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Distributed sensor network localization based on local bearing measurement

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The localizability of local-bearing-based-only directed sensor networks is more common and challenging than that of bearing-based undirected sensor networks. Network localization is the foundation for multiagent systems to perform complex tasks in numerous applications [1–3]. The bearing-based localization algorithm receives growing interest due to the rapid development of bearing-only sensors. A distributed pose localization framework based on direction measurements in leader-follower networks is proposed for multiagent systems [4]. An edge localization graph is proposed to address the issue of estimating bearing vectors between agents based on subtended angle measurements [5].

A new orientation estimation algorithm that does not require relative orientation measurements is proposed in this study using only the local bearing measurement information. A continuous-time distributed localization estimation scheme is proposed in conjunction with the new orientation estimation to address the problems of sensor network absolute localization estimation under a directed graph. The contributions of this study are twofold. First, a new orientation estimation algorithm is proposed using the local bearing measurements. Unlike [6], relative orientation measurements are not needed. The rotation matrix, which is calculated by estimating the unit direction vector between adjacent nodes, can be used to determine the orientation indirectly. Second, a distributed network localization algorithm with a directed acyclic structure is proposed, which can be implemented and extended due to the cascade structure. The proposed algorithm is concise without an orthogonalization procedure while ensuring global convergence.

Preliminaries. The directed graph $\mathcal{G} = (v, \varepsilon)$ consists of a vertex set $v = \{1, 2, \ldots, n\}$ and an edge set $\varepsilon \subseteq v \times v$. For sensor node $i \in v$, the neighbor set of i is defined as $N_i = \{j \in v : (i,j) \in \varepsilon\}$. The edge (i,j) means that the node i can measure the relative bearing of node j and receive the information transmitted by node j. Consider a directed path to be the sequence of edges $(v_1, v_2), (v_2, v_3), \ldots, (v_{k-1}, v_k)$ in edge set ε, graph $\mathcal{G}$ can be called directed acyclic graph if the vertex v_{i_1} cannot return to the origin through finite directed edges; i.e., the directed edge (v_k, v_1) does not exist.

In this study, each sensor node has its own local reference frame, which is not aligned with the global reference frame ${}^g\sum$. ${}^i\sum$ represents the local reference frame of sensor i and θ_i is the orientation angle with respect to the global reference frame ${}^g\sum$. The displacement vector between nodes i and j is defined as $p_{ij} = p_j - p_i$. Note that $g_{ij} = \frac{p_j - p_i}{\|p_j - p_i\|}$ is the unit direction vector, and $g_{ij} = -g_{ji}$. The relative bearing of j with respect to i in ${}^i\sum$ is expressed as g_{ij}^i. Let $R(\theta_i) = \left[\begin{smallmatrix} \cos(\theta_i) & -\sin(\theta_i) \\ \sin(\theta_i) & \cos(\theta_i) \end{smallmatrix}\right]$ denote the rotation matrix from ${}^i\sum$ to ${}^g\sum$; then one has $g_{ij} = R(\theta_i)\, g_{ij}^i$.

The orthogonal projection matrix $Q_{g_{ij}}$ is defined as $Q_{g_{ij}} = I - g_{ij} g_{ij}^{\mathrm{T}}$, where I represents the identity matrix. The orthogonal projection matrix $Q_{g_{ij}}$ is positive semidefinite matrix satisfying $Q_{g_{ij}}^{\mathrm{T}} = Q_{g_{ij}}$, $Q_{g_{ij}}^2 = Q_{g_{ij}}$, and $Q_{g_{ij}} g_{ij} = 0$, where 0 represents the zero vector. In geometry, the orthogonal projection matrix $Q_{g_{ij}}$ can project any vector onto the orthogonal complement vector of g_{ij}, which is widely employed in formation control and localization estimation.

A bearing-based sensor network that can be localized should satisfy certain architectural requirements, referred to as bearing localizability conditions. The following are some definitions.

Definition 1 (Bearing localizability). A sensor network can be called bearing localizable if and only if the position information of all free nodes can be uniquely and accurately determined by the anchor node position information and the local bearing information between adjacent nodes.

Definition 2 (Self-localizability of sensor networks). The sensor network is self-localizable if and only if the following two conditions are met:

(1) The number of anchor nodes is greater than or equal to 2.

(2) Each free node is 2-reachable from the set of anchor nodes (i.e., every free node has at least two disjoint paths to the anchor nodes).

Problem formulation. Consider an n-node sensor network in a two-dimensional Euclidean space, with two an-

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chor nodes (labeled as 1 and 2), whose positions in ${}^{g}\sum$ are known, and the remaining $(n-2)$ nodes are free nodes (labeled as $3,\ldots,n$) to be estimated in ${}^{g}\sum$.

In this study, the free node has its own local reference frame, which is not aligned with the global reference frame ${}^{g}\sum$. Suppose each free node can measure its neighbors' bearing information in its local reference frame ${}^{i}\sum$ and receive the position information sent by the neighbors. We have two assumptions regarding the sensor network under consideration.

Assumption 1. The positions of the sensor nodes do not overlap, and the three neighbor nodes are not collinear.

Assumption 2. The directed topology graph $\mathcal{G}=(v,\varepsilon)$ satisfies the Henneberg construction (the definition of Henneberg construction is given in Appendix A).

Remark 1. Assumption 2 states that the free node $i\in\{3,\ldots,n\}$ receives the position information transmitted by the neighbors, and simultaneously sends its own position estimation information to other neighbors. Since the communication topology of the sensor networks satisfies the Henneberg construction and the communication between sensor nodes is unidirectional, the neighbor node that transmits the position information to i and the neighbor node that receives the information sent from i are distinct nodes.

The objective of this study is to design a distributed estimation scheme to realize the orientation alignment and the absolute position estimation of free node i merely using the local bearing measurement for the sensor network with directed acyclic leader-follower structure topology graph $\mathcal{G}=(v,\varepsilon)$.

Main results. The absolute position information p_i and the relative position information p_i-p_j under the global reference frame ${}^{g}\sum$ cannot be measured in this study, and the orientation angle $\theta_i\in[0,2\pi]$ is also unknown. Therefore, let $\hat{p}_i$ and $\hat{R}(\theta_i)$ be the estimates of absolute position p_i and orientation matrix $R(\theta_i)$.

The distributed orientation and localization estimation algorithms are proposed, respectively, to realize the orientation alignment and the absolute position estimation of free node i. The specific is shown below

$$\dot{\hat{g}}_{jk}=-Q_{\hat{g}_{jk}}\hat{R}(\theta_i)\,g_{jk}^{i}, \tag{1}$$

$$\dot{\hat{p}}_i=-Q_{\hat{g}_{ij}}(\hat{p}_i-\hat{p}_j)-Q_{\hat{g}_{ik}}(\hat{p}_i-\hat{p}_k), \tag{2}$$

where j and k are neighbors of i, $i>j$, and $i>k$. $\hat{g}_{jk}=\frac{\hat{p}_k-\hat{p}_j}{\|\hat{p}_k-\hat{p}_j\|}$, $\hat{p}_k$ and $\hat{p}_j$ represent the estimated position information of j and k, respectively, and are received by i. $\hat{g}_{ij}=\hat{R}(\theta_i)\,g_{ij}^{i}$ is the estimated unit direction vector between nodes i and j in the global reference frame. $\hat{g}_{ik}=\hat{R}(\theta_i)\,g_{ik}^{i}$ is the estimated unit direction vector between nodes i and k. g_{ij}^{i} and g_{ik}^{i}, respectively, represent the unit direction vectors of j and k under the local reference frame ${}^{i}\sum$, which can be calculated directly based on the local bearing measurement.

In estimation schemes (1) and (2), all the available bearing information of the free node i is measured based on its own local reference frame, and the free node i only performs one-way local communication with neighboring nodes, so the proposed estimation algorithms (1) and (2) are also distributed.

To better explain the orientation estimation algorithm (1), a lemma is provided to demonstrate that the orientation angle θ_i can be estimated indirectly using the estimated unit direction vector $\hat{g}_{jk}$.

Lemma 1. Based on local bearing measurement g_{jk}^{i}, the proposed orientation estimation algorithm (1) can estimate the orientation angle θ_i indirectly through estimating the unit direction vector $\hat{g}_{jk}$.

A detailed proof is provided in Appendix B.

Remark 2. The orientation estimation algorithm (1) is an indirect method for estimating the orientation angle θ_i. The estimated $\hat{g}_{jk}$ is used to estimate the rotation matrix $\hat{R}(\theta_i)$, and the orientation angle θ_i can then be calculated using the obtained rotation matrix. $\hat{R}(\theta_i)$ will eventually converge to $R(\theta_i)$ when $\hat{g}_{jk}$ converges to the true value g_{jk}.

The convergence of the estimation algorithms (1) and (2) using only the local bearing measurement is provided.

Theorem 1. If the sensor network satisfies Assumptions 1 and 2, the proposed distributed estimation algorithms (1) and (2) can ensure that the estimated rotation matrix $\hat{R}(\theta_i)$ converges to the real rotation matrix $R(\theta_i)$ and the estimated position $\hat{p}_i$ converges to the absolute position p_i.

See Appendix C for the proof. Simulations are provided in Appendix D.

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Supporting information Appendixes A–D. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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