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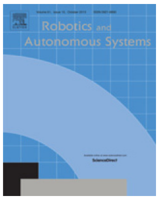

Distributed cooperative localization with lower communication path requirements

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HIGHLIGHTS

- The cross-covariance maintenance is well-organized in distributed manner.
- The missing quantity of cross-covariance update is corrected.
- One-way broadcast communication is enough for the proposed algorithm.
- More alternative communication topologies are suitable for the proposed algorithm.

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ABSTRACT

Free communication topology for cooperative localization cannot be guaranteed in real scenarios. A flexible distributed algorithm aiming at reducing communication path requirements is presented under EKF. In this algorithm, not all agents need to communicate with each other instantaneously for covariance update and it has no adverse effect on state update. We prove that the missed covariance update caused by communication absence can be exactly corrected when it is required. Additionally, we prove that this algorithm is adaptive to most available one-way communication topologies. The equivalent localization performance to free connection communication is achieved.

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1. Introduction

Multi-agent cooperative work is growing in popularity for exploring, monitoring, rescuing [1–4] and so on. Accurate localization is prerequisite for implementing these tasks. It is known that cooperative localization (CL), using both the proprioceptive measurement (e.g., acceleration, velocity) and the exteroceptive measurement (e.g., relative distance/bearing), can achieve more reliable and precise localization than one agent alone [5]. For instance, in the urban canyon, Global Positioning System (GPS) may be unavailable to some agents, then the GPS information from other agents can be shared by all agents [6–8]. Another example is that the high- and low-precision localization equipments are mounted on different agents in order to reduce the cost, where the localization of the low-precision equipment can be improved from the high-precision equipment [9–12]. For these sakes, CL has attracted significant interest in mobile multi-agent community.

Due to different geographical position or hardware level, not all agents in a team can obtain the exteroceptive measurements simultaneously. In this paper, the agent obtaining exteroceptive measurements is called as the **measuring agent**; otherwise, as the **non-measuring agent**. Each agent occasionally measures the relative pose to the others in range.

Communication network is the infrastructure for sharing the measurement benefit. As Fig. 1(a), free connection communication is a common assumption for most CL algorithms. Unfortunately, it cannot be guaranteed in realistic scenarios. For instance, (1) communication path is easy to be interrupted by the poor environment; (2) confined to the communication range, agents cannot communicate with the distant ones [13]; (3) communication topologies preferentially satisfy the higher-level tasks but not the CL [14].

For the challenges, firstly, the communication path requirements must be low; secondly, CL algorithm must be flexible enough to adapt the available communication topologies. Motivated by these considerations, we design a novel CL algorithm where each agent can benefit from the measuring agent as long as there is an one-way communication path between them; see Fig. 1(b). The application scenes are enlarged by the proposed

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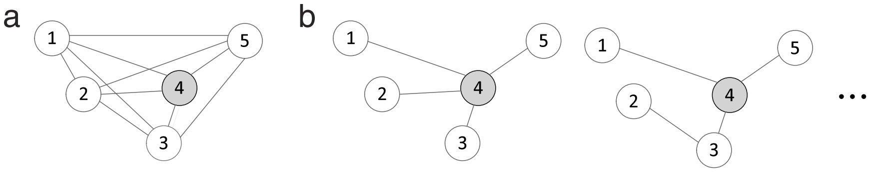

Fig. 1. Illustration of communication path requirements in cooperative localization. Agent 4 (darker shaded node) is the measuring agent at the current time. The unshaded nodes represent the non-measuring agents. The solid line denotes a communication path. (a) Full connection communication topology. (b) Various alternative communication topologies suitable for our algorithm.

algorithm. For instance, (1) one-way broadcast network, (2) Ad hoc network (autonomy without communication management), (3) communication being constrained by range or blackout, the proposed algorithm is still useful.

Typically, the CL algorithm can be implemented either in the centralized manner [15] or the distributed manner [16–18]. In the centralized manner, all measurement data are collected and processed in a central agent. In the distributed manner, each agent exchanges information with its neighbors and estimates its own position by itself. The global optimal positioning accuracy can be achieved by the former. However, considering computational cost, survivability, as well as reliability, the distributed manner is superior to the centralized manner. In this paper, we attempt to reduce the communication complexity[1] in the distributed CL; meanwhile, the proposed algorithm has the centralized-equivalent localization accuracy.

1.1. Related works

The problem of CL has been investigated by several estimation techniques: (a) filtering [19–21], e.g., Extended Kalman Filtering (EKF), particle filtering; (b) parameter estimation [22–24], e.g., maximum a posteriori, maximum likelihood; (c) optimization [25]. In the second and third techniques, only through a lot of iterations and communication, the position estimation is close to the best. Thus, both are not suitable when communication complexity is the primary consideration. In this paper, EKF is employed and it is an excellent mechanism of state-estimation recursion. In the EKF, the **state error correlation** refers to the state estimates of different agents being interdependent and quantified in cross-covariance. The state error correlation plays an important role for CL. Ignoring the correlation [26,17], or utilizing it conservatively [27,28], consequently, (1) the estimated state is overconfidence and tends to divergence; (2) the cooperation function is weaken. Hence, how to keep track of the state error correlation with the low communication complexity is crucial.

Roumeliotis et al. have contributed a lot work for CL [5,19,29, 22,30]. In [19], the feasibility of distributed CL which is based on a series of sub EKF is verified. By singular value decomposition (SVD), the factorized covariance factors are re-assigned to different agents via two-way communication. By this, the independence of the state error correlation propagation is guaranteed well. However, full connection communication network is required to exchange information among all the agents. As a result, the communication complexity is up to $O(N(N-1))$, where N is the number of agents. For convenience, this method is called as the **Sub Filter Cross-Covariance Decomposition (SFCCD)**.

In [16,31], the information filter is used for the distributed localization, where the information parameter update is confined in the measuring agents and the distributed architecture is achieved well. Nevertheless, it is the distributed implementation but with serial communication; the communication complexity for the state recovery is up to $O(N^2p^2)$ (where p denotes the state dimension). The information filter is also adopted in [14], against the extensive communication requirement, where the information matrix is approximated as a constant and need not to be continuously exchanged. This method is well suited to the application where the motion parameters change slowly, while the $O(N(N-1))$ communication complexity is still not reduced for the observation update.

Similarly, in order to reduce the communication path requirements during two available communication, the store and burst [32] is another method in which the information is merely stored. All the stored information is transmitted in a burst to the others once the communication paths are established. Besides the big communication burden at special time as [14], a large amount of storage space is required.

In [33], considering the tradeoff between the measurement resource and the localization accuracy, an optimal strategy on measurement frequency is investigated. The optimal goal lies in improving the measurement efficiency. By this method, the number of the exteroceptive measurements is optimized, whereas the communication requirement for sharing each exteroceptive measurement is still full connection communication topology.

Most of the above works are designed with the assumption that each agent can communicate freely. However, in reality, such ideal communication cannot be guaranteed due to the limited bandwidth resource or communication jamming. Most recently, as for the communication bandwidth, the novel estimation algorithms based on the severe quantization [34,30] have been designed to reduce the message size; however, these algorithms target at releasing the bandwidth constraint but not at reducing the communication path requirements.

In [35], an Origin State Method (OSM) is presented. In this method, the fixed bandwidth packet is required, where the transition from the origin state to the current state of server agent is encoded. Utilizing the encoded information, the state-graph of server agent is reconstructed in the client agent. By a unidirectional communication topology, an equivalent to the centralized CL (CCL) algorithm is implemented in the client agent. This method is applicable to the server/client network mode. The server cannot benefit from the client. For a team in which all agents are equal, the proposed OSM is limited.

In [36], a centralized-equivalent algorithm with the sparse communication network is presented, especially, where free communicating connection is not assumed. The checkpoints and partial checkpoints are introduced to the global and local communication topology, respectively. All the past information is stored and transmitted among the agents. Until the properties of checkpoints are satisfied, the state estimate is performed using all past data. As a result, a centralized-equivalent state estimate is obtained. However, before the centralized-equivalent estimation, in most of the time the exteroceptive measurements are not processed but just stored and transmitted. The utilization of the exteroceptive measurements is low.

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[1] In the following, the **communication complexity** is adopted as an indicator for the algorithm comparison. It reflects the path requirements for implementing CL.

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