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Single landmark based collaborative multi-agent localization with time-varying range measurements and information sharing ☆

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ABSTRACT

This paper considers the collaborative localization problem for a team of mobile agents. The goal is to estimate the relative coordinate of each agent with respect to a stationary landmark. Each agent is supposed to be able to measure its own velocity and the distances to nearby agents as well as the change rates of the distances. Due to limited sensing capability, movements of agents and possible interference of severe environments, the topology describing the measurements and communication information flow among the agents and the landmark is usually time-varying. Under such a scenario, this paper develops a consensus-like fusion scheme together with a continuous-time estimator for the collaborative localization problem. It is proved that the fused estimate of each agent's position globally asymptotically converges to its true value if the movements of the agents satisfy a persistent excitation condition and each agent is uniformly jointly reachable from the landmark in the time-varying topology. The effectiveness of the proposed scheme is verified through simulations without and with measurement noises.
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1. Introduction

Recent advances in computing, communication, and sensing, have made it feasible to envision large numbers of autonomous vehicles working cooperatively to accomplish a task ranging from defense, surveillance, environment monitoring to search and rescue. Usually, the vehicles' location information is vital for location-aware applications. Although Global Positioning System (GPS) is usually used for precise navigation as it provides absolute position information, there are situations such as sky occlusion, hardware failure and GPS jamming, which may inhibit the use of GPS [1]. On the other hand, for low-cost mobile platforms, it may be infeasible to equip with GPS. Moreover, in many situations (e.g., formation control [2]), localizing mobile agents with respect to a common landmark or a leader agent rather than in a global coordinate system is competent. These observations motivate us to study the localization problem with respect to a single landmark.

Existing works study either localizing targets of common interest or self-localization of agents. Localization algorithms can be categorized into two classes depending on whether the network is static or mobile. The first class is concerned with static networks such as sensor networks where sensor nodes keep stationary once deployed. For the self-localization problem, the goal is to determine the Euclidean positions of all nodes in the network based on the knowledge of the positions of a few anchor nodes and inter-agent measurements (e.g., distance, bearing, RSSI, etc.). In the two dimensional space, generally two or three anchor nodes are required for the group of static sensors to locate themselves [3–7]. For the problem of localizing a target of interest, a cluster of static nodes works collaboratively to estimate the location of a target (e.g., a jammer in sensor networks [8]). The second class focuses on a network of mobile agents. For the self-localization problem, mobile agents use one or several landmarks as references to locate themselves. But for the problem of localizing a target of interest, a cluster of mobile agents seeks to determine the coordinate of the target either in a global coordinate system or in their local coordinate systems. For both problems in a mobile setting, the agents utilize relative measurements (distance, bearing, or

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distance plus bearing) from their exteroceptive sensors (e.g. lasers, cameras, etc.) together with their motion information (velocity and turning rate) from interoceptive sensors such as wheel encoders, accelerometers, gyroscopes, etc. [9–16].

This paper falls into the second class and aims to solve the collaborative localization problem of a group of mobile agents with respect to a single landmark. Towards this goal, this paper develops a cooperative estimation scheme for each mobile agent to locate itself, i.e., estimating the relative coordinates of each agent with respect to a stationary landmark. Different from static networks of agents, a mobile agent is able to localize itself with only one landmark, e.g. [17–19]. As a dual problem, a single mobile agent is capable of localizing a target of interest as well [9,20,21]. However, essentially speaking, [17] still utilizes two landmarks (one real and one virtual) while [18] requires both distance and bearing measurements. Moreover, different from most of the existing works (e.g., [14,17–21]), which require to know the absolute positions of landmarks or mobile agents, this paper requires no absolute information but only local measurements. Besides, collaborative localization using multiple mobile agents provides several potential advantages over using single mobile agent, including increased localization accuracy and coverage areas, robustness, and flexibility in case of limited sensing ranges and possible measurement failures due to severe environments. Compared with the probabilistic approach for cooperative localization [15,22,23] and the discrete-time Kalman filter approach to simultaneous localization of a group of mobile robots [12,13], the focus of this paper is on the deterministic and continuous-time aspect. Unlike our earlier work [10], which focuses on how to use a team of mobile agents to localize a target of interest under a fixed topology assumption, this paper addresses the collaborative localization problem under a time-varying topology, which is more challenging.

In this paper, every agent is equipped with onboard interoceptive sensors for the measurement of its own absolute velocity and exteroceptive sensors for the measurement of distances to its nearby agents and the change rates of the distances. Every agent has a local inertial frame attached to its body and the orientation of every agent's local frame is the same as that of the landmark. Moreover, it is assumed that the nearby mobile agents can communicate with each other, but the landmark is silent. We abstract a group of mobile agents together with the landmark as a set of nodes, and then use a directed graph to indicate that an agent i has a relative measurement to another agent j and can receive information from it as well if there is a directed edge connecting from node j to node i. Due to possible measurement failures or possible movements of the agents outside of the sensing range about their neighbors, the directed graph describing the information flow relationship is time-varying. Here we assume the communication between neighboring agents is with acknowledgment receipts going backwards. In this way, an agent knows when its neighboring agents lose track of the information stream and when the information stream is recovered. But it should be noted that the acknowledgment going backward is used only to indicate the status of a communication link, while the main stream of the valuable information goes the way as indicated in the directed graph. It can have certain benefits (saving communication energy for example) when compared with bidirectional communications. Therefore, in this paper, we use the directed graph model to indicate the main stream of information exchange excluding the acknowledgments. To deal with the collaborative localization problem in such a scenario, we first propose a continuous-time estimator for each agent to estimate its relative position with respect to its neighbors by utilizing the distance and change rate measurements, the velocities of itself and its neighbors, and the displacements of neighbors during the intervals when the distance and change rate measurements are lost. Second, a consensus-like fusion scheme is developed for every agent to localize itself with respect to the landmark by fusing the estimate of its own position with respect to the landmark using the range measurements about the landmark when available and the estimates of its position with respect to its neighbors. By doing so, the agents, which are not able to directly measure the distance to the landmark, can also locate itself with the help of its neighbors.

We summarize the major contributions of this work as follows: (1) Different from most existing works that require the knowledge of the absolute positions of some landmarks or agents, this paper develops a collaborative localization scheme to estimate the relative coordinates of a group of mobile agents with respect to a single landmark utilizing only local measurements and limited local information exchange between nearby agents. Thus, the localization scheme is fully distributed. (2) This paper addresses collaborative localization in a very general setting that the information flow graph among the neighboring agents is unidirectional and time-varying to reflect the practical concerns of neighbor changes and measurement failures over time. However, asymptotic convergence of the proposed collaborative localization scheme is still ensured if the information flow graph has the property of being sufficiently connected over time. (3) It is proved that with the collaborative localization scheme proposed in this paper, each agent can have an uninterrupted estimation of its relative coordinate with respect to the landmark even when it does not have any relative measurements about the landmark or its neighbors. (4) The collaborative localization scheme proposed in this paper works not only in the two dimensional space but also in the three dimensional space.

2. Preliminaries and problem formulation

In this section, we first introduce basic notions of graphs, which will be used later. Then the collaborative localization problem is formulated.

2.1. Preliminaries

Let $\mathbb{R}^{n\times n}$ be the set of $n \times n$ real matrices. The superscript T represents the transpose of a real matrix. I_p represents the identity matrix of dimension p. Matrices with nonnegative off-diagonal elements are referred to as Metzler matrices [24]. The matrix inequality $A > (\geq) B$ means that $A - B$ is positive (semi-) definite. $A \otimes B$ denotes the Kronecker product of matrices A and B. For a vector x, $\|x\|$ denotes its 2-norm. For a finite set $\mathcal{S}$, $|\mathcal{S}|$ denotes the cardinality of $\mathcal{S}$.

A directed graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$ consists of a non-empty finite set $\mathcal{V} = \{v_1, \ldots, v_n\}$ of elements called nodes and a finite set $\mathcal{E} \subseteq \mathcal{V}\times\mathcal{V}$ of ordered pairs of distinct nodes called edges. A walk in a graph $\mathcal{G}$ is an alternating sequence $\mathcal{W} : v_1e_1v_2e_2 \cdots v_{k-1}e_{k-1}v_k$ of nodes v_i and edges e_i such that $e_i = (v_i, v_{i+1})$ for every $i = 1, 2, \ldots, k-1$. We call $\mathcal{W}$ a walk from v_1 to v_k. Let $\mathcal{R} \subset \mathcal{V}$ be a subset of nodes in $\mathcal{G} = (\mathcal{V}, \mathcal{E})$. A node $v \in \mathcal{V} - \mathcal{R}$ is said to be reachable from $\mathcal{R}$ if there exists a walk from a node in $\mathcal{R}$ to v.

The set of neighbors of node i is denoted by $\mathcal{N}_i = \{v_j \in \mathcal{V} : (v_j, v_i) \in \mathcal{E}, j \neq i\}$. The Laplacian matrix $L_{\mathcal{G}} = [l_{ij}] \in \mathbb{R}^{n\times n}$ of $\mathcal{G}$ is defined as $l_{ii} = |\mathcal{N}_i|$, $l_{ij} = -1$ if $j \in \mathcal{N}_i$ and $l_{ij} = 0$ otherwise.

When the edge set in a directed graph changes over time, we call it a time-varying graph, denoted as $\mathcal{G}(t) = (\mathcal{V}, \mathcal{E}(t))$. For a time-varying graph $\mathcal{G}(t) = (\mathcal{V}, \mathcal{E}(t))$, a node v is said to be *uniformly jointly reachable* from $\mathcal{R} \subset \mathcal{V}$ if there exists $T > 0$ such that for all t, v is reachable from $\mathcal{R}$ in the union graph $\mathcal{G}([t, t+T])$, whose edge set is the union of the edge set of $\mathcal{G}(t)$ over the time interval $[t, t+T]$. An example is given in Fig. 1, for which v_3 is uniformly jointly reachable from v_1, since we can take $T = 2$ and then for any t the union graph $\mathcal{G}([t, t+T]) = \mathcal{G}_1 \cup \mathcal{G}_2$.

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