}(q_i^{(l)}p_i) = q_i^{(l)}p_i = q_i^{(l)}(q_i^{(l)}p_i, \cdots q_i^{(l)}p_i, q_i^{(l)}p_i, q_i^{(l)}p_i, q_i^{(l)}p_i, \cdots q_i^{(l)}p_i),$$

where the state $q_i^{(l)}p_i \in Q_i$ and $q_i^{(l)}q_i^{(l)}p_i, q_i^{(l)}q_i^{(l)}p_i, q_i^{(l)}q_i^{(l)}p_i = 0, 1, \cdots, K_i$ is the total length, $q_i^{(l)}q_i^{(l)}p_i, q_i^{(l)}q_i^{(l)}p_i, q_i^{(l)}q_i^{(l)}p_i$ is the prefix executed only once and $q_i^{(l)}q_i^{(l)}p_i, q_i^{(l)}q_i^{(l)}p_i, q_i^{(l)}q_i^{(l)}p_i$ is the suffix to be repeated infinitely many times. As proposed in [10].

A nested Dijkstra’s shortest path algorithm can be used to find $R_i^0, P_i$ with the above structure and the minimum total cost, i.e., the summation of prefix and suffix costs; (iv) lastly, the local plan $\tau_i^0, R_i$ can be easily derived as the projection of $R_i^0, P_i$ onto $\Pi_i, R_i$, which also has a prefix-suffix structure. Namely, $\tau_i^0, R_i = \delta_i^{(k)}(\Pi_i, R_i) = \{\pi_{i,s}, g_i, l \} \otimes \{\pi_{i,f}, g_i, l \}$, where $\pi_{i,s}, g_i, l \in \Pi_i, R_i$ and $\pi_{i,s}, g_i, l = 0, 1, \cdots, K_i$. This plan provides an infinite sequence of motion and data-gathering actions to be performed by robot $i$ that satisfy $\varphi_i$. Software implementation details can be found in [10], [42].

**Example 1.** Consider the roadmap shown in Figure 2 within a clustered workspace. Three robots are deployed with different local tasks. For instance, robot $a_0$ needs to visit $r_1$, $r_2$ and $r_3$ in sequence and perform the data-gathering action $g_1$ there. The resulting discrete plan $\tau_i^0, R_i$ is shown in blue in Figure 2.

**Remark 4.** Note that each source robot $i \in \mathcal{N}^I$ synthesizes its discrete plan $\tau_i^0, R_i$ locally without coordination with other robots. Thus, robot $i$ might not execute $\tau_i^0, R_i$ successfully by itself without the help of relay robots to transfer data, due to the infinite sequence of data-gathering actions in $\tau_i^0, R_i$ and its limited buffer size.
B. Coordination of Intermittent Meeting-Events

To execute the plan of each source robot $i \in \mathcal{N}^i$, we need to ensure that its stored data is transferred to at least one relay robot $j \in \mathcal{N}^j$ before its buffer overflows. The main difficulty lies in the limited communication range for both source and relay robots, meaning that both data transfer and coordination are only possible when two robots are within each other’s communication range. As discussed in Section I instead of imposing all-time connectivity as in most related work [6], [14], [16], [21], [22], we propose here a distributed online coordination scheme where the communication network is allowed to become disconnected. In other words, the source and relay robots are only connected when the source robots need to transfer data; otherwise, they are disconnected and move independently.

The key idea is to design a method that allows source and relay robots each time they meet (i.e., connect to each other) to negotiate when and where they should meet the next time, while minimizing the waiting time at the new meeting location. Afterwards, they move independently without communication, until they meet again at the agreed location and time, and the same procedure repeats. The main challenges in realizing this framework are twofold: (i) for source robots to find a suitable time and location to meet with different relay robots, subject to their local LTL tasks and buffer size constraints; (ii) for relay robots to accommodate meeting events from multiple source robots. In the sequel, we present a distributed coordination scheme for both the source robots and relay robots to schedule meeting events, which is based on online request and reply message exchanges, for four different scenarios: (i) the initial coordination phase; (ii) the real-time coordination for the next meeting event; (iii) the spontaneous coordination; and (iv) the swapping of meeting events.

1) Initial Coordination: Initially at $t = 0$, each source robot needs to coordinate its first meeting event with at least one relay robot. Denote by $N'_i(t) \subseteq \mathcal{N}$ the set of robots that robot $i \in \mathcal{N}$ can communicate with at time $t \geq 0$, i.e., $N'_i(t) = \{j \in \mathcal{N} | |p_j(t) - p_i(t)| \leq r \}$. Then, denote by $N'_i(t) = N'_i(0) \cap \mathcal{N}$ the set of relay robots that a source robot $i \in \mathcal{N}^i$ is connected to at time $t = 0$. To begin with, we need the following assumption for the initial configuration to be feasible:

**Assumption 1.** At time $t = 0$, each source robot $i \in \mathcal{N}^i$ is connected to at least one relay robot $j \in \mathcal{N}^j$, i.e., $N'_i(0) \neq \emptyset, \forall i \in \mathcal{N}^i$.

**Meeting requests by source robots:** To begin with, every source robot $i \in \mathcal{N}^i$ needs to estimate where and when it needs to meet with a relay robot $j \in \mathcal{N}^j$, given its discrete plan $\tau^0_{i,R}$ from Section IV-A. In other words, we need to solve the following problem.

**Problem 1.** Given the discrete plan $\tau^0_{i,R}$, the action model and the buffer size of each source robot $i \in \mathcal{N}^i$, find the first waypoint in the plan and the associated time that robot $i$ needs to meet with a relay robot and transfer data, before robot $i$’s buffer overflows.

To solve Problem 1, robot $i \in \mathcal{N}^i$ needs to search through the future sequence of states in $\tau^0_{i,R}$ and determine the first state where the data stored in its buffer would exceed its buffer size $B_i$, if it has not met any relay robot to transfer its data in the meanwhile. Denote by $\pi^k_{i,R} \in \tau^0_{i,R}$ this state and by $\pi^{k+1}_{i,R} \in \tau^0_{i,R}$ the current state of robot $i$, where $k_0 > k_0 > 0$. Specifically, the index $k_0$ of $\pi^k_{i,R} \in \tau^0_{i,R}$ is the index such that

$$\sum_{k_0}^k D_1(g_{i,k}, \epsilon_k) \geq B_i, \sum_{k_0+1}^{k+1} D_1(g_{i,k}, \epsilon_k) \geq B_i,$$

where $\pi^k_{i,R} = (\pi_{i,s,k}, g_{i,k})$, $\forall k_0 \leq k \leq k_0$, and $D_1(g_{i,k}, \epsilon_k)$ is the number of data units gathered after performing action $g_{i,k}$ from $\pi^k_{i,R}$. Thus, the buffer is not full after storing the gathered data up to $\pi^k_{i,R}$, but it will overflow at $\pi^{k+1}_{i,R}$ after performing action $g_{i,k+1}$.

| Robot | Timed path segment |
|-------|---------------------|
| $a_0$ | $\Gamma_{a_0} = \{4.3.2.3, (4.0.2.0), (1.0.1.5), (0.5.3.5), (0.3.5.6)\}$ |
| $a_1$ | $\Gamma_{a_1} = \{9.9.6.6.0, (9.5.4), (9.1.2.7), (9.0.1.5), (8.0.1.7), (7.0.0.7), (4.6.0.5)\}$ |
| $a_2$ | $\Gamma_{a_2} = \{8.9.9.5, (5.0.9.25), (2.5.8.7), (1.5.8.2), (1.0.8.8)\}$ |
| $a_3$ | $\Gamma_{a_3} = \{7.9.14.0.6, 1.6.18.8.17 \}$ |

Table I: Example of ILP solution by $\text{Gurobi}$ [46]. There are 204 binary and 16 integer variables, which took 0.8s and 10 simplex iterations to find the optimal solution using “Gurobi1” [46].

Then, robot $i$ calculates the route and the associated time to transition from $\pi^k_{i,R}$ to $\pi^{k+1}_{i,R}$. Without loss of generality, let $\pi^k_{i,R} | i_1 = \pi_{i,s,k}$ and $\pi^{k+1}_{i,R} | i_1 = \pi_{i,f,k}$. From Section IV-A1 we know that the shortest path from $\pi_{i,s,k}$ to $\pi_{i,f,k}$ is given by $\Gamma_{i,s,k,f} = m_{i,s,k,m_{i,s,k+1} \cdots m_{i,f}}$, and the associated time of reaching each waypoint $m_{i,s,k,m_{i,s,k+1} \cdots m_{i,f}}$ is denoted by $t_{i,k} \in T_{i,s,k,f}$, where $t_{i,s,k,m_{i,s,k+1} \cdots m_{i,f}}$ and $s_k \leq k \leq f$. Similar to $T_i(\cdot)$ in the FTS $T_i$, the time sequence $T_{i,s,k,f}$ is calculated using the reference linear and angular velocities by $\tilde{\Gamma}$. As a result, the request message from a source robot $i \in \mathcal{N}^i$ to a relay robot $j \in \mathcal{N}^j(0)$ at time $t = 0$, denoted by $\text{Req}_i(0)$, is given by

$$\text{Req}_i(0) = (\Gamma_{i,s,k,f}, T_{i,s,k,f}), \forall j \in \mathcal{N}^j(0)$$

where $\Gamma_{i,s,k,f}$ and $T_{i,s,k,f}$ are defined above. Simply speaking, robot $i$ is requesting that robot $j$ should come to meet at any of the waypoints within $\Gamma_{i,s,k,f}$, at the associated time in $T_{i,s,k,f}$.

**Replies by relay robots:** Upon receiving the requests from all source neighbors $i \in \mathcal{N}^j(0)$, where $\mathcal{N}^j(0) \not\supseteq \mathcal{N}^j(0)$, each relay robot $j \in \mathcal{N}^j(0)$ should decide the location and time to meet each source robot $i \in \mathcal{N}^j(0)$ and reply accordingly. Denote by $\text{Rep}_j(0)$ the reply message from robot $j$ to robot $i$ at time $t = 0$, which has the following structure:

$$\text{Rep}_j(0) = (m_{j,i}, t_{j,i}), \forall i \in \mathcal{N}^j(0)$$

where $m_{j,i} \in M$ is the waypoint where the two robots would meet and $t_{j,i} > t$ is the time of the meeting event. In the following we describe how the replies can be determined to satisfy all the requests.

**Problem 2.** Given $\text{Req}_j(0) = (\Gamma_{i,s,k,f}, T_{i,s,k,f}), \forall i \in \mathcal{N}^j(0)$, compute $\Gamma_j(0)$ such that both conditions above are satisfied.
Problem is closely related to the well-known traveling salesman problem (TSP) and the generalized TSP as it contains the TSP as a special case. A similar formulation appears in the computer wiring problem as discussed in [47]. To find the exact solution, we can transform Problem into a TSP. In particular, let $N'_j = N'_j \cup \{j\}$, where $N'_j$ is the set of source neighbors that robot $j$ is connected to and $\nu$ is an artificial node. Recall that the requests $\text{Req}_j(t) = (\Gamma_{i,s_i,f_i}, T_{i,s_i,f_i})$ satisfy $\Gamma_{i,s_i,f_i} = m_{i,s_i} \cdots m_{i,s_i+1} \cdots m_{i,f_i}$ and $T_{i,s_i,f_i} = t_{s_i,k_i} \cdots t_{i,f_i}$ for ease of notation, let $\mathcal{S} = \{s_i, s_i + 1, \ldots, f_i\}$.

As mentioned in condition one, $\Gamma_j$ intersects with $\Gamma_{i,s_i,f_i}$ exactly once, $\forall i \in N'_j$. Let this happen at the $(k_i)_{th}$ element of $\Gamma_{i,s_i,f_i}$, where $k_i \in T_{i,f_i}$. Consider the set of waypoints $\mathcal{T} = \{m_{0,0}, m_{0,m}, m_{k_i}, \forall i \in N'_j, k_i \in T_{i,f_i}\}$, which includes all waypoints within each source robot’s path segment $\Gamma_{i,s_i,f_i}$, and we set $m_{0,0} = m_{0,0} = (x_j(0), y_j(0))$. Also, to simplify the notation, we set $T_{i,f_i} = \{k_i\}$ and $\mathcal{T} = \{k_i\}$. Furthermore, we define a cost function $c : \mathcal{T} \times \mathcal{T} \rightarrow R_0$ between any two nodes in $\mathcal{T}$ such that: (i) for all $i, j \in N'_j$, it holds that

$$c_{k_i,k_j} = \left| t_{i,k_i} + T_j(m_{i,k_i}, m_{k_j}) - t_{i,k_j}\right|,$$

$\forall k_i \in T_{i,f_i}$ and $\forall k_j \in T_{j,f_i}$, where $t_{i,k_i}, t_{i,k_j}$ are the associated time instants of $m_{i,k_i}$, $m_{i,k_j}$ obtained from $T_{i,s_i,f_i}$ and $T_{j,s_j,f_j}$ and the function $T_j(\cdot)$ is the time it takes robot $j$ to travel from $m_{i,k_i}$ to $m_{i,k_j}$, which can be computed similarly to [5]. (ii) for all $i \in N'_j \cup \{j\}$, $c_{k_i,k_{inf}} = 0$, $\forall k_i \in T_{i,f_i}$; and (iii) for all $i \in N'_j$, $c_{k_i,k_j} = +\infty$, $\forall k_i \in T_{i,f_i}$, and $c_{k_i,k_{inf}} = 0$. Furthermore, let $\delta_{k_i,k_j} = 1$ if $\Gamma_j$ contains a segment from $m_{i,k_i}$ to $m_{i,k_j}$ and is 0 otherwise, $\forall k_i \in T_{i,f_i}$, $\forall k_j \in T_{j,f_i}$ and $\forall i, j \in N'_j$. Given the above notations, we can formulate the following integer linear program (ILP):

$$\min \sum_{k_i, k_j \in T_{i,f_i} \cup T_{j,f_i}, h \in N'_j} c_{k_i,k_j} \cdot \beta_{k_i,k_j}$$

s.t. $\sum_{k_i \in T_{i,f_i} \cap h \in N'_j} \beta_{k_i,k_j} = \sum_{h \in N'_j} \beta_{k_j,k_h},$ \hspace{1cm} (11a)

$\forall k_i \in T_{i,f_i}, \forall h \in N'_j,$ \hspace{1cm} (11b)

$\alpha_{k_i} = \alpha_{k_j} + (N'_j + 1) \cdot \beta_{k_i,k_j} \leq N'_j,$

$\forall k_i, k_j \in T_{i,f_i} \cup T_{j,f_i}, \forall h \in N'_j \cup \{\nu\}$.

The first two constraints ensure that exactly one element of $\Gamma_{i,s_i,f_i}$ is intersected by $\Gamma_j$, $\forall i \in N'_j$. The last constraint ensures that all the waypoints $m_{i,k_i}$ and $m_{i,k_j}$ that satisfy $\beta_{k_i,k_j}$ should belong to one big cycle where $m_{i,0}$ is the last waypoint and is connected to $m_{i,0}$. Simply speaking, assume that an additional cycle of waypoints (excluding $m_{i,0}$) with length $N_e > 0$ appears in $\Gamma_j$. Summing up the inequalities within 11 for all waypoints contained in that cycle would yield $N_e \cdot (N'_j + 1) \leq N_e \cdot N'_j$, leading to a contradiction. More explanations can be found in [47].

The ILP problem 11 has $\binom{N}{2}$ Boolean variables and $N$ integer variables, where $N = \sum_{i \in N'_j} |\Gamma_{i,s_i,f_i}|$ is the total number of waypoints and $\binom{N}{2}$ is the binomial coefficient. Thus the complexity of 11 is closely related to the number of source robots that each relay robot initially connects to and their request messages. Note that 11 always has a solution as each relay robot $j$ in $N'_j$ can reach any waypoint in $\mathcal{M}$ (thus any waypoint in $\Gamma_{i,s_i,f_i}$). Lastly, given the solutions $\Gamma_j$ and $T_j$, the replies $\text{Rep}_j(t)$ can be derived as: $m_{i,j} = m_{i,k_i}$ and $t_{i,j} = t_{i,k_j}, \forall i \in N'_j(0)$.

Example 2. Consider three source robots $a_0, a_3, a_6$ that are connected to the relay robot $l_0$ initially at $t = 0$. As shown in Table 7, given the request messages from robots $a_0, a_3, a_6$, the optimal path for robot $l_1$ and the associated time are derived by solving 11. It can be verified that both conditions of Problem 2 are satisfied.

**Confirmation by source robots:** Upon receiving the replies $\text{Rep}_j(t)$ from all relay robots $j \in N'_j(0)$, each source robot $i \in N'_j$ evaluates these replies and sends confirmations back. In particular, denote by $\text{Conf}_{j}(0)$ the confirmation message from the source robot $i$ to robot $j \in N'_j(0)$ at time $0$ so that $\text{Conf}_{j}(0) = \top$ if robot $i$ confirms the meeting location and time with robot $j$, while $\text{Conf}_{j}(0) = \bot$ if robot $i$ refuses the reply and thus is not committed to the meeting event with robot $j$. Given the replies $\text{Rep}_j(t) = (m_{i,j}, t_{i,j})$, $\forall j \in N'_j(0)$, robot $i$ chooses the relay robot $j^* \in N'_j(0)$ that yields the minimum waiting time for itself at the first meeting event, i.e.,

$$j^* = \arg\min_{j \in N'_j(0)} |t_{i,j} - t_{i,k_i}|,$$

where $s_i \leq k_j < f_i$ satisfies that $m_{i,k_j} = m_{i,j}$. Then the confirmation message is given by $\text{Conf}_{j^*}(0) = \top$, for $j^*$ obtained above, while $\text{Conf}_{j}(0) = \bot$, $\forall j \in N'_j(0)$ and $j \neq j^*$. So robot $i$ marks $m_{i,j^*}$ as the meeting location with robot $j^*$ at time $t_{i,k_j}$. On the other hand, after receiving the confirmation messages $\text{Conf}_{j}(0)$ from source robots $i \in N'_j(0)$, each relay robot $j \in N'_j$ removes the meeting event with each source robot $i$ from its path $\Gamma_j(0)$ that was computed by 11 if the confirmation message from the source robot $i$ satisfies $\text{Conf}_{j}(0) = \top$, $\forall i \in N'_j(0)$. In other words, each relay robot $j \in N'_j$ is only committed to meet the source robots that have confirmed the meeting event.

2) Coordination for Next Meeting Event: After the initial coordination at $t = 0$, robots $i$ and $j^*$ will meet at the waypoint $m_{i,j^*}$ at time $t = t_{i,j^*}$, $\forall i \in N'_j$. For the ease of notation, we replace $j^*$ by $j$ in this section. Then, the data at robot $i$’s buffer will be transferred to robot $j$’s buffer and will be uploaded to the data center, see Section V-C. When this happens, the two robots will need to coordinate in order to determine their next meeting event following the procedure described below.

First, robot $i$ needs to determine again the segment of its future plan when it should meet with a relay robot, before its buffer overflows. The same equation as in 11 can be applied given that the robot’s current buffer size is zero and $\pi_{k_{inf}}$ is the current state. Denote the new request message by $\text{Req}_j(t) = (\Gamma_{i,s_i,f_i}, T_{i,s_i,f_i})$, where $\Gamma_{i,s_i,f_i} = m_{i,s_i} \cdots m_{i,f_i}$ and $T_{i,s_i,f_i} = t_{s_i,k_i} \cdots t_{i,f_i}$ are defined analogously as before. Then, after receiving the request, robot $j$ needs to reply with its preferred next location and time to meet with robot $i$, denoted by $m_{j^*}$ and $t_{j^*}$, respectively. Let $\Gamma_j(t) = m_{j,k_j} \cdots m_{j,f_j}$ be the remaining path obtained by 11 at time $t$, and the associated sequence of time instants is $T_j(t) = t_{j,k_j} \cdots t_{j,f_j}$. Thus, the last committed meeting location and time of robot $j$ with another source robot are given by $m_{j^*}$ and $t_{j^*}$. Then $m_{j^*}$ can be determined by choosing among the waypoints that belong to $\Gamma_{i,s_i,f_i}$ such that moving from $m_{j^*}$ to $m_{j^*}$ yields the minimum waiting time for robot $i$. In other words, it holds that $m_{j^*} = m_{i,k_j}$.
Algorithm 1: Relay Robots Swapping Meeting Events

Input: $\Gamma_{j_1}, T_{j_1}, \Gamma_{j_2}, T_{j_2}$ at time $t'$.
Output: the updated $\Gamma_{j_1}, T_{j_1}, \Gamma_{j_2}, T_{j_2}$.
1 Create a sequence $\Upsilon'$ of $(m_i, t_i)$ by composing $\Gamma_{j_1}$ and $T_{j_1}$, and $\Gamma_{j_2}$ and $T_{j_2}$.
2 Sort $\Upsilon'$ by $t_i$ into $\Upsilon = (m_1, t_1)(m_2, t_2)\cdots(m_L, t_L)$.
3 Initialized $\Upsilon_1 = [(m_{j_1}, t_1'), \Upsilon_2 = [(m_{j_2}, t_2')]$.
4 forall $(m_i, t_i) \in \Upsilon$ do
   5 Compute waiting time $\tau_{i, j_1}$ given $\Upsilon_1$ and $(m_i, t_i)$ by (13).
   6 Compute waiting time $\tau_{i, j_2}$ given $\Upsilon_2$ and $(m_i, t_i)$ by (13).
   7 if $\tau_{i, j_1} \geq \tau_{i, j_2}$ then
      8 Append $(m_i, t_i)$ to $\Upsilon_2$.
   9 else
      10 Append $(m_i, t_i)$ to $\Upsilon_1$.
11 Decompose $\Upsilon$ into $\Upsilon_{j_1}$, $T_{j_1}$, and $\Upsilon_{j_2}$, into $\Gamma_{j_2}, T_{j_2}$.

and $t_{j_1}^{i} = t_{i, j_1^*}$, where the index $j_1^{i}$ satisfies that
\[ s_{j_1}^{i} = \arg \min_{s_{j_1}, t_{j_1} \leq t_{i, j_1}} \| t_{j_1} - t_{i, j_1} \|, \]
(13)
where $T_j(m_{j_2}, t_{j_2})$ is the time robot $j$ would take to navigate from waypoint $m_{j_2}$ to $m_{i, j_1^*}$. This optimization problem can be solved by iterating through all waypoints in $\Gamma_{i, j_1^*}$ to find the minimum waiting time.

Therefore, the reply message from robot $j$ to $i$ is given by $\text{Rep}_{ji} = (m_{j_1}^{i}, t_{j_1}^{i})$, where $m_{j_1}^{i}, t_{j_1}^{i}$ are derived above. After receiving the reply message, robot $i$ will send back the confirmation as $\text{Conf}_{i} = \Upsilon$ and mark $m_{j_1}$ as the next meeting location with robot $j$. On the other hand, after receiving the confirmation, robot $j$ will concatenate its path $\Gamma_j$ with the shortest path from $m_{j_2}$ to $m_{i, s_{j_1}}$ within $\mathcal{M}$, i.e., $\Gamma_j(m_{j_2}, m_{s_{j_1}})$, and mark $m_{j_1}$ as the next meeting location with robot $i$.

Remark 5. Note that source robots are not allowed to transmit data to each other even when they are within the communication range. This assumption can be relaxed and is part of our ongoing work.

3) Spontaneous Meeting Events: When there are more than one relay robots in the team, it is possible that robot $i \in \mathcal{N}_i^t$ meets with another relay robot $j' \in \mathcal{N}_i^t$ on its way to meet the confirmed relay robot $j^*$. We call this situation a spontaneous meeting event. In this case, robot $i$ transfers the stored data in its buffer to robot $j'$, and coordinates with $j'$ for the next meeting event in a similar way as described in Section IV-B2 but now robot $i$ takes into account the fact that it will meet with $j_1^{i}$ at $m_{j_1}^{i}$ as previously confirmed. Thus, the next path segment of $\Gamma_i$ where robot $i$ needs to meet with a relay robot should be calculated as in (7) by setting $\tau_{i, j_1} = (m_{j_1}^{i}, 90)$, i.e., robot $i$'s buffer is zero after meeting robot $j'$ at $m_{j_1}^{i}$. After the coordination with robot $j'$, robot $i$ continues to meet robot $j^*$. In this way, a source robot can meet and transfer data through all relay robots it has met, instead of being restricted to the relay robot it was connected to initially. Each time it coordinates with a new relay robot, it takes into account the fact that it will meet with all the relay robots it has committed to and particularly its buffer will be empty after the last meeting event.

Remark 6. It is crucial that the source robot $i$ still meets its initially confirmed relay robot $j_1^{i}$ (even with an empty buffer), after a spontaneous meeting with another relay robot $j^* \in \mathcal{N}_i^t$. Due to the limited communication range, robot $i$ can not inform robot $j_1^{i}$ to cancel the confirmed next meeting. If robot $i$ simply skips

| Robot | Timed path segment |
|-------|---------------------|
| $j_1$ | $\Gamma_{j_1} = [(0.1, 4.0), (0.6, 6.0), (0.6, 9.5), (4.6, 0.5), (4.3, 2.3)]$, $T_{j_1} = [0, 8.7, 12.9, 15.1, 17.5]$ |
| $j_2$ | $\Gamma_{j_2} = [(4.6, 4.3), (4.6, 9.5), (9.3, 9.0), (0.3, 5.6), (7.6, 6.0), (6.0, 2.1)]$, $T_{j_2} = [0, 3.8, 6.6, 7.4, 16.6, 18.1]$ |

| Table II: Example of swapping meeting events by Algorithm 1 from Section IV-B4. The total waiting time has been reduced from 43.3s to 12.1s. An illustration of the paths before and after the swapping algorithm is shown in Figure 3. |

Figure 3: Visualization of robots $j_1, j_2 \in \mathcal{N}_i^t$'s paths before and after the swapping algorithm presented in Section IV-B2. Initial position of robots $j_1$ and $j_2$ are indicated by filled stars. Numerical details can be found in Example 5 and Table II.

4) Relay Robots Swap Meeting Events: Until now, we have discussed the communication between source and relay robots. In this part, we discuss how relay robots can communicate with each other and swap their committed meeting events with source robots, in order to reduce the total waiting time. Particularly, assume that two relay robots $j_1, j_2 \in \mathcal{N}_i^t$ meet at time $t' > 0$. The remaining path and the associated time stamps of robot $j_1$ are given by $\Gamma_{j_1}(t') = m_{j_1, k_1} \cdots m_{j_1, f_1}$, and $T_j(t') = t_{j_1, k_1} \cdots t_{j_1, f_1}$, respectively. Similarly, the remaining path and time stamps of robot $j_2$: $\Gamma_{j_2}(t') = m_{j_2, k_2} \cdots m_{j_2, f_2}$ and $T_j(t') = t_{j_2, k_2} \cdots t_{j_2, f_2}$. Our goal is to rearrange the entries in $\Gamma_{j_1}$ and $\Gamma_{j_2}$ such that the total waiting time for source robots is further reduced.

Clearly, the optimal way to rearrange $\Gamma_{j_1}$ and $\Gamma_{j_2}$ that yields the minimum waiting time is to formulate a mixed integer problem similar to (11). It can be thought of as a traveling salesman problem problem with two salesman. Here we propose a greedy algorithm that takes advantage of the ordered structure of the paths $\Gamma_{j_1}$ and $\Gamma_{j_2}$. The proposed algorithm is shown in Algorithm 1. First, we construct (in Lines 1-2) a new sequence of 2-tuples $\Upsilon = (m_1, t_1)(m_2, t_2)\cdots(m_L, t_L)$, where $L = |\Gamma_{j_1}| + |\Gamma_{j_2}|$. It holds that $m_i = \Gamma_{j_1}[l_1]$ with the index $l_1$ that satisfies $k_1 \leq l_1 \leq f_1$, or $m_i = \Gamma_{j_2}[l_2]$ and $l_2 = T_{j_2}[l_2]$ with the index $l_2$ that satisfies $k_2 \leq l_2 \leq f_2$, $\forall l = 1, \cdots, L$. More importantly, $\Upsilon$ is ordered by $t_1 < t_2 < \cdots < t_L$, i.e., an increasing time order according to which each waypoint should be visited. Second, let $\Upsilon_1$ and $\Upsilon_2$ be two subsequences of $\Upsilon$
that we want to construct. They are initialized in Line 3 by \( Y_3 = (m_{j_3}(t^{'}, t)) \) and \( Y_2 = (m_{j_2}(t^{'}, t)) \), where \( m_{j_3}(t') \) and \( m_{j_2}(t') \) are the waypoints robots \( j_1 \) and \( j_2 \) are located, respectively. Then, in Lines 4-10, we iterate over each entry of \((m_i, t_i) \in Y\) and evaluate the waiting time using (13) if the paths of robots \( j_1 \) or \( j_2 \) contain this entry as their last meeting event. If robot \( j_1 \) yields a smaller waiting time, we add \((m_i, t_i)\) to the end of \( Y_1 \); otherwise, if robot \( j_2 \) yields a smaller waiting time, we add \((m_i, t_i)\) to the end of \( Y_2 \) (in Lines 7-10). At last, in Line 11, \( Y_1 \) is decomposed into the new \( \Gamma_{j_1} \) and \( T_{j_1} \) for robot \( j_1 \), while \( Y_2 \) is decomposed into the new \( \Gamma_{j_2} \) and \( T_{j_2} \) for robot \( j_2 \). Since Algorithm \( \mathcal{A} \) is greedy, we can compare the total waiting time under the new paths \( \Gamma_{j_1} \) and \( \Gamma_{j_2} \), which is then compared to the original total waiting time. If the total waiting time is reduced, the updated \( \Gamma_{j_1} \) and \( \Gamma_{j_2} \) will be used; otherwise, the paths remain unchanged, as they were before running Algorithm \( \mathcal{A} \).

In this way, some of the meeting events are swapped between relay robots \( j_1 \) and \( j_2 \) and consequently the total waiting time is reduced.

**Example 3.** Consider two relay robots \( j_1 \) and \( j_2 \), with paths and time stamps \( \Gamma_{j_1}, \Gamma_{j_2}, T_{j_1}, T_{j_2} \) that are shown in Table II (Algorithm \( \mathcal{A} \) is used to swap the meeting events of \( \Gamma_{j_1} \) and \( \Gamma_{j_2} \) as described above. The reference velocities of robots \( j_1, j_2 \) are given in Section IV-B. The numerical results are shown in Table II and illustrated in Figure 2.)

The total waiting time is reduced from 43.3s to 12.1s.

### C. Integrated System

Real-time execution of the system consists of two essential components: (i) the local plan execution of source robots that includes navigation and data-gathering actions and (ii) the meeting events between source and relay robots to exchange and upload data.

#### 1) Plan Execution:
After the system starts, each source robot \( i \in N^f \) executes its discrete plan \( \tau_i^0 = \pi_{i,R}^0 \pi_{i,R}^1 \cdots \pi_{i,R}^k \cdot 1 \left( 1 \cdot \cdots \cdot \pi_{i,k}^R \right) \), where \( \pi_{i,k}^R = \langle \pi_{i,s}, g_i(t_\ell) \rangle \in \Pi_i, \forall k = 0, 1, \cdots, K_i \), which was derived in Section IV-A2.

Starting from the initial position \( \pi_{i,s} \), robot \( i \) first navigates to region \( \pi_{i,s} \) through the corresponding path \( \Gamma_{i,\pi_{i,s}} \).

The control inputs follow the turn-and-forward switching control:

(C.1): \( v_i = 0 \) and \( \omega_i = \omega_i^{ref} \); and (C.2): \( v_i = v_i^{ref} \) and \( \omega_i = 0 \).

The controller (C.1) is activated to turn robot \( i \) towards the next waypoint in \( \Gamma_{i,\pi_{i,s}} \) and then, (C.2) drives it forward with the reference speed. Once robot \( i \) reaches \( \pi_{i,s} \), it performs the data-gathering action \( g_i(t_\ell) \). After the action is completed, robot \( i \) navigates to region \( \pi_{i,s} \) through \( \Gamma_{i,\pi_{i,s}} \) and performs action \( g_i(t_\ell) \). This procedure repeats itself until robot \( i \) reaches the \( (k_c)_{th} \) state \( \pi_{i,R}^k \) according to (7). During this period of time, the amount of data units stored in robot \( i \)’s buffer is increased incrementally by \( D_i(g_i(t_\ell)) \) using (2), \( \forall k = 0, 1, \cdots, k_c \). Then on its way from state \( \pi_{i,R}^k \) to \( \pi_{i,R}^{k+1} \), robot \( i \) meets with robot \( j_i^* \) at waypoint \( m_{i,s} \).

It is ensured by the formulation of (7) that the buffer is never overflown and all data-gathering actions can be performed before reaching \( \pi_{i,R}^{k+1} \). After the meeting, robot \( i \) continues executing the rest of its plan until the next meeting event with \( j_i^* \) or another relay robot. Similarly, any relay robot \( j \in N^d \) starts by executing the path \( \Gamma_{j} \) derived from (11) at time 0, which is then modified by adding new segments each time robot \( j \) coordinates with a source robot about the next meeting event.

#### 2) Meeting Event Execution:
Assume that \( \Gamma_{i,s} = m_{i,s_0} \cdot m_{i,s_1} \cdot \cdots \cdot m_{i,s_f} \) is the path that robot \( i \) follows to navigate from \( m_{i,s_0} \) to \( m_{i,s_f} \), and assume also that its confirmed meeting waypoint with robot \( j_i^* \) is \( m_{i,s_{j^*}} \). Starting from \( m_{i,s_0} \), robot \( i \) moves towards \( m_{i,s_{j^*}} \). Then two cases are possible: (i) if robot \( j_i^* \) is already waiting at \( m_{i,s_{j^*}} \), then robot \( i \) continues moving towards \( m_{i,s_{j^*}} \) until robot \( j_i^* \) is within its communication range. When this happens, robot \( i \) transfers all the data stored in its buffer to robot \( j_i^* \). As a result, the stored data units in the buffers of robots \( i \) and \( j_i^* \) are updated according to \( b_i(t^{'}) = 0 \) and \( b_j^*(t^{'}) = b_j^*(t^{'}) + b_i(t^{'}) \). When the data transfer is completed, robot \( j_i^* \) uploads all the data in its buffer to the data station immediately. Thus its stored data is updated according to \( b_j^*(t^{'}) = 0 \). If the stored data at robot \( i \) is more than robot \( j_i^* \)’s buffer size \( B_{j_i^*} \), these data need to be divided into smaller batches, which are then transferred to robot \( j_i^* \) sequentially; (ii) if robot \( j_i^* \) has not arrived at \( m_{j_i^*} \), yet, then robot \( i \) waits until robot \( j_i^* \) enters its communication range and then follows the same procedure as in (i). It can be seen that due to the waiting procedure described above, an exact synchronization of the meeting time is not required between a source robot and a relay robot. Therefore, the proposed method can handle uncertainty in the travel times obtained by \( \mathcal{A} \).

Note that delays due to lack of synchronization do not propagate to the future meeting events as the next event is always coordinated based on the current time. In other words, the delay is always re-initialized to zero whenever two robots meet.

**Proposition 1.** Under Assumption II, stating that each source robot is connected to at least one relay robot at time \( t = 0 \), the framework described above ensures that each source robot \( i \) can satisfy its local task \( \varphi_i \) and also that its buffer will not overflow, \( \forall i \in N^f \).

**Proof.** First, the correctness of the local plan for each source robot is guaranteed by the model-checking algorithm. Moreover, since all local tasks are independent, these local plans can be executed independently. Thus we need to show that the plan can be executed successfully by each source robot, i.e., the data-gathering actions can be performed and the data buffer never overflows.

Initially, each source robot is connected to at least one relay robot, meaning that it will be confirmed to meet with at least one relay robot. When the two robots meet, the stored data can be transferred and uploaded, before the source robot’s buffer overflows due to the formulation of (7). Then the coordination for the next meeting event in Section IV-B2 ensures that every source robot always waits to meet a relay robot and transfer the stored data before performing the next data-gathering action. Similarly, the spontaneous meeting events described in Section IV-B3 ensure that all data-gathering actions up to the next meeting time can be performed and the data buffer never overflows. The same procedure repeats itself and holds for all source robots.

### V. ROBOT FAILURES, DYNAMIC ROBOT MEMBERSHIP, AND DATA CENTER CONSTRAINTS

In this section, we discuss how the proposed framework can be extended to account for a fixed data center, robot failure, and dynamic membership.

#### A. Fixed Location of Data Center

As mentioned in Remark I, assume that a relay robot \( j \), instead of uploading its stored data immediately after meeting a source robot, needs to visit a fixed data center \( H_j \) within the workspace to upload the data, \( \forall j \in N^d \). Then the proposed scheme can be modified as follows: Consider the meeting between robot \( j \) and the source robot \( i \in N^f \). First, during the execution of the meeting event as discussed in Section IV-C2, robot \( j \)’s motion plan needs to be modified to include visiting the data center. In particular, if the amount of data robot \( i \) needs to transfer is less than robot \( j \)’s buffer size, robot \( j \) can receive all the data at once and then travel to the data center via the shortest path to upload the data. On the other hand, if the amount of data robot \( i \) needs to transfer is more than robot \( j \)’s buffer size, robot \( j \) can receive the data in batches that are
less than its buffer size, and then travel to the data center multiple times. Second, regarding the coordination of the next meeting event as discussed in Section [IV-B], robot j’s choice of the next meeting location according to (13) can be modified as follows:

$$s_{ji}^+ = \arg\min_{s_{ji} \leq f_i} \{ \| t_{j,f_j} - t_i,s_{ji} \|
+ T_j(m_{j,f_j}, m_{i,s_{ji}}) + N_{ji} \cdot T_i(H_j, m_{i,s_{ji}}) \},$$

where $N_{ji} = 2 \cdot |B_j/B_i|$ is the number of times robot j needs to travel to the data center $H_j$, $B_j/B_i$ is the ratio between robot j and robot i’s buffer size, the function $\lceil \cdot \rceil$ is the previous largest integer; and $T_j(H_i, m_{i,s_{ji}})$ is the traveling time for robot j to navigate from waypoint $m_{i,s_{ji}}$ to $H_j$ and back. In other words, (14) takes into account the extra time that is needed for robot j to travel to $H_j$ in order to empty robot i’s buffer given robot j’s buffer limit. Last but not least, if there are multiple data centers that robot j can choose from, we can easily modify (14) to find the optimal one among them.

### B. Robot Failures

Let us assume first that a source robot $i \in \mathcal{N}^j$ fails. If robot i can still communicate with all relay robots $j \in \mathcal{N}^i$ it has committed to meet, then robot i can initiate a cancel message to each of the relay robots to cancel the committed meeting events. In this way, these relay robots can skip the meeting with robot i and continue meeting the next source robot (instead of waiting indefinitely for robot i). However, if robot i fails when it is not in the communication range of one or more relay robots $j \in \mathcal{N}^i$, then to avoid deadlock we can introduce a maximum waiting time $T_{\text{max}} > 0$, so that if a robot waits at a confirmed meeting location for a period of time longer than $T_{\text{max}}$, then it assumes that this meeting is canceled and continues executing its discrete plan until the next meeting event.

Assume now that a relay robot $j \in \mathcal{N}^i$ fails. If robot j can still communicate with the source robots $i \in \mathcal{N}^j$ it is committed to meet, it can cancel the meeting events directly as in the previous case. However, in this case, robot i is in $\mathcal{N}^j$ and can not simply skip this meeting event and continue its plan execution as its buffer will overflow. Instead, robot i needs to navigate to its next meeting location directly, upload its stored data and more importantly keep the next meeting event unchanged. In other words, the next meeting event will be executed twice. Last but not least, if robot j is the only relay robot that robot i is committed to, robot i may have to wait until it meets another relay robot to upload its data. This can only happen spontaneously as robot i has no knowledge of the location of other relay robots due to limited communication range. This situation can be solved by allowing source robots to relay data to each other, which is part of our ongoing work, see also Remark 5.

At last, if a source or relay robot recovers after failure, it will be treated as a robot that newly joins the system, as discussed below.

### C. Dynamic Membership

By dynamic membership, we mean that (i) existing robots within the team can leave the team without resulting in a deadlock; and (ii) new robots can join the team seamlessly without the need to restart the system. The first case can be achieved in a similar way as described in Section [V-B] to handle robot failures. Particularly, before a source robot leaves the team, it needs to meet with each relay robot that it is committed to meet, without coordinating the next meeting event. For the second case, due to the distributed and online nature of the proposed scheme, new source or relay robots can be easily added to the system during run time. Specifically, if the new relay robot $j'$ that just joined the team is connected to an existing source robot $i \in \mathcal{N}^j$, robot i will treat this meeting as a spontaneous meeting event as described in Section [IV-B]. Namely, robot $j'$ is added to the set of relay robots that robot i is committed to meet. The same procedure applies when an existing relay robot meets a new source robot that just joined the team during run time.

### VI. CASE STUDY

This section presents simulation results for a team of 12 data-gathering robots. All algorithms are implemented in Python 2.7. “Gurobi” [46] and “poly2tri” [44] are external packages and “P. MAS-TG” [42] is developed by the authors. All simulations are carried out on a laptop (3.06GHz Duo CPU and 8GB of RAM).

#### A. System Description

All 12 robots satisfy the unicycle dynamics [1]. There are 9 source robots (denoted by $a_0, a_2, \ldots, a_8$) and 3 relay robots (denoted by $l_1, l_2, l_3$). Their common workspace has size $10m \times 10m$ and contains three polygonal obstacles, as shown in Figure 2. The triangular partition is derived from [44]. All robots’ communication ranges are set to be uniformly distributed from 0.5 to 1.0 m. The reference linear and angular velocities are chosen randomly between $[0.5, 0.8]m/s$ and $[0.1, 0.3]rad/s$. The buffer size of all source robots is chosen randomly between $[3, 5]$ data units, while all relay robots have buffer size of 5 data units.

To simplify the task description, we divide the source robots into three categories: (i) the first category ($a_0, a_2, a_3$) gathers type-1 data in region $r_1$, type-2 data in region $r_2$ and type-3 data in region $r_3$ (in any order), infinitely often. This specification can be expressed by the LTL formula: $\varphi_1 = -\bigcirc (r_2 \land g_2) \bigcirc (r_3 \land g_3)$. (ii) the second category ($a_3, a_4, a_5$) gathers type-4 and type-5 data in regions $r_4$, type-6 data in region $r_5$ and type-7 data in region $r_6$, infinitely often, respectively. (iii) the third category ($a_6, a_7, a_8$) gathers type-6 data in regions $r_7, r_8$ and type-7 data in region $r_9$, infinitely often, respectively. The actions $g_2, g_3, g_4, g_6$ gather 2 units of data, while actions $g_1, g_5, g_7$ gather 1 unit. Moreover, any data-gathering action takes 1s while the data transfer or upload actions take 2s. Initially, robots $a_0, a_3, a_6, l_1$ start from $(6.5m, 6.0m)$, robots $a_1, a_4, a_7, l_2$ start from $(5.6m, 5.0m)$, and robots $a_2, a_5, a_8, l_3$ start from $(4.6m, 4.3m)$. Thus every source robot is connected to at least one relay robot, as required by Assumption 1.

#### B. Simulation Results

First, the roadmap of each robot is constructed using a triangular partition of the workspace, as described in Section [IV-A]. For robots $a_0, a_1, a_2$, the FTS $R_i$ has 16 nodes and 112 edges, the NBA $A_{w_1}$ has 4 nodes and 13 edges, and the product $P_i$ has 64 nodes and 476 edges. For robots $a_3, a_4, a_5$, the FTS $R_i$ has 12 nodes and 72 edges, the NBA $A_{w_1}$ has 7 nodes and 32 edges, and the product $P_i$ has 84 nodes and 342 edges. For robots $a_6, a_7, a_8$, the FTS $R_i$ has 12 nodes and 72 edges, the NBA $A_{w_1}$ has 4 nodes and 13 edges, and the product $P_i$ has 48 nodes and 312 edges.

Then each source robot synthesizes its discrete plan using the algorithm in [10] and the package [42]. It took approximately 0.03s, 0.05s and 0.01s for the above three groups to synthesize their discrete plans. For instance, $a_0$ has prefix cost 57.22 and suffix cost 46.14, while $a_3$ has prefix cost 60.60 and suffix cost 45.69. Specifically, the first category has the discrete plan $\tau_1 = r_0(r_1; g_1 r_2 g_2 r_3 g_3)$, the second category $\tau_2 = r_0(r_4 g_4 r_5 g_5 r_6 g_6)$, and the third category...
category $\tau_{\forall} = r_0 (7r_0 g r_0 g r_0)$. The request and reply messages exchanged between relay robot $l_3$ and its neighboring source robots $a_4, a_3, a_6$ at $t = 0$ are shown in Table I. It took 0.3s by Gurobi [46] to find the optimal solution of (11), which determines the initial paths of all relay robots. The discrete plans are executed according to Section IV-C1, while the data are transferred and uploaded during the meeting events as described in Section IV-C2. The coordination for the next meeting event and spontaneous meetings follow Sections IV-B2 and IV-B3. We simulate the system for 100s. Snapshot of the simulation at 40s is shown in Figure 4 where we show the number of data units stored at each robot’s buffer and the data gathering or transfer actions taken by each robot. The evolution of the stored data units at each robot’s buffer is shown in Figure 5. Notice that the communication network among the robots is almost never connected, given the communication range of 1m. In particular, the maximum number of connected robots remains below 5 during most of the simulation, as shown in Figure 8. Furthermore, we also monitor the times that relay robots $l_0, l_1, l_2$ swap meeting events as described in Section IV-B4. Figure 9 shows the reduction in total waiting time after two relay robots swapping their meeting events. In total, 137 units of data are uploaded, as shown in Table III and Figure 10. The complete simulation videos can be found in [48].

C. Comparisons to Other Approaches

In this part, we compare the data-gathering performance of the proposed scheme to the centralized approach and two static approaches introduced below. Simulation videos for all three approaches can be found in [48].
1) Centralized Approach: An optimal solution, in terms of total distance traveled, to the data-gathering problem under consideration can be determined by composing the motion models and task specifications of all robots into a large product automaton that can then be model checked to find an optimal centralized plan for the whole team that satisfies communication and data constraints. Furthermore, this plan needs to be executed in a *fully-synchronized* way by all robots. However, this solution is computationally intractable for systems of large number of robots with complex tasks, due to the combinational size of product system and the double-exponential complexity of the model-checking process [6]. For this system, the product motion model would have approximately $16^5 \cdot 12^3 \cdot 12^3 \cdot 24^3 \approx 1.6 \times 10^{14}$ states and $112^3 \cdot 72^3 \cdot 72^3 \cdot 70^3 \approx 7.3 \times 10^{22}$ transitions. The product Büchi automaton has approximately $4^4 \cdot 7^3 \cdot 4^3 \approx 1.4 \times 10^5$ states and $13^3 \cdot 32^3 \cdot 13^3 \approx 1.5 \times 10^{11}$ transitions. Thus to construct the product automaton for the whole system is computationally infeasible. Moreover, given this complete product automaton, how to incorporate both the limited communication-range constraint and the limited buffer constraint during the model-checking process remains an open problem.

2) Static Approaches: Alternatively, a straightforward solution to the data-gathering problem considered in this paper is to require that all relay robots remain static at their initial positions for all time. As a result, as long as each source robot is informed about the location of at least one relay robot, every source robot can simply navigate to the closest relay robot once it has gathered enough data that needs to be transferred and uploaded. This static approach is *always* feasible for the problem considered here, but can be very inefficient if the workspace is large and many relay robots are located close to each other. We implement the above approach and simulate the system for 100s under the same settings presented in Section VI-A. As a result, 58 units of data are uploaded in total, as shown in Table III and Figure 10 compared with 137 units via the proposed dynamic approach. The difference is that in our approach every relay robot can actively navigate to meet multiple source robots that need to transfer data while minimizing the total waiting time.

Finally, another simple solution is to force all source and relay robots to move as a group that is within communication range for all time. In this case the source robots can follow a predefined static order to execute their local plans. Since all relay robots are within the communication range, the data gathered by any source robot can be transferred to any relay robot and uploaded directly. This static approach imposes all-time connectivity of the communication network. It can also be very inefficient since the source robots cannot execute their local plans simultaneously and independently, while relay robots are not fully utilized regarding their data-uploading ability. We implement the above approach and simulate the system for 100s under the same settings. The source robots take turns to execute their local plans according to the order of their IDs. As shown in Table III and Figure 10 only 8 units of data are uploaded in total, compared to 137 units via our approach. The difference is that the proposed intermittent communication framework allows all source robots to move and execute their local plans independently. Thus the source and relay robots only meet when they need to transfer data and coordinate their next meeting event.

The above comparative studies show that the proposed dynamic approach has much less computational burden compared to the centralized approach and improves greatly the overall data-gathering efficiency compared to the other two static approaches.

### VII. Experimental Study

In this section, we present the experimental study to validate the proposed approach. Four differential-driven “iRobots” are deployed within a $2.5m \times 2.0m$ workspace, as shown in Figure 11, whose positions and orientation can be tracked in real-time via an Optitrack motion capture system. The communication among the proposed control module, the robot actuation module, and the Optitrack is handled via the Robot operating system (ROS).
A. System Description

Three iRobots serve as source robots (denoted by \(a_0, a_1, a_2\)) while one serves as the relay robot (denoted by \(l_1\)). As shown in Figure 11, there are six regions of interest and two obstacles within the workspace; and a visualization panel is used to monitor the robot data-gathering actions and communications in real time. For source robots, their regions of interest, allowed actions and local tasks are defined as follows: Robot \(a_0\) has two regions of interest \(r_1, r_2\) and two actions \(g_1, g_2\) associated with one type-1 and two type-2 data units, respectively. Its task is to gather type-1 data in region \(r_1\) and then type-2 data in region \(r_2\) (in this order) infinitely often, i.e., \(\varphi_0 = \sqcap \circ (r_1 \land g_1) \land \sqcap \circ (r_2 \land g_2)\); Robot \(a_1\) has two regions of interest \(r_4, r_5\) and two actions \(g_3, g_4\) associated with two type-3 and one type-2 data units, respectively. Its task is to gather type-3 data in region \(r_4\) and then type-4 data in region \(r_5\) (any order) infinitely often, i.e., \(\varphi_1 = \sqcap \circ (r_4 \land g_3) \land \sqcap \circ (r_5 \land g_4)\); Robot \(a_2\) has two regions of interest \(r_7, r_8\) and two actions \(g_5, g_6\) associated with two type-5 and one type-6 data units, respectively. Its task is to gather type-5 data in region \(r_7\) and then type-6 data in region \(r_8\) (any order) infinitely often, i.e., \(\varphi_2 = \sqcap \circ (r_7 \land g_5) \land \sqcap \circ (r_8 \land g_6)\).

All robots have a limited buffer size of 4 data units and a communication range of 0.8 m. The initial position of robots \(a_0, a_1, a_2, l_1\) is given by \((1.1, 0.8), (1.1, 0.2), (2.0, 0.7), (1.6, 0.5)\) in meters, respectively. Thus the relay robot \(l_1\) is initially connected to all source robots \(a_0, a_1, a_2\), which satisfies Assumption 1.

B. Experiment Results

Following the procedure described in Section IV-C, we first synthesize the offline plan for each source robot. For robot \(a_0\), it took approximately 0.01 s for the solver [42] to obtain the initial plan; similarly for \(a_1, a_2\). For the initial coordination phase described in Section IV-B1, it took 0.16 s for Gurobi [46] to find the optimal initial plan for robot \(l_1\). Once the robots starts moving, the plan execution and coordination of meeting events during run time follows Section IV-C. Note that swapping meeting events between relay robots is not considered as there is only one relay robot. The experiment was performed for a duration of 3 minutes, and the full video can be found online at [50]. The sampled trajectory of each robot is plotted in Figure 12. It can be seen that each robot satisfies its local task and avoids collisions with the static obstacles. Moreover, the amount of data stored within each robot’s buffer over time is shown in Figure 13 which verifies that buffer constraints are always respected. Finally, during the experiment, 27 data units were transferred in total from source robots to the relay robot and then uploaded to the data center, as shown in Figure 14.

C. Comparison to Static Approaches

We also compare the performance of our method to the two static approaches introduced in Section VI-C. The experiment videos for all three cases can be found in [50].

First, as shown in Figure 15, we conducted an experiment using the static approach one for a duration of 3 minutes. Robot \(l_1\) remains...
still at its initial location for all time, while robots \(a_0, a_1, a_2\) navigate back to robot \(l_1\) once they have gathered enough data that needs to be transferred. As shown in Figure 16, 17 units of data are uploaded in total. Second, as shown in Figure 16, we conducted an experiment using the static approach two, also for a duration of 3 minutes. The robots form a platoon in the order \(a_2, a_0, l_1, a_1\), so that all source robots \(a_0, a_1, a_2\) are always within the communication range of robot \(l_1\). Robots \(a_0, a_1, a_2\) take turns to execute their local plans by navigating (with the whole group) to their desired regions to gather data and transfer the data directly to \(l_1\). As shown in Figure 16, 16 units of data are uploaded in total, compared to 27 units using the proposed dynamic approach.

Thus similar conclusions can be obtained as in Section VIII that the proposed dynamic approach improves greatly the overall data-gathering efficiency compared to the other two static approaches. It is worth mentioning that sequence of spontaneous meeting events that happened during the experiment is quite different from the simulated result, due to the inter-robot collision avoidance scheme.

**VIII. CONCLUSION AND FUTURE WORK**

In this work we proposed a distributed online framework for multiple robots that jointly coordinates local data-gathering tasks and intermittent communication events so that the collected data at the robots are transferred to a data center while ensuring that robot buffers do not overflow. Unlike most relevant literature that relies on all-time connectivity for coordination, the proposed intermittent communication framework allows the robots to operate in disconnect mode and accomplish their tasks free of communication constraints, significantly improving on the performance of data acquisition and delivery. We validated our method through numerical simulations and real experiments, and showed that all local data-gathering tasks are satisfied and the local buffers do not overflow.
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