Decentralized Leader-Follower Control under High Level Goals without Explicit Communication

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Abstract— **In this paper, we study the decentralized control problem of a two-agent system under local goal specifications given as temporal logic formulas. The agents collaboratively carry an object in a leader-follower scheme and lack means to exchange messages on-line, i.e., to communicate explicitly. Specifically, we propose a decentralized control protocol and a leader re-election strategy that secure the accomplishment of both agents' local goal specifications. The challenge herein lies in exploiting exclusively implicit inter-robot communication that is a natural outcome of the physical interaction of the robots with the object. An illustrative experiment is included clarifying and verifying the approach.**

I. INTRODUCTION

The study of multi-robot systems has received increasing attention over the last decades. Using a group of robots instead of a single one, may yield several advantages, such as increase in capabilities, redundancy, versatility and fault tolerance. Thus, many tasks, like carrying heavy or large payloads, assembling multiple parts without using special fixtures, and handling objects that are flexible or possess extra degrees of freedom, impossible to be executed by a single robot, become feasible.

Ultimately, we would like to use robots not only to execute simple tasks or action primitives, but also to accomplish complex high-level goals involving requirements on safety ("never enter a dangerous region"), surveillance ("keep visiting regions A and B infinitely often"), sequencing ("collect data in region C and upload them in region D"), or their combinations. *Temporal logics* provide a means to express such goals in a rigorous, yet quite user-friendly way [1]. Furthermore, there exist certain computational frameworks that automatically synthesize control strategies, leading to provable satisfaction of a temporal logic formula. Hence, temporal logics seem to be good candidates to specify higher-level semantics of desired robot behaviors. In fact, recently, temporal logic-based planning and control have gained a considerable amount of attention both in single-agent and multi-agent setup [2]–[8].

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However, many new challenges arise in multi-agent planning and control. For instance, when the number of robots becomes large, traditional approaches that rely on centralized control rapidly reach their limits and are prone to individual faults. Therefore, decentralization is necessary. Decentralization is even more crucial in temporal logic planning; centralized approaches for team planning are computationally expensive even for a small number of agents. Unfortunately, though, most decentralized schemes depend on heavy on-line inter-robot explicit communication, which is defined specifically as an act of conveying direct information to other robots in the team (e.g., exchange of control messages or local sensory data), thus resulting in crowded bandwidth and requiring careful planning of communication protocols [9]. On the other hand, implicit communication, that occurs as a side-effect of robots' interactions with the environment or other robots, either physically [10]–[12] (e.g., the interaction forces between a grasped object and a robot) or non-physically [13] (e.g., visual observation), may offer several advantages over the explicit form, such as simplicity, robustness to faulty communication environments, low power consumption and stealthiness. Even though explicit communication, when accurately employed, may yield more effective teams, still, there are tasks for which it is not essential, especially when the implicit form is available, or cases where more complex communication networks may offer little or no benefit at all over implicit communication.

In this paper, we introduce a strategy towards addressing the aforementioned challenging problem. For the time being, we consider two robots collaboratively carrying an object in a leader-follower scheme. Their individual goal specifications are given as Linear Temporal Logic (LTL) formulas. The challenge herein lies in completely replacing explicit with implicit communication, that results indirectly from the physical interaction of the robots via the commonly carried object. In this sense, we develop a decentralized protocol that translates the interaction force/torque measurements into robot (motion) intentions and subsequently employs them in the control design. Since the follower is not aware of the current leader's goal, it tries to keep up towards maintaining the contact stable and getting aligned with the object, via the available interaction force/torque sensory information. Finally, a leader re-election strategy, that is based exclusively on implicit communication, is adopted in order to guarantee the fulfillment of both robots' goal specifications. The main contributions of this work are summarized as follows. The proposed automatic control algorithm: i) guarantees that both high-level goal specifications will be met, ii) employs only implicit communication between the agents and iii) maintains the robot/object contact stable by preventing the object from falling.

A. Related Work

Several distinct approaches have been proposed in decentralized temporal logic-based multi-agent planning. Many of them view the problem from top-down perspective, i.e., a single temporal logic formula is given as a mission specification for the whole team. Typically, the formulas are decomposed into tasks for individual robots and are executed independently [4], or with some level of synchronization [6]. On the other hand, in bottom-up point of view, the agents are given several temporal logic goals, often involving requirements on the other team members' behaviors [5], [8], [14], [15]. In this work, we follow the bottom-up approach and consider local independent formulas. The advantages of the bottom-up viewpoint involve generally better computational efficiency of the planning procedure, less synchronization, and natural incorporation of team heterogeneity and online task reassignments. To the best of our knowledge, this work addresses, for the first time, a scenario with *no explicit communication* between the agents. To satisfy both agents' temporal logic formulas, we employ a leader re-election strategy similarly to [14], where, however, the re-election procedure relies on explicit information exchange.

Related literature on cooperative manipulation involves many works that implement centralized schemes [16], [17] and which inevitably suffer from the drawbacks we mentioned earlier. Other works implement decentralized schemes, which however, depend on heavy explicit communication via exchanging on-line control signals, sensory data and desired trajectories [18], [19]. Decentralized works which make use of implicit communication include [10], [11]. Both papers propose a leader-follower scheme, where the cooperating robots are non-holonomic. In [12] a pushing scenario is considered, where the leader is responsible for the steering angle, while the follower only pushes. However, the system model is not included and as a result, the proposed method is mainly heuristic and does not guarantee convergence in a provable way.

II. Preliminaries

The kinematics of a *non-holonomic mobile robot* moving on a horizontal plane is expressed as follows:

$$\dot{x} = u\cos\theta,\; \dot{y} = u\sin\theta,\; \dot{\theta} = r, \tag{1}$$

where x, y and θ denote the robots' position and orientation with respect to an inertial frame in a bounded *workspace* $\mathbb{W} \subset \mathbb{R}^2$ and u, r denote the robot's linear and angular velocities respectively.

Given a set S, we denote by 2^{S} the set of all subsets of S. Given a finite sequence $\mathsf{s}_1 \ldots \mathsf{s}_n$ of elements of S, we denote by $(\mathsf{s}_1 \ldots \mathsf{s}_n)^\omega$ the infinite sequence $\mathsf{s}_1 \ldots \mathsf{s}_n \mathsf{s}_1 \ldots \mathsf{s}_n \ldots$ created by repeating $\mathsf{s}_1 \ldots \mathsf{s}_n$. We also define a ball-area of radius $r > 0$ centered at a point $c \in \mathbb{R}^2$ by $B_r(c) = \{q \in \mathbb{R}^2 : ||q - c|| \leq r\}$.

Definition 1 (LTL): A *Linear Temporal Logic (LTL) formula* ϕ over *the set of services* Π is defined inductively as follows: (i) every service $\pi \in \Pi$ is a formula and (ii) if ϕ_1 and ϕ_2 are formulas, then $\phi_1 \vee \phi_2$, $\neg\phi_1$, $\mathsf{X}\,\phi_1$, $\phi_1\,\mathsf{U}\,\phi_2$, $\mathsf{F}\,\phi_1$, and $\mathsf{G}\,\phi_1$ are formulas as well, where $\neg$ (negation) and $\vee$ (disjunction) are standard Boolean connectives, and X (next), U (until), F (eventually), and G (always) are temporal operators.

The semantics of LTL are defined over infinite words over 2^Π. Intuitively, an atomic proposition $\pi \in \Pi$ is satisfied on a word $w = \varpi_1\varpi_2\ldots$ if it holds at its first position ϖ_1, i.e. if $\pi \in \varpi_1$. Formula $\mathsf{X}\,\phi$ holds true if ϕ is satisfied on the word suffix that begins in the next position ϖ_2, whereas $\phi_1\,\mathsf{U}\,\phi_2$ states that ϕ_1 has to be true until ϕ_2 becomes true. Finally, $\mathsf{F}\,\phi$ and $\mathsf{G}\,\phi$ are true if ϕ holds on w eventually, and always, respectively. For a full formal definition of the LTL semantics see, e.g. [20].

III. Problem Formulation

We consider two non-holonomic mobile agents carrying an object in a leader-follower scheme on a horizontal plane. Each of them is given a high-level goal that is unknown to the other. Our aim is to automatically synthesize a controller so that both goals are accomplished while the agents communicate solely implicitly.

A. System Model

1) Force/torque dynamics: The non-holonomic nature of the agents increases the difficulty of the object transportation task and restricts the mobility of the overall formation. To tackle this problem, we mount the object on revolute joints on the platforms, to allow relative angular displacements between it and the agents. Both joints as well as the contact between the object and the robot are considered compliant, which enables us to introduce force and torque in the kinematic model of the aforementioned system.

Formally, the kinematics of the two robots are expressed as in Eq. (1). Since we consider a leader-follower scheme, from now on the leading and the following agent will be denoted by the l and f indices, respectively. As it will become clear later, the agents repeatedly exchange their role, hence l and f are not fixed for each agent. Notice that the object is attached to the agents via a compliant contact. The compliance of the considered contact model arises naturally from the elasticity of the object and the compliance of the robots in both the end effector (soft robot tips) and the joints (elastic joints). We denote by L the distance between the two robots. This distance is, indeed, not constant since it depends on the displacement of the compliant contact. We also denote by θ the orientation of the object and by ϕ_i, $i \in \{l, f\}$ the angle displacement between it and the robots:

$$\phi_l = \theta_l - \theta,\; \phi_f = \theta - \theta_f. \tag{2}$$

The exerted force and torque obey an elastic model and depend on the translational δx and angular ϕ_f deformations respectively. In particular, the force is applied on the object's direction and contact is maintained only when the object is squeezed, otherwise it may fall. Its magnitude F is given by a strictly increasing and continuously differentiable nonlinear function of the deformation $\delta x = L_o - L$ as follows:

$$F = \mathbf{F}(\delta x) < \overline{F},\ \frac{\partial \mathbf{F}}{\partial L} < 0, \tag{3}$$

where L denotes the distance of the agents and L_o, which depends on the object geometry, is the nominal inter-robot distance when the deformation and consequently the interaction force is zero. Beside the aforementioned properties, no exact knowledge about the force model is available. On the other hand, the torque is orthogonal to the horizontal plane and its magnitude T is also a strictly increasing and continuously differentiable nonlinear function of the angle ϕ_f:

$$T = \mathbf{T}(\phi_f),\ \frac{\partial \mathbf{T}}{\partial \phi_f} > 0,\ \mathbf{T}(0) = 0. \tag{4}$$

Furthermore, in order to avoid singular configurations, the deformation angle ϕ_f should be kept within the interval $(-\frac{\pi}{2}, \frac{\pi}{2})$. Therefore, even though the exact torque function is considered unknown, we need to estimate the values $\mathbf{T}\left(\pm\frac{\pi}{2}\right)$ that will be employed in the control design to constrain ϕ_f within the aforementioned bounds. Finally, differentiating (3) and (4) with respect to time and substituting (1), we obtain the force/torque dynamics:

$$\dot{F} = \frac{\partial \mathbf{F}}{\partial L}\left(-u_f \cos\phi_f + u_l \cos\phi_l\right) \tag{5}$$

$$\dot{T} = \frac{\partial \mathbf{T}}{\partial \phi_f}\left(-r_f + \frac{u_l \cos\phi_l}{L} + \frac{u_f \sin\phi_f}{L}\right). \tag{6}$$

2) Behaviors: We assume that both robots share a common obstacle-free workspace $\mathbb{W}$ that involves M areas of interest $\mathcal{P} = \{p_1, \ldots, p_M\} \subseteq \mathbb{W}$, where $p_j = B_r(c_j)$ denotes the ball-area or radius r around the point of interest $c_j = [x_j, y_j]^T \in \mathbb{W}$. A set of simple tasks, called *services* Π_1 and Π_2 can be provided by the respective agents in the corresponding areas of interest. Formally, for $i \in \{1, 2\}$, the labeling function $\mathcal{L}_i : \mathcal{P} \to 2^{\Pi_i}$ assigns a set of available services $\mathcal{L}_i(p)$ to each area of interest $p \in \mathcal{P}$ in the workspace. With a slight abuse of notation, we use $\mathcal{L}_i(q_i)$ to denote the labeling of a robot's state $q_i = [x_i, y_i]^T$, such that $\mathcal{L}_i(q_i) = \mathcal{L}_i(p)$ if $q_i \in p$, and $\mathcal{L}_i(q_i) = \emptyset$ otherwise. Furthermore, we define the reverse labeling function $\bar{\mathcal{L}}_i : \Pi_i \to 2^{\mathcal{P}}$, where $\bar{\mathcal{L}}_i(\pi_i) = \{p \in \mathcal{P} \mid \pi_i \in \mathcal{L}(p)\}$ denotes the set of areas where service π_i is available. Without loss of generality, we assume that $\Pi_1 \cap \Pi_2 = \emptyset$.

A *behavior* $\beta_i = (q_i(t), \sigma_i)$ of an agent i is given by its trajectory $q_i(t)$, for all $t \geq 0$ and the sequence of services $\sigma_i = \pi_{i1}\pi_{i2}\pi_{i3}\ldots$ that are *provided* along the trajectory. A behavior is considered valid if there exists a time sequence $t_1 t_2 t_3 \ldots$ with $0 \leq t_{j-1} \leq t_j$ such that $\pi_{ij} \in \mathcal{L}_i(q_i(t_j))$ for all $j \geq 1$.

Definition 2: Behavior $\beta(i) = (q_i(t), \sigma_i)$ *satisfies* an LTL formula ϕ if and only if $\sigma_i \models \phi$.

Intuitively, the sequence of provided services has to comply with the areas of interest that the robot visited along its trajectory. Note however, that σ_i is not the sequence of services that are available in the areas visited along the trajectory. Hence, for instance behavior $\beta_i = (q_i(t), \sigma_i)$ can satisfy $\mathsf{G}\neg\pi$ even if the trajectory $q_i(t)$ leads through a area p, such that $\pi \in \mathcal{L}_i(p)$.

B. Problem Formulation

The control objectives are given for each robot separately as LTL formulas ϕ_1 and ϕ_2 over Π_1 and Π_2 respectively. An LTL formula ϕ_i is satisfied if the behavior of the robot i is $\beta_i = (q_i(t), \sigma_i)$ where σ_i is infinite and satisfies ϕ_i.

Problem 1: Given two non-holonomic mobile robots subject to the leader-follower force/torque dynamics (5)-(6), and two LTL formulas ϕ_1, ϕ_2 over their respective service sets Π_1, Π_2, *achieve* robot behaviors β_1 and β_2 that yield the satisfaction of both LTL formulas ϕ_1 and ϕ_2.

C. Solution Overview

Our approach towards solving Problem 1 consists of three phases that are described in details in Sec. IV.

Phase A: For each agent, we generate a sequence of services that, if provided, guarantee the satisfaction of the respective formula. Using the reverse labeling functions $\bar{\mathcal{L}}_1$ and $\bar{\mathcal{L}}_2$, we find *high-level plans*, i.e. corresponding sequences of areas, called *waypoints*, where these services can be provided. Thus, we decompose the problem of planning under LTL goals into a sequence of reachability control problems for each agent.

Phase B: We arbitrarily denote one of the agents as the leader and the other as the follower. We propose an implicit communication-based leader-follower control scheme that guides the leader in finite time to its next waypoint in its high-level plan while the follower assists it without requesting any explicit feedback.

Phase C: When a waypoint is reached, the corresponding service is provided. The leader is then re-elected and a new reachability goal is set to the next waypoint in the plan. We introduce a systematic switching protocol of the agents' roles, based exclusively on implicit communication, by which we ensure that both agents keep making progress towards their respective LTL goals, i.e. they both gradually visit waypoints in their high-level plans.

IV. Main Results

A. High-Level Plan Generation

The first ingredient of our solution is the high-level plan, which can be generated using standard techniques inspired by automata-based formal verification methodologies. In Section IV-B, we propose a continuous control law that allows the robots to transition between any $p_i, p_j \in \mathcal{P}$ in the given workspace $\mathbb{W}$. Thanks to this and to our definition of LTL semantics over the sequence of provided services, we can abstract the motion capabilities of each robot as a fully connected, labeled transition system $\mathcal{T}$ whose states are the areas of interest $\mathcal{P}$. The given LTL formula ϕ_i is translated into a Büchi automaton $\mathcal{A}_i$. Then, a product of $\mathcal{T}$ and $\mathcal{A}_i$ is built, viewed a graph and analyzed using graph search algorithms. Loosely speaking, an accepted run of the automaton is projected directly onto a sequence of services to be provided and hence onto a sequence of *waypoints* to be visited. Although the semantics of LTL is defined over infinite sequences of services, it can be proven that there always exists a high-level plan that takes a form of finite waypoint sequence followed by an infinite repetition of a finite service/waypoint sequence. More details on the technique are beyond the scope of the paper and we refer the reader to related literature, e.g., [20].

Following the aforementioned methodology, we obtain a *high-level plan* for each robot as sequences of waypoints and services $\varsigma_i = (p_{i1} \dots p_{iN})(p_{iN+1} \dots p_{iN+M})^\omega$ and $\sigma_i = (\pi_{i1} \dots \pi_{iN})(\pi_{iN+1} \dots \pi_{iN+M})^\omega$, $i \in \{1, 2\}$ where $p_{ij} \in \mathcal{P}$ and $\pi_{ij} \in \mathcal{L}_i(p_{ij})$, for all $i \in \{1, 2\}$, $j \in \{1, \dots, N+M\}$ and a finite $N, M \in \mathbb{N}$.

B. Continuous Control Design

1) Control Objectives: The leader's control objective is to arrive at an area of interest $B_r(c_d)$, that corresponds to a particular *waypoint* in the workspace given by the high-level plan, with close to zero orientation[1]. In this sense, a control scheme that guarantees the stabilization of a unicycle model at c_d will be adopted. In particular, we shall employ a well-established closed loop steering control law for unicycle-like vehicles, originally presented in [21], that drives the leader within the area of interest $B_r(c_d)$ in finite time with close to zero orientation. On the other hand, since the follower does not know the position and orientation goal of the leader, we shall design a control law that is based on implicit feedback from the force and torque induced by the motion of the leader at the follower's side, and which are measured by a force/torque sensor appropriately mounted at the object-robot contact.

More specifically, the follower's force goal is to keep F almost constant close to a desired value F_d. The satisfaction of this goal establishes sufficient internal force to secure the stability of the contact. It also guarantees safety by limiting excessive forces. In this sense, the aforementioned goal may be formulated as $0 < F(t) - F_d < \rho_f(t) < \overline{F} - F_d$, where $\overline{F}$ is the maximum allowed force and $\rho_f(t)$ is a positive and decreasing function of time, called performance function [22], that incorporates the desired transient and steady-state performance specifications. A common choice is an exponentially decaying function $\rho(t) = (\rho_o - \rho_\infty)e^{-kt} + \rho_\infty$. Moreover, to ensure that contact is not lost, $F(t) - F_d$ is only allowed to be positive. Hence, defining $e_f(t) = F(t) - F_d - \frac{\rho_f}{2}$, the force goal may be written equivalently in a compact form as:

$$|e_f(t)| < \frac{\rho_f(t)}{2}. \tag{7}$$

Regarding the torque, the follower should keep it close to zero in order to align itself with the object. Additionally, the torque should not be allowed to reach $\mathbf{T}\left(\pm\frac{\pi}{2}\right)$, in order to avoid singular configurations. Similarly, adopting a performance function $\rho_\tau(t)$ and defining $e_\tau(t) = T(t)$, we express the torque control objective as:

$$|e_\tau(t)| < \rho_\tau(t) < \left|\mathbf{T}\left(\pm\tfrac{\pi}{2}\right)\right|. \tag{8}$$

2) Control Scheme: Selecting appropriate performance functions $\rho_f(t)$, $\rho_\tau(t)$ that: i) satisfy $\rho_f(0) > 2|e_f(0)|$ and $\rho_\tau(0) > |e_\tau(0)|$ as well as $\rho_f(t) < \overline{F} - F_d, \forall t \geq 0$ and $\rho_\tau(t) < \mathbf{T}\left(\pm\frac{\pi}{2}\right), \forall t \geq 0$ and ii) incorporate the desired transient and steady state performance specifications, we design the following input velocities:

$$u_f = -k_f \ln\left(\frac{1+\frac{2e_f}{\rho_f(t)}}{1-\frac{2e_f}{\rho_f(t)}}\right),\ r_f = k_\tau \ln\left(\frac{1+\frac{e_\tau}{\rho_\tau(t)}}{1-\frac{e_\tau}{\rho_\tau(t)}}\right) \tag{9}$$

where k_f, k_τ are positive control gains. In contrast to most decentralized schemes, the proposed one is independent of leader's velocity inputs u_l, r_l. Thus, no explicit communication is needed. However, the trade-off for this lack of knowledge (i.e., guaranteed ultimate boundedness of force-torque errors instead of asymptotic stability) is compensated by the appropriate selection of $\rho_{f\infty}$ and $\rho_{\tau\infty}$ that dictate convergence to an arbitrarily small predefined residual set of magnitude equal to $\rho_{f\infty}$ and $\rho_{\tau\infty}$. The following lemma (its proof is similar to [22]) summarizes the main results of this subsection.

Lemma 1: Consider the force-torque dynamics (5) and (6). Given a bounded leader's velocity u_l, the control scheme (9) guarantees (7) and (8) for all $t \geq 0$.

C. Leadership Switching based on Implicit Communication

An extra issue to be discussed herein is how to select the leader after a certain task has been accomplished (i.e., which agent should be assigned the leadership). We propose to adopt a decentralized decision scheme according to which the agent with the shortest/closest task should claim the leadership. However, relying only on a distance criterion is not truly "fair", especially in cases where each agent's tasks are collected in distant and disjoint areas. In this way, only one agent would gain the leadership repeatedly, since the other's goals are far away. Thus, we have to make a trade-off between time efficiency and "fairness" such that all individual goals of both agents are eventually accomplished. Therefore, a "racing" algorithm should be adopted after a task is fulfilled, based on which both agents will claim the leadership in a time interval that is proportional to the distance from their next task as well as to the number of consecutive times they have been leading the formation until then. Hence, the agent that has not been leading much lately, with a relatively close task as well, will ultimately be getting the leadership. In this way, we formulate for each agent the following "racing" criterion:

$$C_i = W_1 \|q_i - q_{i_d}^{Next}\| + W_2 N_i^{Led},\ i = 1, 2 \tag{10}$$

where W_1, W_2 are positive weights, favoring either the efficiency or the "fairness" of the criterion, q_i, $q_{i_d}^{Next}$ are the current state and the next *waypoint* according to the agents' individual task specifications and N_i^{Led} denotes the number of successive leaderships of each agent until now.

[1] Such specification turns out to be equivalent to any desired orientation via a simple rotation of the workspace with the corresponding angle.

It should be noticed that in order to apply properly the aforementioned "racing" algorithm after a task has been fulfilled, the agents have to be synchronized first. Nonetheless, explicit communication, which is the easiest way to achieve it, is not feasible in our work. Thus, the synchronization should be accomplished via implicit communication through the physical interaction of the agents. However, such implicit information should be acquired independently of the force/torque measurements that are employed by the follower's scheme to cooperate with the leader (i.e., the force along the object and the torque around the vertical axis), since otherwise an implicit "misunderstanding" would occur. In this sense, we propose to use the measurement of the force exerted at the follower's side by a periodic rotation of the leader around itself (i.e., a force applied at the follower/object contact normally to the object and consequently to the force employed in its control scheme). Such motion primitive does not affect the follower's motion, since it does not change the force/torque feedback employed in its control scheme (notice that the force/torque dynamics expressed in (5)-(6) do not involve the leader's rotational velocity).

Hence, a leadership switching strategy based solely on implicit communication is formulated as follows:

I. *The current leader, after having accomplished its task, starts rotating periodically with a predefined frequency F_{syn} around itself for a certain prespecified time $T_{syn} > \frac{2}{F_{syn}}$.*

II. *The follower measures the exerted force and detects the time instant at which the leader stopped rotating by observing when the Maximum Likelihood frequency estimate index $C_{ML}(\omega)$ is maximized [23], for a given frequency $\omega_{syn} = 2\pi F_{syn}$ within a set of N force measurements (i.e., $f_m[i]$, $i = 0, \ldots, N-1$) in a moving window of T_{syn} duration, where:*

$$C_{ML}(\omega) = \frac{a_{22}(\omega) I^2(\omega) - 2a_{12}(\omega) I(\omega) Q(\omega) + a_{11}(\omega) Q^2(\omega)}{a_{11}(\omega) a_{22}(\omega) - a_{12}^2(\omega)}$$

with $I(\omega) = \sum_{i=0}^{N-1} f_m[i] \cos(i\omega)$, $Q(\omega) = \sum_{i=0}^{N-1} f_m[i] \sin(i\omega)$, $a_{11}(\omega) = \sum_{i=0}^{N-1} \cos^2(i\omega)$, $a_{12}(\omega) = \sum_{i=0}^{N-1} \sin(i\omega)\cos(i\omega)$ *and* $a_{22}(\omega) = \sum_{i=0}^{N-1} \sin^2(i\omega)$.

III. *After T_{syn} time, the leader stops rotating and the follower has been synchronized with it via Step **II**. Subsequently, both agents wait in follower mode for C_i time respectively, as defined in (10), until the one with the shorter criterion gains the leadership.*

Remark 1: Notice that the only information that should be agreed between the agents consists in the synchronization parameters F_{syn} and T_{syn}, which, however, can be easily attained at the beginning, before starting the execution of their plans. Moreover, the computation of the ML frequency estimator C_{ML} involves very few and simple calculations and thus can be implemented on-line without introducing further delays.

D. Algorithm Analysis

The subsequent theorem summarizes the main results of this work:

Theorem 1: Following the three Phases A, B and C of the solution, we achieve robot behaviors that are both infinite and satisfy ϕ_1 and ϕ_2 respectively.

Proof: Owing to the correctness of well-established algorithms for finding high-level plans described in Phase A, it is sufficient to prove that Phases B and C ensure that the plans are executed. In Phase B, we have proven that the desired area $B_r(c_d)$ is reached in finite time. Furthermore, Eq. 10 in Phase C guarantees that for any time instant t, when $C_1 < C_2$, there exists $t' > t$ such that $C_2 < C_1$ and vice versa, (i.e., if $C_2 < C_1$ at t, then $C_1 < C_2$ at $t' > t$). Thus, each agent becomes leader infinite times and remains leader till it reaches its next desired area $B_r(c_d)$ (i.e., the next *waypoint* of the high-level plan). Therefore, we conclude that both agents visit the prescribed *waypoints* infinitely many times and hence their behaviors satisfy ϕ_1 and ϕ_2. ■

V. Experimental Results

The experimental setup involves two *ActivMedia Pioneer 2* mobile robots (namely Agent-A and Agent-G) interconnected with a long rod (i.e. the carried object) via a compliant mechanism consisting of a linear and a torsional spring. The robots are equipped with a 6 DoF Force - Torque Sensor that measures the corresponding interaction forces and torques. For ground truth measurements, a vision system consisting of a PS3 calibrated camera is being used. The camera is mounted on the ceiling, monitoring the whole workspace, and each mobile robot is equipped with a distinct marker positioned on its top.

The workspace is depicted in Fig. 1(a). Agent-A, who is initially the leader and the trace of which is illustrated by green line, should keep picking up products of type A in P1, P4 and P5 (marked by squares in Fig. 1) sequentially. On the other hand, Agent-G should repeatedly pick up products of type G in points P2 and P3 (marked by circles), in an arbitrary order. The corresponding LTL formulas are given as follows: $\phi_1 = \mathsf{G}\,\mathsf{F}\,(P_{11A} \wedge \mathsf{X}(P_{14A} \wedge \mathsf{X}\, P_{15A})))$ and $\phi_2 = \mathsf{G}\,\mathsf{F}\, P_{22G} \wedge \mathsf{G}\,\mathsf{F}\, P_{23G}$. We used the off-the-shelf tool called LTL2BA [24] to obtain a Büchi automaton and we implemented graph analysis of the corresponding automaton in MATLAB. The resulting high-level plans for the robots are $\varsigma_1 = (P1\ P4\ P5)^\omega$, $\sigma_1 = (P_{11A}\ P_{14A}\ P_{15A})^\omega$, $\varsigma_2 = (P2\ P3)^\omega$, $\sigma_2 = (P_{22G}\ P_{23G})^\omega$. The resulting trajectories are illustrated in Fig. 1. Notice that the leadership switches after Agent-A has visited P1 (Fig. 1(b)) and subsequently P4 (Fig. 1(c)), even though P5, which is its next goal, is closer than the goal of Agent-G (i.e., P2) owing to the fact that Agent-A was the leader two consecutive times. The same also happens after Agent-G has visited P2 (Fig. 1(d)) and P3 (Fig. 1(e)), when Agent-A regains the leadership and visits its subsequent point P5 (Fig. 1(f)). As it was predicted by the theoretical analysis, all tasks of both agents are fulfilled without necessitating any explicit communication between them during the operation. Finally, the accompanying video demonstrates clearly the efficiency of the proposed methodology.

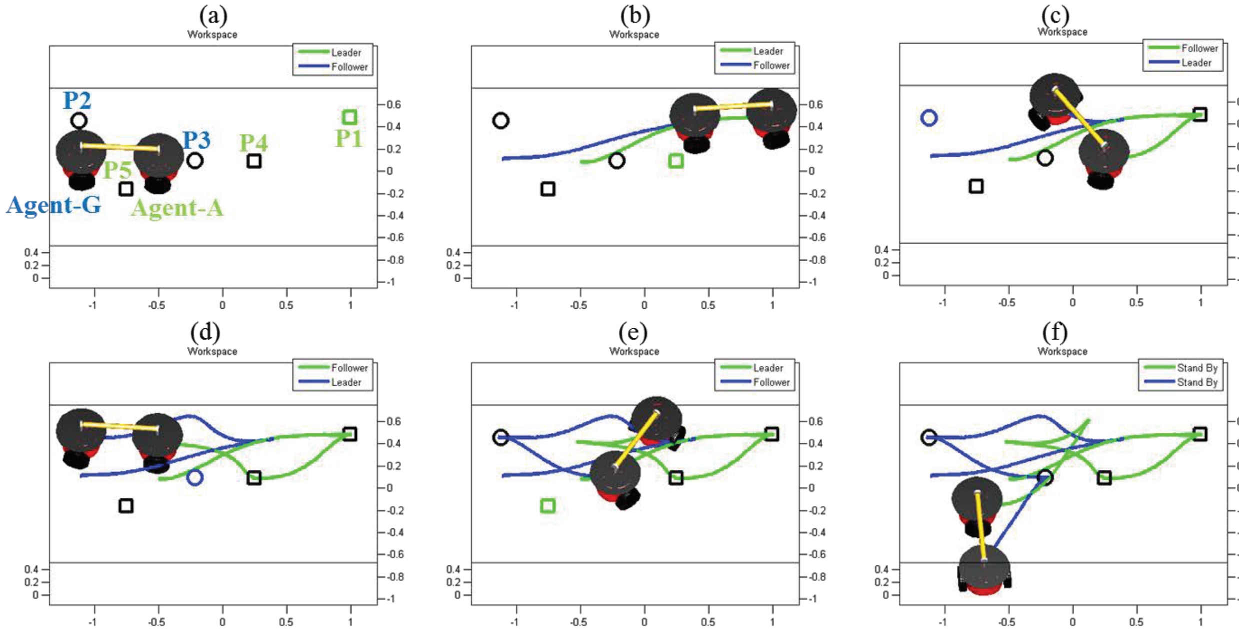

Fig. 1. The evolution of the proposed methodology in 6 consecutive time instants. In each subplot, the leadership is presented in the legend and the current goal is highlighted with the appropriate color (green for Agent-A and blue for Agent-G).

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