Research Article

Self-Organized Connectivity Control and Optimization Subjected to Dispersion of Mobile Ad Hoc Sensor Networks

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This paper addresses the problem of the connectivity control and the self-organized deployment/dispersion of a team of mobile ad hoc sensor nodes. First, to reduce redundant communication links while preserving global connectivity, a distributed link removal algorithm is developed that only requires local information of no more than two-hop neighbors. Secondly, for the purpose of preserving essential links while avoiding collisions, a combined piecewise-continuous motion controller is designed to regulate the motion of mobile sensors between two consecutive switches. The proposed hybrid control system can autonomously disperse a team of mobile sensors towards their final configuration with guaranteed connectivity and collision avoidance. Theoretical analysis and computer simulations have confirmed the efficiency and scalability of the proposed schemes.

1. Introduction

The self-organized connectivity control and dispersion of mobile ad hoc sensor networks (MASNs) has been extensively investigated due to its promising potential applications in various fields, such as remote supervision of hazard substances, exploration of unknown fields, and cooperative sensing. Enhancing the coverage of the MASNs could be beneficial, if not critical, for a variety of missions, such as environmental monitoring and disaster management. Moreover, from the wireless communication point of view, the sparse network structure resulted from the enhanced coverage can effectively reduce radio interferences, which is critical for the elimination of excessive message overheads and the reduction of the latency [1]. Furthermore, in energy critical wireless sensor networks, the reduction of message overheads as well as the complexity of the self-organizing algorithms can extend the service lifetime of the systems.

In a mobile sensor network, the mobility of sensor nodes provides the possibility for the nodes to deploy to a configuration with desired properties from an arbitrary initial distribution in a self-organized manner. The aforementioned concept of MASNs has attracted numerous research efforts. Among various topics that have been covered, emphasis is placed on the consensus of a group of mobile sensors, such as flocking and rendez-vous, with a particular interest in coverage and connectivity control. Self-organized dispersion, on the other hand, is another fundamentally essential aspect of the system and requires more research efforts.

Self-organized dispersion of MASNs can be loosely defined as maximizing coverage with a minimum number of mobile sensors [2]. Significant application potentials of self-organized dispersion have recently led to a surge of research attentions. Techniques including inverse agreement control law [3], clique-intensity algorithm [2], and “artificial physics” framework [4] have been developed to regulate the evolution of the underlying networks. Coverage control of mobile networks is another promising research area that is closely related to self-organized dispersion, and numerous efforts have concentrated on the deployment of mobile sensors [5–8], coverage control in stationary WASN [9], and coverage control of autonomous agents [10]. Commonly used models include Voronoi diagrams [7, 8] and potential functions [10, 11]. Voronoi diagrams method can partition the field into many subareas dedicated to each mobile sensor, allowing sensors to move to maximize coverage in its own subarea. However, the assumption that mobile sensors can easily detect most of its Voronoi neighbors through local
communication may not be satisfied in a real network, due to the limited communication range of the mobile sensors, which may not be sufficient for covering all Voronoi neighbors. Potential function, on the other hand, is able to fulfill the self-organized coverage control of mobile sensor nodes in a more local and distributed manner. The concept of this approach is to imitate the behavior of electromagnetic particles: whenever two electromagnetic particles are too close in proximity, a repulsive force pushes them apart. In mobile ad hoc sensor networks, this method can help move sensors from high density to low density areas, thereby dispersing the team to improving the overall network coverage.

*Connectivity control* of MASNs is rapidly becoming a hot research topic in the field of multiagent systems, and various strategies have been developed in recent years, including both centralized [12, 13] and decentralized [14–20] approaches. A common way to maintain connectivity in mobile networks is to shrink the communication links between any two neighbors whenever they tend to break [21]. Most studies have attempted to maximize *Fiedler value* [13] and to add communication links to increase connectivity [22]. However, these approaches often result in a tight network structure with dense communication links, which may largely restrict the mobility of mobile sensors and jeopardize the coverage and cooperation efficiency. More importantly, from the wireless communication point of view, high network density can severely aggravate radio interferences [1]. To deal with these problems, Zavlanos and Pappas [15] proposed a distributed market-based control strategy, which is able to reduce redundant communication links based on local estimation of *spanning subgraph*. This strategy, however, requires full knowledge of the network structure, which may cause large delay in dense and large-scale networks [23]. In [17], a connectivity control strategy is presented with a particular consideration of the relationship between the communication range and the sensing range, that is, radio range is at least twice the sensing range. The proposed control scheme can guarantee a connected network with optimized sensing coverage. How to disperse the networked sensors to achieve a sparse topology is not yet discussed. It is also worthwhile to mention that certain topology control methods [24, 25] in ad hoc sensor networks have been developed that similarly deal with the issue of removing redundant communication links. However, these works are mainly based on stationary network structure. The important issues of combing global connectivity and dispersion of mobile sensors with respect to mobility control strategy have not been addressed properly.

**Contributions.** Aiming at bridging the gap between dispersion and connectivity, we first present a distributed link removal algorithm (DLRA) to reduce redundant communication links while preserving global connectivity. The proposed algorithm is fully distributed and only requires local information of no more than two-hop neighbors. Then, by integrating DLRA with a novel combined piecewise-continuous potential function, a distributed connectivity control system is developed to disperse a team of mobile sensors with guaranteed connectivity and collisions avoidance. The present work provides answers to the following questions.

1. How to remove communication links with respect to global connectivity based only on local information of neighbor status?
2. How to disperse a team of sensors with connectivity preservation, collision avoidance, and limited actuation?
3. Is the generated network structure sparse enough to fulfill dispersion requirement?

The rest of the paper is organized as follows: Section 2 provides necessary terminologies and notations. Section 3 presents the DLRA algorithm that is developed to address the link removal problem with respect to global connectivity. Section 4 introduces a distributed combined piecewise-continuous potential function to control the motion of mobile sensors. Computer simulations are included in Section 5, and this paper is concluded in Section 6 with a discussion of future research works.

### 2. Problem Formulation

Let the dynamic graph \( \mathcal{G}(t) = (V, E(t)) \) denote a mobile network of \( n \) mobile sensor nodes with integrated wireless communication capabilities, where \( V = \{1, \ldots, n\} \) denotes the set of vertices indexed by the set of mobile sensors and \( E(t) = \{i, j \mid f_{ij}(t) \geq \varepsilon, i, j \in V\} \), \( 0 < \varepsilon < 1 \) denotes the time-variant set of communication links. We define \( 0 \leq f_{ij}(t) \leq 1 \) to be a normalized nonnegative weighting function symmetric in its arguments, that is, \( f_{ij}(t) = f_{ji}(t) \), and assume that \( f_{ij}(t) \neq f_{ik}(t), j \neq k \). In this case, the adjacency matrix \( A(t) = (a_{ij}(t)) \in \mathbb{R}^{n \times n} \) (we define \( a_{ii}(t) = 0 \) for all \( i \), thus there are no self-loops in the network) can be defined as follows:

\[
a_{ij}(t) = \begin{cases} a_{ij}(t) = f_{ij}(t), & (i, j) \in E(t), \\ 0, & \text{otherwise}. \end{cases}
\]

(1)

Note that *any normalized nonnegative function* can be treated as a weighting function. Nevertheless, to associate with the link quality, it is rather a natural choice that \( f_{ij}(t) \) denotes received signal strength. Moreover, as indicated in radio propagation theory [1], in obstacle-free environment, signal fading can be treated as an exponential decay function of the Euclidean distance between \( i \) and \( j \). In particular, we have the following definitions.

**Definition 1.** For any node \( i \) in \( \mathcal{G}(t) = (V, E(t)) \), the normalized received signal strength from node \( j \) is set to be:

\[
f_{ij}(t) \triangleq \begin{cases} 1, & \|\xi(t) - \xi(t)\| < a_{0}, \\ \exp\left[-\beta\left(\|\xi(t) - \xi(t)\| - a_{0}\right)\right], & \text{otherwise}, \end{cases}
\]

(2)

where \( \beta \) (the value of \( \beta \) depends on the radio frequency, antenna gain, system loss, and environmental factors, etc.)
is positive path-loss value, and $a_0$ is reference distance (see Figure 1).

Definition 2. An undirected weighted dynamic graph $G(t) = (\mathcal{V}, E(t))$ is defined as connected at time $t$ if and only if there is at least one communicative path between any two vertices within it.

Furthermore, consider the vertices in $G(t)$ as $n$ mobile sensors with single-integrator kinematic model given by the following:

$$\dot{\xi}_i(t) = u_i(t), \tag{3}$$

where $\xi_i(t) \in \mathbb{R}^N$ and $u_i(t) \in \mathbb{R}^N$ denotes the position and velocity of node $i$, respectively.

Now the main objectives of this paper can be described as follows:

(1) for any nodes $i$ and $j$ in $G(t) = (\mathcal{V}, E(t))$, determine whether link $(i, j)$ is an essential communication link for connectivity maintenance, and then remove redundant communication links. The generated subgraph $\mathcal{G}_i(t) = (\mathcal{V}, E_i(t))$ contains only essential communication links, that is, $(i, j) \in E_i(t)$;

(2) for the corresponding kinematic system $\dot{\xi}_j(t) = u_j(t)$, derive a dynamic motion controller $u_i(t) \in \mathbb{R}^N$ for all sensors $i$ between any two consecutive switches, so that (1) for any $(i, j) \in E_i(t)$, it is guaranteed that $\varepsilon \leq f_{ij}(t) < \varphi$; (2) for any $(i, j) \notin E_i(t)$, nodes $i$ and $j$ are dispersed into the set $\{i, j \mid f_{ij} \leq \varepsilon, i, j \in \mathcal{V}\}$ (see Figure 2).

3. Distributed Link Removal Algorithm with Respect to Global Connectivity

The objective of this section is to develop a distributed local connectivity control algorithm, aiming at removing redundant communication links to facilitate the self-organized dispersion of mobile sensors with respect to global connectivity.

3.1. Principle of DLRA. Let us first introduce the following definitions which categorize neighboring sensors into two distinctive neighbor relationship sets, namely, physical neighbor set and logical neighbor set.

Definition 3. Node $j$ is in the physical neighbor set of $i$, denoted $j \in \mathcal{N}_p[i](t)$, if and only if $(i, j) \in E(t)$.

Definition 4. Node $j$ is the logical neighbor set of $i$, denoted $j \in \mathcal{N}_l[i](t)$, if and only if $(i, j) \in E_i(t)$.

Definition 5. For any node $i$ in the network, we denote $\mathcal{N}_i^{[\mathcal{I}]}(t) = (a_{ik}(t))$ as the neighbor relationship matrix (NRM) at time $t$, where $j \in \mathcal{N}_l[i](t)$ and $k \in \mathcal{N}_l[j](t)$.

Based on the aforementioned definitions, the proposed DLRA is described as follows.

Information Exchange. The information that sensor $i$ requires for the link removal algorithm is obtained by periodically receiving Heartbeat messages from all its neighbors in $\mathcal{N}_p[i](t)$. The periodical messages sent by neighbor $j$ should at least contain the following information: node ID, position, logical neighbor set $\mathcal{N}_l[j](t)$, and link weight with all its logical neighbors. After exchanging information with all its neighbors, each node is only aware of the status of its one-hop physical neighbors and two-hop logical neighbors.

Selecting Candidate Links to Be Removed. Upon receiving Heartbeat message from each individual physical neighbor, node $i$ updates $\mathcal{N}_p^{[\mathcal{I}]}(t)$. As it is assumed that the initial
network is connected, DLRA starts at time \( t = t_0 \). Then, the process is started with initial condition that \( N^i_\pi (t_0) = \mathcal{N}_i(t_0) \) and \( N^i_\pi (t_0) \) is constructed for each \( i \). The selection of candidate links is as follows.

**Step 1.** Look up neighbor relationship matrix \( N^i_\pi (t_0) \). If \( \exists a_{ij}(t_0) \in N^i_\pi (t_0) \), \( j \in \mathcal{N}_i(t_0) \), there exists a triangle consist of sensor \( i, j, k \). And if only \( a_{ij}(t_0) = \max(a_{ij}(t_0), a_{ik}(t_0), a_{jk}(t_0)) \), then denote link \((i, j)\) as candidate link to be removed from \( \mathcal{N}^i_\pi (t) \), put sensor \( j \) into candidate removal set \( C^i_\pi (t) \), and remove corresponding row vector in \( N^i_\pi (t) \) (cf. line 2–7 in Algorithm 1).

**Step 2.** Update \( N^i_\pi (t) \), so that there is no triangle in the updated topology. Let \( N^i_\pi (k) = [a_{jk}(t), a_{ik}(t), \ldots a_{nk}(t)] \) be the column vector of \( N^i_\pi (t) \), where \( (j, l, \ldots n) \in \mathcal{N}^i_\pi (t) \). Check \( N^i_\pi (k) \) for every \( k \in \mathcal{N}^i_\pi (t) \), if \( \exists a_{jk}(t), a_{ik}(t), j \neq l \) and \( a_{jk}(t) \neq a_{ik}(t) \neq 0 \), compare link weights \( a_{jk}(t), a_{ik}(t), a_{jk}(t) \) and \( a_{ik}(t) \), if \( a_{jk}(t) = \max(a_{jk}(t), a_{ik}(t), a_{ik}(t), a_{jk}(t)) \), then denote link \((i, j)\) as candidate link to be removed from \( \mathcal{N}^i_\pi (t) \), and put \( j \) into \( C^i_\pi (t) \) and remove corresponding row vector in \( N^i_\pi (t) \) (cf. line 8–15 in Algorithm 1) (\( \Delta t \) is the execution time for node \( i \) in every edge removal procedure, we assume \( \Delta t \) is constant for any node).

**Synchronized Local Coordination for DLRA (Algorithm 2).** A major challenge when dealing with dynamic network is that, the network topology may be changed during any consecutive switches, due to the movement and leaving/joining of the mobile sensors. Meanwhile, an unpredictable message delay may occur at any time. Therefore, a synchronization process is required for such situations. In particularly, a request and acknowledge mechanism is utilized to dynamically synchronize the disconnection of any redundant communication links between the corresponding vertices. That is, upon the determination of redundant communication link, for example, \( j \in C^i_\pi (t) \), a request message \( \text{ReqD}(i,j) \) will be sent from \( i \) to \( j \). Upon receiving \( \text{ReqD}(i,j) \) sensor \( j \) will remove sensor \( i \) from the logical neighbor set \( \mathcal{N}^j_\pi (t) \) and send back a acknowledge message \( \text{AckD}(j,i) \) based on the condition that \( i \in C^i_\pi (t) \). The network structure will be constructed based on the subgraph \( \mathcal{G}(t) \), which is generated from the proposed local coverage enhancement algorithm (cf. Algorithm 2).

### 3.2. Capabilities and Message Complexity of DLRA

We first prove that the connectivity is guaranteed while the redundant links are removed from the underlying network.

**Theorem 6.** Given a network \( \mathcal{G}(t_0) = (\mathcal{V}, E(t_0)) \) with initial connectedness and controllable links, the subgraph \( \mathcal{G}(t) = (\mathcal{V}, E(t)) \) generated from DLRA is connected all the time.

**Proof.** Since neighbor discovery procedure and adding redundant links into \( \mathcal{N}^{i}(t) \) do not violate network connectivity, we only need to consider the link removal mechanism for connectivity preservation.

Consider two nodes \( i_0, i_n \) where \( i_0, i_n \) are initially connected in \( \mathcal{G}(t_0) \) through a series of vertices, for example, \( i_0 \rightarrow i_1 \rightarrow i_2 \rightarrow \ldots i_{n-1} \rightarrow i_n \). Suppose that \( (i_k, i_{k+1}) \notin E(t) \) and \( i_k, i_{k+1} \) are disconnected in \( \mathcal{G}(t) \), we have the following.

**Case 1.** \( \exists \nu \in \mathcal{V}^i_\pi (t_0) \) and \( \nu \in \mathcal{V}^i_\pi (t_0) \), since \( (i_k, i_{k+1}) \notin E(t) \). According to step 2 in Algorithm 1, we have \( a_{i_k, i_{k+1}}(t_0) = \max(a_{i_k, i_{k+1}}(t_0), a_{i_k, i_{k+1}}(t_0), a_{i_k, i_{k+1}}(t_0)) \), so \( \exists \nu \rightarrow \nu \rightarrow i_{k+1} \), contradiction reached.

**Case 2.** \( \exists \nu, u \in \mathcal{V}^i_\pi (t) \), and \( u, \nu \in \mathcal{V}^i_\pi (t_0) \), since \( (i_k, i_{k+1}) \notin E(t) \), \( a_{i_k, i_{k+1}}(t_0) = \max(a_{i_k, i_{k+1}}(t_0), a_{i_k, i_{k+1}}(t_0), a_{i_k, i_{k+1}}(t_0), a_{i_k, i_{k+1}}(t_0)) \), so we have \( \exists \nu \rightarrow \nu \rightarrow u \rightarrow i_{k+1} \), contradiction reached.

The proof of Theorem 6 is completed.

In addition, for Case 1, suppose that there exists a path \( i \rightarrow \nu \rightarrow u \rightarrow \nu \rightarrow \nu \rightarrow \nu \rightarrow \nu \rightarrow \nu \), and \( a_{i_k, i_{k+1}}(t_0) = \max(a_{i_k, i_{k+1}}(t_0), a_{i_k, i_{k+1}}(t_0), a_{i_k, i_{k+1}}(t_0)) \). From Algorithm 1 it can be seen that \( (i, \nu) \notin \mathcal{G}(t) \), so contradiction reached. Similarly, for Case 2, suppose there exists \( i \rightarrow \nu \rightarrow u \rightarrow \nu \rightarrow \nu \rightarrow \nu \rightarrow \nu \rightarrow \nu \), same contradiction can also be met, which leads to the following corollary.

**Corollary 7.** For any generated subgraph \( \mathcal{G}(t) = (\mathcal{V}, E(t)) \), the shortest cycle is 5, that is, there are no such links as \( i \rightarrow \nu \rightarrow u \rightarrow i \) or \( i \rightarrow \nu \rightarrow u \rightarrow j \rightarrow i \).

Furthermore, through removing redundant links, node degree in \( \mathcal{G}(t) \) can be constrained within a certain spectrum. In particular, one has the following.

**Corollary 8.** For a generated subgraph \( \mathcal{G}(t) = (\mathcal{V}, E(t)) \) where \( \xi(t) \in \mathbb{R}^2 \), the upper bound of node degree is 5.

**Proof.** To see contradiction, it is assumed that there are two links \( (i, j) \) and \( (i, k) \) in \( \mathcal{G}(t) \), where \( (i, j) \) and \( (i, k) \) enclose an angle \( \alpha \leq \pi/3 \) at node \( i \). Furthermore, suppose that \( a_{ij}(t) < a_{ik}(t) \) and \( j, k \in \mathcal{N}^{i}_\pi (t) \), from Definition 1 we know that link weight is a monotonic function of vertices’ Euclid distance, for example, \( a_{ij}(t) < a_{ik}(t) \Rightarrow \|\xi_i(t) - \xi_j(t)\| < \|\xi_i(t) - \xi_k(t)\| \). Since \( a_{ij}(t) < a_{ik}(t) \) and \( \alpha \leq \pi/3 \), it is straightforward that \( \|\xi_i(t) - \xi_j(t)\| < \|\xi_i(t) - \xi_k(t)\| \). Because \( \|\xi_i(t) - \xi_j(t)\| < \|\xi_i(t) - \xi_k(t)\| \), we can conclude from Algorithm 1 that \( k \notin \mathcal{N}^{i}_\pi (t) \), for example, \( (i, k) \notin \mathcal{G}(t) \), thus we reach a contradiction to the assumption that \( (i, k) \in \mathcal{G}(t) \). This proved that no adjacent links in \( \mathcal{G}(t) \) enclose an angle equal or less than \( \pi/3 \), from which the corollary follows.

In addition, the request and acknowledge mechanism in Algorithm 2 guarantees that, despite of trivial one-hop delays of the acknowledge information, the communication links in \( \mathcal{G}(t) \) remain symmetric all the time. Moreover, DLRA depends only on local information of no more than two-hop neighbors, so that the information exchange between mobile sensors will not invite large delay and communication overhead. In particular, we have the following.

**Theorem 9.** The worst-case message complexity of DLRA is \( O(n^2/2) \), where \( n \) is the number of sensors.

**Proof.** Since DLRA depends only on two-hop neighbor information to determine redundant communication links, this
Upon receiving Hello message from $j$, update $\mathcal{N}_p(i)(t)$, send Hello message back. Upon finishing neighbor discovery, set time $t = t_0$ and $\mathcal{N}_p(i)(t_0) = \mathcal{N}_p(i)(t_b)$. Construct $\mathcal{N}_p(i)(t_b)$, initialized.

(1) For $i \in V$
(2) while $\exists a_{ij}(t_b) \in \mathcal{N}_p(i)(t_b)$ and $j \in \mathcal{N}_p(i)(t_b)$ do
(3) $\forall k \in \mathcal{N}_p(i)(t_b)$
(4) if $a_{ik}(t_b) = \max\{a_{ij}(t_b), a_{jk}(t_b), a_{ik}(t_b)\}$
(5) $\mathcal{E}_d^{i}(t_b + \Delta t) := \mathcal{E}_d^{i}(t_b) \cup \{j\}$, send ReqD$(i, j)$ to $j$
(6) end if
(7) end while
(8) $\mathcal{N}_p(i)(t)$, $\mathcal{E}_d^{i}(t)$, hold
(9) Construct $\mathcal{N}_p^{[a]}(t) = \{a_{ij}(t), a_{jk}(t), \ldots a_{ik}(t)\}$
(10) $\forall k \in \mathcal{N}_p^{[a]}(t)$
(11) while $a_{ik}(t) \times a_{jk}(t) \neq 0$ do
(12) if $a_{ij}(t) = \max\{a_{ij}(t), a_{jk}(t), a_{ik}(t), a_{ik}(t)\}$
(13) $\mathcal{E}_d^{i}(t + \Delta t) := \mathcal{E}_d^{i}(t) \cup \{j\}$, send ReqD$(i, j)$ to $j$
(14) end if
(15) end while
(16) End

Algorithm 1: Link removal mechanism for DLRA.

Upon receiving ReqD$(i, j)$ from $j$
(1) For $i \in v$
(2) if $j \in \mathcal{E}_d^{i}(t)$
(3) $\mathcal{N}_p^{[i]}(t + \Delta t) := \mathcal{N}_p^{[i]} \\setminus \{j\}$, send AckD$(i, j) = 1$ to $j$
(4) else if $\exists \mathcal{N}_p^{[i]}(t)$
(5) $\mathcal{N}_p^{[i]}(t + \Delta t) := \mathcal{N}_p^{[i]}(t) \setminus \{j\}$, send AckD$(i, j) = 1$ to $j$
(6) else send AckD$(i, j) = 0$ to $j$
(7) end if
(8) else send AckD$(i, j) = 0$ to $j$
(9) end if
(10) Upon receiving AckD$(i, j)$
(11) if AckD$(i, j) = 1$
(12) $\mathcal{N}_p^{[i]}(t + \Delta t) := \mathcal{N}_p^{[i]}(t) \setminus \{j\}$
(13) else
(14) $\mathcal{E}_d^{i}(t + \Delta t) := \mathcal{E}_d^{i}(t) \setminus \{j\}$
(15) end if
(16) End

Algorithm 2: Synchronized coordination for DLRA.

\[ \frac{n}{\pi} \leq \alpha \leq n \]

Figure 3: As indicated in proof of Corollary 8, $\parallel \xi(t) - \xi_k(t) \parallel < \parallel \xi(t) - \xi_j(t) \parallel$ if and only if $a_{ij}(t) < a_{ik}(t)$ and $\alpha \leq \pi/3$.

requires two messages per sensor, and total $2n$ messages will be sent. In addition, request and acknowledge mechanism requires two messages to remove each redundant link. In the worst case where $\mathcal{G}(t_0)$ is a undirected complete graph (UCG), and $E_i(t) = n - 1$, the maximum redundant communication links to be removed is $n(n-1)/2 - (n - 1) = (n-1)(n-2)/2 + 2n = (n^2 + n)/2$. In conclusion, DLRA has a total message complexity of $O(n^2/2)$.

Note that for large scale mobile networks with limited communication range, it is an unlikely case that the initial configuration is a UCG. Therefore, the message complexity can be reduced dramatically, which makes DLRA scalable to MASNs with a large number of mobile sensors.

4. Dispersion of Mobile Sensors

The invariance of network structure between any two consecutive switches in $\mathcal{G}(t)$ is prerequisite for the realization of
connectivity preserving dispersion of mobile sensors. The aim of this section is to develop a distributed motion controller that regulates the dispersion of mobile sensors in continuous space. First, we utilize a combined potential function to ensure that all essential links are maintained and interagent collisions are avoided all the time during the self-organized dispersion of mobile sensors between any two consecutive topology updates.

We first introduce a repulsive potential function to deal with the collision avoidance between sensor $i$ and all its physical neighbors $j \in \mathcal{N}_p^{i\downarrow}(t)$, defined as $\psi_{ij}^r(t)$, where $\psi_{ij}^r(t) = \sum_{j \in \mathcal{N}_p^{i\downarrow}(t)} \psi_{ij}^r(t)$. In particular, we have $\psi_{ij}^r(t) \triangleq \left(1 - \frac{f_{ij}(t) - \varepsilon}{1 - \varepsilon}\right)^{-\rho}$, where $\rho \in \mathbb{R}^+$, and in this paper, associated with $f_{ij}(t)$ in (2), it yields $\psi_{ij}^r(t) \triangleq \left(1 - \frac{\exp[-\beta(\|\xi_i(t) - \xi_j(t)\| - a_0)] - \varepsilon}{1 - \varepsilon}\right)^{-\rho}$.

(5)

It is straightforward that, whenever two mobile sensors approach to each other, the repulsive potential $\psi_{ij}^r(t)$ will continuously grow until $\varepsilon \rightarrow 1$, where the potential $\psi_{ij}^r(t) \rightarrow \infty$, so that intersensor collision is avoided. Similarly, to restrict all essential communication links within $f_{ij}(t) \geq \varepsilon$ for all $j \in \mathcal{N}_p^{i\downarrow}(t)$, we introduce an attractive potential function, denote as $\psi_{ij}^a(t)$, where $\psi_{ij}^a(t) = \sum_{j \in \mathcal{N}_p^{i\downarrow}(t)} \psi_{ij}^a(t)$. Specifically, we have

$$\psi_{ij}^a(t) \triangleq \left(1 - \frac{f_{ij}(t) - \varphi}{\varepsilon - \varphi}\right)^{-\rho} = \left(1 - \frac{\exp[-\beta(\|\xi_i(t) - \xi_j(t)\| - a_0)] - \varphi}{\varepsilon - \varphi}\right)^{-\rho}.$$  

(6)

It can be seen from (6) that whenever two mobile sensors with critical communication links move away from each other, the attractive potential $\psi_{ij}^a(t)$ will continuously grow until $\varepsilon \rightarrow \varphi$, where the potential $\psi_{ij}^a(t) \rightarrow \infty$, so that the intersensor connection is guaranteed.

The proposed potential functions entitle us to assign each node $i$ in the network a distributed control law, which is given as the combination of the negative gradients of the two potentials in the $\xi_i(t)$ direction

$$u_i'(t) \triangleq -K_r \nabla \xi_i(t) \sum_{j \in \mathcal{N}_p^{i\downarrow}(t)} \psi_{ij}^r(t) - K_a \nabla \xi_i(t) \sum_{j \in \mathcal{N}_p^{i\downarrow}(t)} \psi_{ij}^a(t).$$  

(7)

It is easy to observe from (7) that, the potential force can become infinite between pairs of sensors whenever $f_{ij}(t) \rightarrow 1$ or $f_{ij}(t) \rightarrow \varepsilon$. In practice, such unbounded actuation is unrealistic for most mobile sensor systems. In this paper, a piecewise-continuous function method is proposed with respect to sensors’ actuation to approach the objective of bounded input.

Denote $u_{i\infty}(t)$ as the upper bound of velocity for node $i$, in particular, for homogeneous systems, we have $u_{i\infty}(t) = u_{ij}(t)$, where $i \neq j$ & $i \in \mathcal{V}$.

Definition 10. Given a mobile sensor networks with fixed underlying network structure $\bar{g}(t)$, a distributed piecewise-continuous control law is assigned to each mobile sensor as follows:

$$u_i(t) \triangleq \begin{cases} u_i'(t), & u_i'(t) \leq u_{i\infty}(t), \\ u_{i\infty}(t) \times u_i'(t) / ||u_i'(t)|| & u_i'(t) > u_{i\infty}(t), \end{cases}$$  

(8)

where $u_i'(t) = u_i'(t)/||u_i'(t)||$ represents the unit vector of $u_i'(t)$.

The definition of piecewise-continuous control law gives rise to the development of hybrid connectivity control system $C$, as is described in Figure 4. In the connectivity control system, the proposed DLRA algorithm will first take every updated location of the mobile sensors as its input matrix to calculate the topology of the network. Therefore, after every interaction process, the redundant communication links will be determined and updated. Meanwhile, the output value of network topology from DLRA will in turn be utilized by the motion controller in every mobile sensor to assign different control functions to every neighboring sensor according to their neighboring types, that is, physical or logical neighbor. And the final output of the system is sensors’ velocity and moving direction in the next step. The bounded velocity is implemented by comparing the output velocity from the controller with the designated maximum speed in the mobile sensor systems.

Now we can conclude the main result of this paper.

Theorem 11. Given a MASNs with initially connected underlying network $\bar{g}(t_0)$, the distributed connectivity control system $C$ guarantees that the connectivity of $\bar{g}(t)$ is maintained, interagent collisions are avoided and sensors’ velocities are bounded for all time $t > t_0$.

Proof. See Appendix.

Furthermore, preserving connectivity without removing redundant communication links often results in a restricted network structure, as indicated in Figure 5(a). We argue that the restriction can be avoided by utilizing DLRA. In particular, from Corollary 7 we proved that the generated core structure (core structure is a subgraph of $\bar{g}(t)$ that contains only the logical neighbor links) of $\bar{g}(t)$ is a substructure of $\alpha$-Lattice [4, 26] (pentagon), and the absence of cycle shorter than 5 guarantees that no mutual influences exist between any distinctive links. Therefore, for any two logical neighbors $i$ and $j$, we have

$$u_{ij}'(t) \triangleq -K_r \nabla \xi_i(t) \psi_{ij}^r(t) - K_a \nabla \xi_i(t) \psi_{ij}^a(t).$$  

(9)
The simulations are focused on the connectivity control and dispersion of mobile sensor networks in $\mathbb{R}^2$ and $\mathbb{R}^3$ spaces. General parameters are set as in Table 1.

First, to evaluate the correctness and efficiency of the proposed DLRA, a static simulation is conducted. In the first scenario, 15 static sensors are initially deployed within an area of $20 \times 20$ m, as can be seen from Figure 6(a), where dense communication links are observed, after the execution of DLRA, the topology of the wireless sensor network is finally simplified with only 15 communication links (cf. Figure 6(b)). In case of large sensor networks, a 100 sensors scenario is then performed, the initial configuration of the network topology can be found in Figure 6(c). The final results from DLRA is shown in Figure 6(d), where the sensor network becomes extremely sparse with only a few redundancy.

To evaluate the proposed connectivity control system C. We first simulate the dispersion of 10 sensors initially located within $20 \times 20$ m $\mathbb{R}^2$ space. The evaluation of mobile sensor network is shown as in Figures 7(a)–7(d). For the purpose of illustration, the diamonds represent mobile sensors, and the circles represent the semidistance (semidistance represents a value that is 5% shorter than half of the communication range. The use of it here is for the sake of facilitating the observation) of communication range. Sensors are under the communication range of each other if and only if the two corresponding circles overlap. The total trajectories of mobile sensors are shown in Figure 7(e), where the solid diamonds denote the initial position of the sensors, final position is represented as hollow ones, and the trajectory is shown as the dotted lines. Furthermore, upon removal of redundant communication links, sensors are dispersed into $\mathbb{R}^2$ space, and the network reaches its final configuration within 30 seconds (see Figure 8(a)). Moreover, the average velocity of the sensors is decreased from the peak that is $5 \text{ m/s}^{-1}$ (see Figure 8(c)), the bounded velocity is guaranteed.

We further conduct a simulation for 100 sensors to verify the scalability of the proposed approach. Similarly to the case of 10 sensors, sensors are initially location in a $200 \times 200$ m $\mathbb{R}^2$ space, the trajectories of networked sensors evolve as in Figures 6(f)–6(i). It is noticeable that the average degree of node in both simulations are between

![Diagram](https://via.placeholder.com/150)

**Figure 4:** Control system C for the dispersion of MASNs.

**Table 1: Simulation parameters.**

| Symbol | Quantity | Value |
|--------|----------|-------|
| $\Delta t$ | Execution time slot | 0.01 s |
| $\Delta T$ | Interval of consecutive switches | 0.1 s |
| $\epsilon$ | Minimum sensing capability of normalized RSSI | 10% |
| $\varphi$ | Optimized sensing value of normalized RSSI | 40% |
| $a_0$ | Restricted radium (Reference distance) | 2 m |
| $\beta$ | Path loss (outdoor, 802.11b) | 0.02 |
| $\rho$ | Exponential gain | 0.7 |
| $K_r$ | Repulsive potential gain | 2500 |
| $K_a$ | Attractive potential gain | 200 |
| $K_e$ | Restoration potential gain | 10 |
| $u^m(t)$ | Maximum sensor velocity | 5 m/s$^{-1}$ |

**Corollary 12.** Considering a MASNs with initially connected underlying network $g_i(t_0)$, where the position of vertices $\xi_j(t) \in \mathbb{R}^2$. The evolution of the system under the control system C can reach a set of condition $\mathcal{K}(\mathcal{D}_j(t)) \doteq \{ \mathcal{D}_j(t) \mid \mathcal{D}_j(t) \geq a_0 - \ln((1 + \epsilon \cdot \Phi)/(1 + \Phi))/\beta, i, j \in \mathcal{N} \}$ within finite time $t < \infty$.

**5. Simulations**

To evaluate the performance of the proposed control system for the self-organized dispersion of mobile sensor networks, a variety of simulations have been conducted, and the results are presented in this section. The simulations are focused on the connectivity control and dispersion of mobile sensor networks in $\mathbb{R}^2$ and $\mathbb{R}^3$ spaces. General parameters are set as in Table 1.

First, to evaluate the correctness and efficiency of the proposed DLRA, a static simulation is conducted. In the first scenario, 15 static sensors are initially deployed within an area of $20 \times 20$ m, as can be seen from Figure 6(a), where dense communication links are observed, after the execution of DLRA, the topology of the wireless sensor network is finally simplified with only 15 communication links (cf. Figure 6(b)). In case of large sensor networks, a 100 sensors scenario is then performed, the initial configuration of the network topology can be found in Figure 6(c). The final results from DLRA is shown in Figure 6(d), where the sensor network becomes extremely sparse with only a few redundancy.

To evaluate the proposed connectivity control system C. We first simulate the dispersion of 10 sensors initially located within $20 \times 20$ m $\mathbb{R}^2$ space. The evaluation of mobile sensor network is shown as in Figures 7(a)–7(d). For the purpose of illustration, the diamonds represent mobile sensors, and the circles represent the semidistance (semidistance represents a value that is 5% shorter than half of the communication range. The use of it here is for the sake of facilitating the observation) of communication range. Sensors are under the communication range of each other if and only if the two corresponding circles overlap. The total trajectories of mobile sensors are shown in Figure 7(e), where the solid diamonds denote the initial position of the sensors, final position is represented as hollow ones, and the trajectory is shown as the dotted lines. Furthermore, upon removal of redundant communication links, sensors are dispersed into $\mathbb{R}^2$ space, and the network reaches its final configuration within 30 seconds (see Figure 8(a)). Moreover, the average velocity of the sensors is decreased from the peak that is $5 \text{ m/s}^{-1}$ (see Figure 8(c)), the bounded velocity is guaranteed.

We further conduct a simulation for 100 sensors to verify the scalability of the proposed approach. Similarly to the case of 10 sensors, sensors are initially location in a $200 \times 200$ m $\mathbb{R}^2$ space, the trajectories of networked sensors evolve as in Figures 6(f)–6(i). It is noticeable that the average degree of node in both simulations are between
Figure 5: Illustration of network structure (a) restricted link \((j,k)\) is observed without removal of redundant links; (b) a typical \(\alpha\)-Lattice (pentagon) structure generated by DLRA, absence of external constrains.

Figure 6: Simulation results for DLRA. (a) Original topology for 15 nodes; (b) final topology for 15 nodes; (c) original topology for 100 nodes; (d) final topology for 100 nodes.
Figure 7: Continued.
Figure 7: Simulation results for 2D distributed mobile multiagent dispersion. (a)–(d) Evolution snapshots for 10 nodes; (f)–(i) evolution snapshots for 100 nodes; (e) mobile sensor’s trajectories in 10 nodes case; (d) mobile sensor’s trajectories in 100 nodes case.

2 and 3, this phenomenon indicates that an asymptotically 1-connectivity (graph is 1-connected if it contains only one path between any pair of distinct vertices) graph structure is generated during the evolution of the network, such that the final configurations are sparse with only trivial signal conflicts.

The self-organized dispersion of MASNs in $\mathbb{R}^3$ space is also evaluated with similar simulation methodology. Sensors locate within 95% communication range of each other is connected by a blue line (see Figure 9), networks with 10 and 100 sensors are all investigated, and in both case, the initial locations are within $20 \times 20 \times 20$ m $\mathbb{R}^3$ space. Note that Corollary 12 may not hold in the case of 3-dimensional space coverage optimization, this is due to fact that the lower bound of the node degree cannot be obtained and a certain freedom of mobile sensors may not exist with respect to the uncertain structure of the networks. Therefore, we then conducted a simulation to study the coverage efficiency of proposed system $C$ with respect to different number of sensors. As it can be seen from Figure 10(c), with the aid of the proposed coverage enhancement system, 7 mobile sensors can cover an area up to 25000 m$^2$ in size (nearly the size of total 4 standard football fields), under the constrain of limited communication range ($R = 100$ m). The interagent distances between logical neighbors are converged into a constant value, which is above the minimum distance derived from Corollary 12, and the distances between nonlogical neighboring sensors are strictly above the communication range (see either Figures 10(a) or 10(b)). The results verified the proposed control system in
its capability of coverage enhancement. Moreover, as it can be seen from Figures 10(a) and 10(b), no interagent distance whatsoever can reach zero, which indicates that the proposed method can also effectively handle the issue of collision avoidance. Moreover, the simulation results unfolded in Figure 10 suggest that the lower bound of the neighbors’ distance can also be guaranteed in a network of 10 mobile sensors. The question of whether this is a common case in 3-dimensional space coverage enhancement will be investigated in our future research. Nonetheless, the capability of the coverage enhancement system in 3-dimensional space, for example, can cover up to $1.4 \times 10^6$ m$^3$ with 7 mobile sensors, is still fairly convincing.

It is worthwhile to notice that simulation results in $\mathbb{R}^3$ space are analogous to that in the case of $\mathbb{R}^2$ (see Figure 7), which entitles us to obtain the following conclusions.

**Correctness.** A variety of simulations in $\mathbb{R}^2$ and $\mathbb{R}^3$ spaces verified the correctness of the distributed control system for self-organized sensor dispersion, so that objectives can be achieved.

**Sensibility.** The required time for reaching the final configuration is distinctive in $\mathbb{R}^2$ and $\mathbb{R}^3$ spaces. The dimension-sensible property shows a better performance in spatial dispersion.

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**Figure 8:** Simulation results for 2D distributed mobile multiagent dispersion. (a) The converge of average number of physical neighbors and logical neighbors during simulation in 10 nodes case; (b) the converge of average number of physical neighbors and logical neighbors during simulation in 100 nodes case; (c) average velocity of mobile sensors during simulation in 10 nodes case; (d) average velocity of mobile sensors during simulation in 100 nodes case.
Figure 9: Evolution trajectory (snapshot) of 3D distributed dispersion of mobile sensors in different scales. (a) $n = 20$, $t = 1$; (b) $n = 20$, $t = 5$; (c) $n = 20$, $t = 15$; (d) $n = 20$, $t = 30$; (e) $n = 100$, $t = 1$; (f) $n = 100$, $t = 15$; (g) $n = 100$, $t = 40$; (h) $n = 100$, $t = 80$. 
Figure 10: The efficiency of the proposed connectivity control system. (a) Interagents distances in case of 2-dimensional coverage optimization; (b) interagents distances in case of 3-dimensional coverage optimization; (c) coverage area in case of 2-dimensional coverage optimization; (d) coverage space in case of 3-dimensional coverage optimization.

Sparseness. Despite of dimension and network capacity, the final configurations of the networks are always sparse with small node degrees.

6. Conclusions

Self-organized dispersion of mobile ad hoc sensor networks with guaranteed connectivity and collision avoidance is studied in this paper. A distributed self-organized control system combined with a local dynamic link removal algorithm, namely, DLRA, is proposed to reduce redundant communication links and regulate the dispersion of mobile sensors. The proposed control system can disperse a team of mobile sensors with guaranteed connectivity and collision avoidance, and the DLRA does not require access to the whole topology information, and thus, the proposed approach is scalable and will not invite excessive delays and communication overhead in large scale networks.

Several extensions to this presented work will be studied in future research: to apply the mobile sensor networks into indoor environment, we plan to study the dispersion of networked mobile sensors in nonconvex environments; the impact of wireless communication on the connectivity of multiagent system is another promising topic. The proposed
approach can also be extended for dispersion in leader-follower system and potential applications in hazardous and battlefield environments.

**Appendix**

**Proof of Theorem 11**

To facilitate the proof of Theorem 11, we first unfold the following lemmas.

**Lemma A.1.** For a mobile sensor network driven by the distributed control law defined by (2) and (8) with a set of initial condition \( J(\xi(t_0)) \equiv \{ \xi(t_0) \mid f_{ij}(t_0) < 1, \, i, \, j \in \mathcal{V}, \, i \in \mathcal{N}_j^{[1]}(t_0) \} \), then \( J(\xi(t)) \) is invariant for the trajectory of the closed-loop system.

**Proof.** Suppose that \( J(\xi(t)) \) varied at time \( t = t_r \), furthermore, assume the variant was irritated by \( f_{ij}(t_r) = 1 \), thus there exist a small positive constant \( \sigma(0 < \sigma < 1 - \varepsilon) \), that \( \bar{u}_i(t) \cdot (\xi_j(t) - \xi_i(t)) \geq 0 \) in every \((1 - \sigma, 1]\). Whereas, from the definition of (7), we know that \( \lim_{f_{ij}(t) ightarrow 1} \psi_{ij}(t) = \infty \), thus there exist a small positive constant \( \theta(0 < \theta < 1 - \varepsilon) \), that \( \bar{u}_i(t) \cdot (\xi_j(t) - \xi_i(t)) \leq 0 \) in every \((1 - \theta, 1]\), contradiction is reached, this completes the proof. \( \square \)

Lemma A.1 established collision avoidance between any pairs of sensors within each other’s physical neighbor set. Now we investigate the connectivity preservation capability of the motion controller in \( \hat{g}(t) \).

**Lemma A.2.** For a MASNs driven by the distributed control law defined by (2) and (8) with a set of initial condition \( J(\xi(t_0)) \equiv \{ \xi(t_0) \mid f_{ij}(t_0) > \varepsilon, \, i, \, j \in \mathcal{V}, \, i \in \mathcal{N}_j^{[1]}(t_0) \} \), then \( J(\xi(t)) \) is invariant for the trajectory of the closed-loop system.

**Proof.** Following the same methodology in the proof of Lemma A.1, we assume a variant of \( \bar{g}(\xi(t)) \) was irritated by \( f_{ij}(t_r) \ = \varepsilon \), thus there exist a small positive constant \( \sigma(0 < \sigma < \varphi - \varepsilon) \), that \( \bar{u}_i(t) \cdot (\xi_j(t) - \xi_i(t)) \leq 0 \) in every \( [\varepsilon, \varphi) \). Whereas, from the definition of (8), we know that \( \lim_{f_{ij}(t) ightarrow \varepsilon} \psi_{ij}(t) = \infty \) and \( \lim_{f_{ij}(t) ightarrow \varepsilon} \psi_i(t) = 0 \), thus there exist a small positive constant \( \theta(0 < \theta < \varphi - \varepsilon) \), that \( \bar{u}_i(t) \cdot (\xi_j(t) - \xi_i(t)) \leq 0 \) in every \( [\varepsilon, \varphi) \). We choose \( \sigma \geq \theta \), contradiction is reached, which completes the proof. \( \square \)

Lemmas A.1 and A.2 guaranteed that link connections are all preserved and interagent collisions are avoided during the dispersion between any two consecutive topology updates. On the other hand, the synchronization mechanism in DLRA causes delays in both link addition and link removal procedures in \( \hat{g}(t) \). We now show that the ineluctable delays cannot jeopardize network connectivity. Assume the interval time between two consecutive switches is \( \Delta T \), where \( \Delta T = n \cdot \Delta t, \, n \in \mathbb{N}^+ \), we have the following cases.

**Case 1.** \( j \not\in \mathcal{N}_i^{[1]}(t) \) at time \( t \), considering a small positive time-interval \( \tau \mid 0 < \tau < \Delta T \), assume \( j \not\in \mathcal{N}_i^{[1]}(t + \tau) \), thus \( \bar{g}(\xi(t)) \) is invariant for \( [t + \tau, t + \Delta T] \), where the communication links are rather unnecessarily maintained than disconneted.

**Case 2.** \( j \not\in \mathcal{N}_i^{[1]}(t) \) and \( j \not\in \mathcal{N}_i^{[1]}(t + \tau) \) at time \( t \), assume that \( j \in \mathcal{N}_i^{[1]}(t + \tau) \) and \( j \not\in \mathcal{N}_i^{[1]}(t + \Delta T) \), thus \( j \not\in \mathcal{N}_i^{[1]}(t + \Delta T) \). Since candidate link \((i, j)\) for link addition is redundant, connectivity is not violated. This result also hold for the case that \( j \not\in \mathcal{N}_i^{[1]}(t) \) and \( j \not\in \mathcal{N}_i^{[1]}(t + \Delta T) \), while hypothetically we assuming that \( j \in \mathcal{N}_i^{[1]}(t + \tau) \) and \( j \not\in \mathcal{N}_i^{[1]}(t + \Delta T) \).

Derived directly from the aforementioned analysis and Theorem 6, we conclude the proof of Theorem 11.

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