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Brief paper

A team-based approach for coverage control of moving sensor networks☆

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ABSTRACT

The present paper proposes a new team-based approach that allows for forming multiple teams of agents within the coverage control framework. The objective function defined for this purpose tends to minimize the accumulative distance from each agent while reckoning with the given density function that defines the probability of events in the environment to be covered. The proposed team-based approach via the defined optimization problem allows for forming teams of agents when for a variety of reasons, e.g., heterogeneity in their embedded communication capabilities or the dynamics, it is required to keep the similar agents together in the same team. To realize this, the overall objective function is defined as the accumulated sensing cost of individual agents belonging to different teams. The defined collective cost function captures the interdependency of the team's Voronoi cells on the position of the agents that can be viewed as the impact of the dynamic boundaries on the agents. A gradient descent-based controller is designed to ensure the locally optimum configuration of the teams and agents within each team. The convergence of the proposed method is studied to ensure the stability of the implemented controller in both teams and agents final configuration. In addition, a new formation control approach is proposed using the team-based framework to impose either the same or different formation structures while performing the underlying coverage task. It is shown that maintaining the desired configuration through the proposed formation control is achieved at the cost of sacrificing the sensing performance. Finally, the proposed coverage and formation methods are examined via a numerical example where multiple heterogeneous teams of agents with potentially different number of agents are deployed.

1. Introduction

There have been advancements in developing techniques for deploying a group of robots in a given environment to perform assigned distributed tasks within the coverage framework. Examples of such tasks include surveillance, search and rescue operations, sensing, and data collection (Atınç, Stipanović, & Voulgaris, 2014; Lee, Diaz, & Egerstedt, 2015; Nowzari & Cortés, 2012). The previous works neglect the fact that the partitioning might be subjected to other constraints like the deployment of robots with various communication range or different embedded sensory devices. Furthermore, it might be required to assign different tasks with respect to the robots capability or even deploy robots in groups of agents each of which should carry out a specific task while collaborating with other agents. The existing approaches for the coverage control are based on the assumption that all agents belong to a single team (Patel, Frasca, & Bullo, 2013). The traditional Voronoi cells and their underlying objective function divide the main region among the agents as there are multiple individual agents with no consideration of their potential differences. However, this assumption is not realistic in many real-world applications, as the agents may differ from, e.g., dynamics or communication perspective (Sharifi, Chamseddine, Mahboubi, Zhang, & Aghdam, 2015; Stergiopoulos & Tzes, 2013). A multi-robot system can generally be considered as a homogeneous or heterogeneous system depending on the similarities or differences in their properties, e.g., desired performance index, dynamics, etc., that is required when coping with various complex assigned tasks as in Kantaros, Thanou, and Tzes (2015) and Song, Liu, Feng, and Xu (2016). As an example, it might be necessary to deploy agents equipped with different sensors to collect various types of data from the environment. In addition, the heterogeneity in dynamics may affect the relative distance of the

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agents leading to a communication loss or sensing performance degradation. Hence, new flexible frameworks are needed to ensure that different types of heterogeneous agents can be utilized and operated in a distributed manner in an unknown, unstructured environment.

In the present work, a new coverage strategy is proposed that aims at taking into account the differences in the robots dynamics by offering a team-based design approach, where, each robot might team up with others based on its assigned task, associated dynamics or embedded communication capabilities. A different paradigm to tackle this problem is to define a two-level optimization problem at the teams and agents level independently (Abbasi, Mesbahi, & Velni, 2016). However, this framework neglects the dependency of the team boundaries on the position of the agents. Also, the proposed optimization problem does not account for imposing certain local formations. In the present paper, the underlying optimization problem is defined in such a way that it can allow for partitioning the teams and the agents collectively. This translates to taking into account the dependency of the teams' Voronoi cells on the position of the agents. This would make it possible to improve reliability and flexibility of the deployment algorithm. Throughout this work, it is assumed that the structure of the teams and the agents within each team is known a priori. The proposed approach addresses the problem of agents deployment by considering teams of robots instead of evaluating each agent individually. The agents in each team can be classified into two groups of interior members and members on the boundaries based on whether or not they share a boundary with the agents belonging to other teams.

As an application of the proposed team-based method, we study formation control problem via introducing a formation term into the performance function. The additional term ensures a certain distance from the nucleus by changing the formation factor. This factor enforces the agent to either expand or compress with respect to the desired formation. Different formations can be also achieved through selection of various formation factors.

The contributions of the present work are threefold. First, it is shown that incorporating the team concept into the coverage related tasks facilitates the deployment of multiple heterogeneous agents to handle multiple assigned tasks. Second, the agents can be allocated over a region in various teams with (possibly) different number of members each to address different scenarios like the case where a higher number of agents are needed to accomplish a certain assigned task. Finally, the proposed framework enables to impose local formations by giving a number of agents a team entity. This stems from the inevitable existence of constraints or certain objectives in practice, e.g., the limited communication radius or the need for a better coverage by maintaining a certain formation while ensuring an optimal coverage through collaborating with other teams.

The remainder of this paper is structured as follows. Definitions and the problem statement are provided for the team-based coverage control in Section 2. Section 3 introduces an approach for formation control. Section 4 presents numerical simulation results to illustrate the team-based partitioning and formation control.

1.1. Notations

We use $\mathbb{N}$, $\mathbb{R}$, and $\mathbb{R}_+$ to respectively denote the sets of natural, real, and nonnegative real numbers. Throughout the paper, I_r denotes $r \times r$ identity matrix. We define Q as a convex polytope in $\mathbb{R}^2$ and let $\mathcal{Q} = \{Q_1, Q_2, \dots, Q_t\}$ be a *partition* of Q as a collection of t closed subsets with disjoint interiors. The boundary of Q is denoted by ∂Q. Moreover, the so-called *distribution density function* is denoted by φ where $\varphi : Q \to \mathbb{R}_+$ represents the probability of some phenomenon occurring over space Q. The function φ is assumed to be measurable and absolutely continuous. The Euclidean distance function is denoted by $\|\cdot\|$, and $|Q|$ represents the Lebesgue measure of convex subset Q. The vector set $\mathcal{P}_t = (p_{t1}, p_{t2}, \dots, p_{tn_t})$ is the location of n_t agents belonging to tth team.

2. A team-based approach for coverage control

In this work, we present a modified version of the locational function that is suitable for the proposed team-based method. The team-based partitioning of the agents introduced in this paper addresses this by dividing agents into multiple teams pursuing assigned tasks.

2.1. Voronoi partitions

The main objective of this work is to adopt a team-based concept in the agents deployment and partitioning framework. To achieve this, we first need to define an optimization problem that can handle not only the deployment and partitioning tasks inside teams but also the partitioning inside the defined polytope Q. This optimization problem should consider the agents individual cost function, as well as their accumulated cost within their teams. To start with, we define the set of teams by $\mathcal{L} = (l_1, l_2, \dots, l_n)$ where $l_t, t = 1 : n$, represents the nucleus of the tth team that is a function of the agents position in the associated team, i.e., $l_t = g(p_{t1}, p_{t2}, \dots, p_{tn_t})$. The dependency of l_t on the position of the agents is discussed later. Next, we partition the polytope Q into a set of Voronoi cells $\mathcal{V}(\mathcal{L}) = \{V_1, V_2, \dots, V_n\}$ considered as the optimal partitioning for a set of agents with fixed locations at a given area as $V_t = \{q \in Q \mid \|q - l_t\| \le \|q - l_s\|, s = 1, \dots, n; s \ne t\}$. The obtained Voronoi cells associated with the nuclei of the teams are then considered as the convex polytope set to deploy their associated agents. Therefore, the sub-partitions are defined on the basis of the Voronoi cells V_t obtained from the team level partitioning. The Voronoi partitions $\mathcal{V}_t(\mathcal{P}_t) = \{V_{t1}, V_{t2}, \dots, V_{tn_t}\}$ generated by the agents $(p_{t1}, p_{t2}, \dots, p_{tn_t})$ belonging to the tth team are defined as

$$V_{tm} = \{q \in V_t \mid \|q - p_{tm}\| \le \|q - p_{tr}\|, r = 1, \dots, n_t, r \ne m\}, \quad (1)$$

where p_{tm} denotes the location of mth agent in tth team for $m \in \{1, \dots, n_t\}$. The agents in each team are divided into two subgroups, boundary and interior groups, where the cells associated with each group require a different set of data, i.e., their neighbors' position, to be maintained. The interior group represents the agents that share boundaries only with the agents belonging to the same team while the agents in the boundary group have neighbors not only in the same team but also in the neighboring teams—they may also share boundaries with the convex polytope Q. In general, a boundary associated with each agent ∂V_{tm} is either an edge shared with the agents within the same team or edges shared with the teams in the neighborhood depending on the position of the agent within the team. The agents in the boundary group share at least one edge with other teams. An edge that is shared with the neighboring agent f in the same team is shown by $\partial V_{tm,f}$. The edges associated with the agents in the boundary group shared with the neighboring team k and the main convex polytope Q are represented by ∂V_{tb}^k and ∂V_{tb}^0, respectively. Fig. 1 illustrates the boundaries and their normal vectors for Voronoi V_{tm}. It is noted that the agents in the boundary group may share boundaries with the agents in the interior group where the same notation as the boundaries of the interior agents is used to represent these edges. We recall the basic characteristics of the Voronoi partitions including their associated mass and centroid defined as $M_{V_{tm}} = \int_{V_{tm}} \varphi(q) \mathrm{d}q$ and $C_{V_{tm}} =$