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Coverage Enhancement of Multi-Agent System with Network Constraints

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Abstract— **This paper addresses the issue of coverage enhancement using mobile multi-agent system in the presence of network constraints. The network of agents must always be globally connected for proper communication. The proposed method is composed of two steps which are topology control and potential field. The topology control involves appropriately selecting redundant links that restrict the spread of the system. Then, the potential field is used to disperse the agents towards the region of interest while preventing collisions. It also keeps the agents from going too far away from their corresponding topological neighbors so that the links are kept for global connectivity. This algorithm allows coverage enhancement even in compact system with arbitrary initial positions of agents.**

Keywords—Coverage control; Mobile multi-agent systems; Collision avoidance; Connectivity preservation

I. INTRODUCTION

The coverage enhancement of multi-agent system has become a widely researched field in the recent years. There are abundant uses to its applications including surveillance, exploration, task assignment and mobile sensor networks. A few specific examples in which coverage enhancement plays a key part are environmental monitoring and disaster management. In such applications as well as the ones that use multi-agent systems, data exchange and communication among agents are essential.

One of the greatest advantages of using more than one robot is the immense scale of data that could be acquired simultaneously. However, the data is meaningless if it cannot be delivered to where necessary when needed as the robots cannot actively collaborate with one another without updated information of their neighbors. Hence, a network in which all the agents are connected, otherwise known as globally connected network, is required. In actual systems, despite the high autonomy of robots, people should always be able to intervene and take control of the robots whether it be to access data or prevent failure of mission. Without global connectivity, some robots may stray off to an undesired condition and lower the efficiency of the whole system or even worse, compromise the entire mission.

The systems that people have direct access to are often stationary such as computers or control towers. However, the network range is limited Due to this constraint, the topology should be able to easily and rapidly modify itself to a suitable structure for effective coverage enhancement.

The importance of connectivity has been emphasized multiple times but network topology wise, an excessively dense network could be less practical than a sparse network as it causes radio interferences, a major cause of communication delays and errors. Hence, maintaining a certain level of connectivity and sparsity is key.

Besides topology control, another powerful tool for coverage enhancement is potential field. An appropriate potential field is required for avoiding collisions and guiding the robots towards a region of interest. Also, it is crucial to keep the distance between agents so coverage can be increased while maintaining the topological conditions mentioned above.

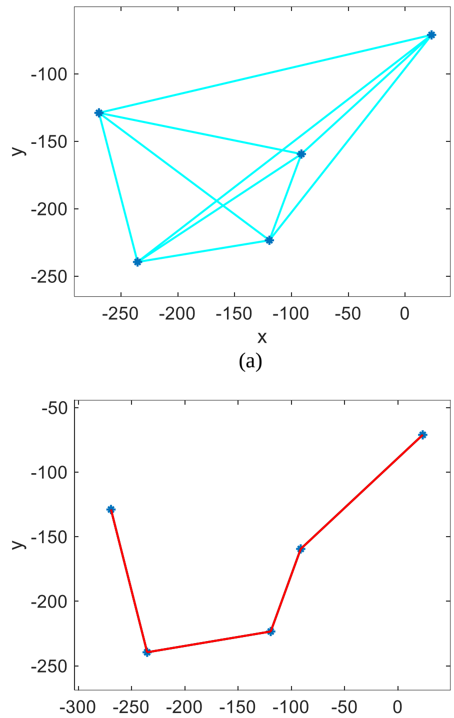
Many various coverage control and enhancement techniques have been proposed. In [1], an XTC algorithm was proposed in which redundant links were quickly and easily calculated. Connectivity is guaranteed but the network derived is not sparse enough to obtain a satisfactory level of coverage. A method suggested in [2], managed to obtain a sparser network by deleting redundant links in order to expand the coverage. In [3], a decentralized method that utilized a topology control algorithm similar to XTC was used. However, it did not address the issue of moving the mobile robots towards a region of interest.

In this paper, a method that uses topological control and a fitting potential field that satisfies the necessary conditions of the pertaining topology was suggested. The topology control which uses the same algorithm as [3] is a decentralized method that determines the redundant links. These links restrict the coverage from expanding due to the network range limit. The primary goal of the potential field is to disperse the agents with collision avoidance. It should also be able to drive the agents toward a region of interest while spreading out. One of the agents is considered the base and thus cannot move. The above two tools put together can disperse a compact multi-agent system with guaranteed connectivity and collision avoidance.

II. PRELIMINARIES

A unit disk graph is a type of topology in which all the agents in the network range are connected. Another variation of topology is Minimum Spanning Tree (*MST*) that has minimum possible total edge weight when all the nodes are connected.

When there are N number of mobile agents, an undirected dynamic graph of communication links among agents is denoted as $\mathcal{G}(t) = (\mathcal{V}, E(t))$ where $\mathcal{V}$ is the set of vertices that represents the agents $i \in [1, \dots, N]$ and $E(t)$ is the communication links. The Euclidean distance between agent i and j is denoted as a_{ij} and it cannot be greater than the



(a)

(b)

Fig. 1. Variations of topology. (a) Unit disk graph; (b) Minimum spanning tree.

network range if the two agents are to be one-hop neighbors of each other. An undirected dynamic graph $\mathcal{G}(t)$ is globally connected if there is at least one path from an arbitrary agent to all the other agents. A subgraph $\mathcal{G}_s(t) = (\mathcal{V}, E_s(t))$ of $\mathcal{G}(t)$ has only the essential links that keep the global connectivity where E_s is the set of essential communication links.

Definition 2.1: Node j is in the physical neighbor set of i, denoted as $j \in \mathcal{N}_p^{[i]}(t)$, if and only if $(i, j, t) \in E(t)$.

Definition 2.2: Node j is in the logical neighbor set of i, denoted as $j \in \mathcal{N}_l^{[i]}(t)$, if and only if $(i, j, t) \in E_s(t)$.

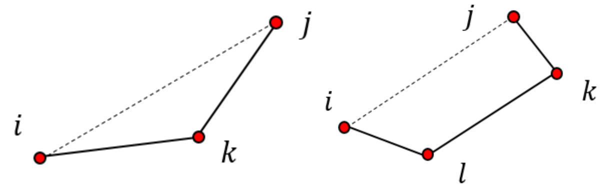
III. Topology Control

The suggested topology control involves determining redundant link candidate set ${C_d}^{[i]}(t)$ for each agent locally and synchronizing the redundant link set globally. For each agent, the only available information is information of itself, its one-hop neighbors and two-hop neighbors. The information includes the locations and the Euclidean distances from all the physical neighbors.

A. Redundant link candidate determination

From the information gathered by up to two-hop neighbors, it is possible to create a Neighbor Relationship Matrix (*NRM*). NRM is denoted $\mathcal{N}_r^{[i]}(t) = (a_{jk}(t))$ where $j \in \mathcal{N}_l^{[i]}(t)$ and $k \in \mathcal{N}_l^{[j]}(t)$ at time t.

Determining the redundant link candidates involves two steps. In the first step, each agent compares the length of the edges formed by the triangle comprised of itself, one-hop neighbor and two-hop neighbor agents. Then the longest link of the triangle is determined as the redundant link candidate.



(a) (b)

Fig. 2. Redundant link candidate determination. (a) Step 1; (b) Step 2.

As shown in Fig. 2 (a), due to the longest distance $a_{ij} = \max\{a_{ij}, a_{ik}, a_{jk}\}$, link between i and j is considered the redundant link. The second step is similar to the first and it is used for making the network sparser. Its main purpose is to delete most of the paths to a two-hop neighbor when there are more than one path. Using the neighbor relationship matrix, $\mathcal{N}_r^{[ik]}(t) = [a_{jk}(t), a_{lk}(t), \ldots, a_{nk}(t)]$ can be constructed. $\mathcal{N}_r^{[ik]}$ is the distance from a two-hop neighbor k to all the agents in $\mathcal{N}_l^{[i]}$. From the matrix, all the links that meet the condition of $a_{ij}(t) = \max\{a_{ij}(t), a_{il}(t), a_{jk}(t), a_{lk}(t)\}$ are regarded as the redundant link candidate.

B. Synchronization of dynamic graph

As the system utilizes a decentralized method, it is difficult to synchronize the redundant links among agents. For some agents, they could be the redundant link candidates of an agent, but those same agents may not consider the agent as a redundant link candidate. Hence, synchronization is a challenging yet necessary process.

TABLE I. Algorithm

Redundant link candidate determination
Set time $\boldsymbol{t} = \boldsymbol{t_0}$. Initialize $\boldsymbol{\mathcal{N}_p^{[i]}}(\boldsymbol{t_0})$ and set $\boldsymbol{\mathcal{N}_l^{[i]}}(\boldsymbol{t_0}) = \boldsymbol{\mathcal{N}_p^{[i]}}(\boldsymbol{t_0})$. Construct $\boldsymbol{\mathcal{N}_r^{[i]}}(\boldsymbol{t_0})$.
For $\boldsymbol{i} \in \boldsymbol{\mathcal{V}}$
for $\forall \boldsymbol{k} \in \boldsymbol{\mathcal{N}_r^{[i]}}(\boldsymbol{t_0})$
if $\boldsymbol{a_{ij}(t_0) = \max\{a_{ij}(t_0), a_{ik}(t_0), a_{jk}(t_0)\}}$
$\boldsymbol{{C_d}^{[i]}(t_0 + \Delta t) := {C_d}^{[i]}(t_0) \cup \{j\}}$
end if
end for
Update $\boldsymbol{\mathcal{N}_r^{[i]}(t), {C_d}^{[i]}(t)}$
for $\forall \boldsymbol{k} \in \boldsymbol{\mathcal{N}_r^{[i]}(t)}$
while $\boldsymbol{a_{jk}(t) \times a_{lk}(t) \neq 0}$ **do**
if $\boldsymbol{a_{ij}(t) = \max\{a_{ij}(t), a_{il}(t), a_{jk}(t), a_{lk}(t)\}}$
$\boldsymbol{{C_d}^{[i]}(t + \Delta t) := {C_d}^{[i]}(t) \cup \{j\}}$
end if
end while
end for
End

To achieve this, request and acknowledge messages are used. Simply put, once an agent is considered a redundant link candidate of an agent, it is sent a request message checking if they are a redundant link candidates of each other. Then, an acknowledgement message is sent back if the agent is indeed a redundant link candidate. For example, if agent $j \in C_d{}^{[i]}$, agent i sends a request message to agent j. Upon receiving the request message, agent j checks if $i \in C_d{}^{[j]}$. If agent i is in the redundant link candidate set, then agent j sends an acknowledgement message to agent i. Next, i is removed from logical neighbor set of agent j and vice versa which results in $i \notin \mathcal{N}_l^{[j]}$ and $j \notin \mathcal{N}_l^{[i]}$. This confirmation process is absolutely crucial because deleting a link may lead to violation of global connectivity although connection may not be a problem.

As shown, the topology control process uses the information of distance, so it is important to generate the network topology when the agents are stationary. Once, the topology is set, potential field is used to guide the mobile robots.

C. Properties of the dynamic graph

By using the above topology control algorithm, certain properties can be observed. If a dynamic graph of $\mathcal{G}(t) = (\mathcal{V}, E(t))$ is given as initial condition, subgraph $\mathcal{G}_s(t) = (\mathcal{V}, E_s(t))$ is always globally connected. To prove this, one has to beware only the synchronization step because adding a link does not cause global disconnection. Take two agents, agent i_0 and i_n that are initially connected in $\mathcal{G}(t)$ by a path comprised of different nodes i.e., $i_0 \leftrightarrow i_1 \leftrightarrow i_2 \leftrightarrow \cdots \leftrightarrow i_n$. If any of the nodes in between are considered i_k or i_{k+1} and not directly linked, the following can be shown.

$\exists\, u$ where $u \in \mathcal{N}_l^{[i_k]}$ and $u \in \mathcal{N}_l^{[i_{k+1}]}$. It can be seen from the algorithm that $a_{i_k i_{k+1}} = \max\{a_{i_k i_{k+1}}, a_{i_k u}, a_{i_{k+1} u}\}$, so only the link between i_k and i_{k+1} is deleted.

$\exists\, u, v$ where $u \in \mathcal{N}_l^{[i_k]}$, $u \in \mathcal{N}_l^{[v]}$ and $v \in \mathcal{N}_l^{[i_{k+1}]}$. It can be seen from the algorithm that $a_{i_k i_{k+1}} = \max\{a_{i_k i_{k+1}}, a_{i_k u}, a_{i_{k+1} v}, a_{uv}\}$, so only the link between i_k and i_{k+1} is deleted.

Hence, the connectivity is preserved at all times because any two arbitrary nodes are connected by at least one route.

In addition, in order to have certain level of sparsity, there should be a lower bound to the cycle. By the redundant link determination process, it is not possible to have a cycle smaller than five. The first part of the algorithm prevents cycle of three while the second part prevents cycle of four. In other words, the shortest cycle would be $i \leftrightarrow j \leftrightarrow k \leftrightarrow l \leftrightarrow m \leftrightarrow i$.

IV. Potential Field

The potential field is useful for such coverage enhancement problems. It does not require intense calculation that is computationally heavy. Also, it only requires the location of the neighbors and the destination. After some time, the agents reaches local minima that cancels out the push and pull from obstacles and neighbors. If the gains of the push and pull are set appropriately, the agents push each other far enough to achieve coverage enhancement.

The primary goal is to disperse the agents while maintaining global connectivity. The topology structure that guarantees global connectivity is given by the logical neighbor set from the topology control. If multi-agent system always keeps the unit disk graph as communication links, all the agents within the network are physical neighbors. For coverage enhancement, the physical neighbors should push each other away from their communication range. Hence, repulsive force acts upon all the physical neighbors within the range. The repulsive force $R_{ij}(a_{ij})$ on agent i due to physical neighbor j is inversely proportional to the distance.

The combined repulsive force R_i on agent i from all the physical neighbors is as follows:

$$R_i = \sum_{j \in N_p^{[i]}(t)} \frac{K_r}{a_{ij}} * (\cos\theta_i * \vec{u} + \sin\theta_i * \vec{v}) \quad (1)$$

In the above equation, $\vec{u}$ and $\vec{v}$ are the unit vectors of the 2D-Cartesian coordinate system while θ_i is the angle formed by the link between agent i and j.

If $a_{ij} > R$ where R is the communication range, then R_i = 0. This allows the physical neighbors to go slightly over the communication range.

The logical neighbors are also physical neighbors, so they are pushed away as well which is acceptable up to certain extent. However, to preserve global connectivity, the logical neighbors must be within communication range. Therefore, attractive forces from logical neighbors act when the logical neighbors are nearly at the boundary of communication range. Highest weighting is given to this term so that the logical neighbor link is always kept. The attractive force $A_{ij}(a_{ij})$ on agent i due to logical neighbor j is inversely proportional to the distance.

The combined attractive force A_i on agent i from all the logical neighbors is as follows:

$$A_i = \sum_{j \in N_l^{[i]}(t)} \frac{K_a}{a_{ij}} * (\cos\theta_i * \vec{u} + \sin\theta_i * \vec{v}) \quad (2)$$

If $a_{ij} > R$ or $a_{ij} < 0.9 * R$, then $A_i = 0$. This drives the logical neighbors close to the boundary of the communication range without going over it.

Next, the center of the region of interest that needs to be explored, indicated as $d(x, y)$, should also cause attractive force on the agent so that the agents spread out in the desired direction. The attractive force from the center of the destination on agent i, D_i is proportional to the distance from agent i to $d(x, y)$ denoted as a_{id}. One difference from the above two force functions is that the gain reduces with time. It is designed as such in order to reduce the weighting of attraction from the destination. Otherwise, excessive chattering occurs as the outer agents try to move towards the destination and thereby becoming a redundant neighbor.

$$D_i = K_d(t) * a_{id} * (\cos\theta_i * \vec{u} + \sin\theta_i * \vec{v}) \quad (3)$$

For every agent, the velocity of an agent i denoted m_i is the sum of all the forces.

$$m_i = -R_i + A_i + D_i \quad (4)$$

After some iterations of the potential field, there could be agents that are unable to move towards the region of interest due to the stationary base. Some agents are logical neighbors of the base and therefore cannot go near the region of interest. This problem can be easily solved by reconfiguration of topology control. As the topology control is operated by the distances between agents, a new configuration will be

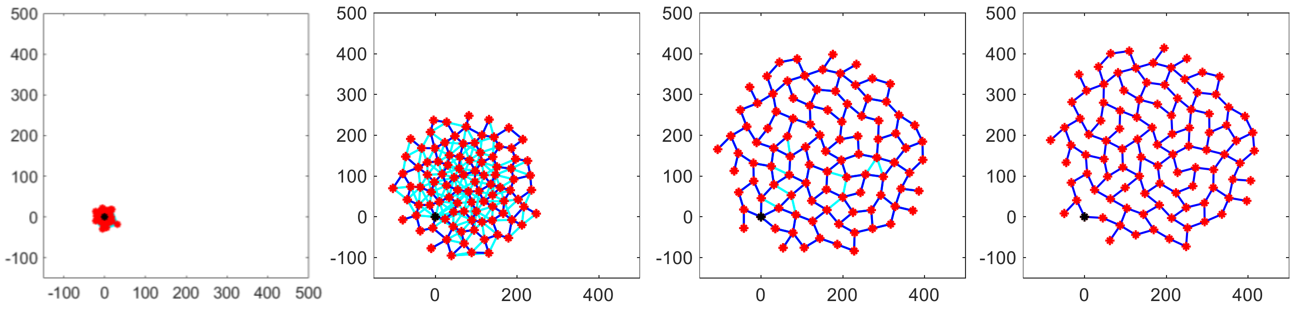


Fig. 3. Simulation of potential field iterations. (a) Initial condition; (b) 100 iterations; (c) 1000 iterations; (d) End of potential field: 2123 iterations.

obtained from the new distances resulting from the potential field. In other words, topology has to be updated regularly for the potential field to operate effectively.

V. Simulation

The proposed method was implemented and simulated in order to verify its performance. A total of 100 agents with network range of 50 m were used. The center of region of interest was set to be (200, 200). The gains were set as $K_r = 20, K_a = 40, K_d(t) = \frac{1}{100+5t}$. The stationary base is at (0, 0) and the topology was recalculated after every 100 potential field iterations.

The entire simulation took 2123 iterations of the potential field for the physical neighbors to converge to the logical neighbors. In Fig. 3, the red dots are mobile agents and the black dot is the base station. The logical neighbor link is shown in dark blue line while the excessive physical neighbors are represented by light blue. As it can be seen from Fig. 3 (d), there are no more physical neighbors other than the logical neighbors. The coverage is visibly increased as compared to the initial condition. The resulting formation shows coverage area of 259,013 m^2. For comparison, same potential field was used to spread the unit disk graph of the same initial condition. The resulting coverage area without the topology control was 30,794 m^2 which is significantly smaller than the result obtained using the suggested method.

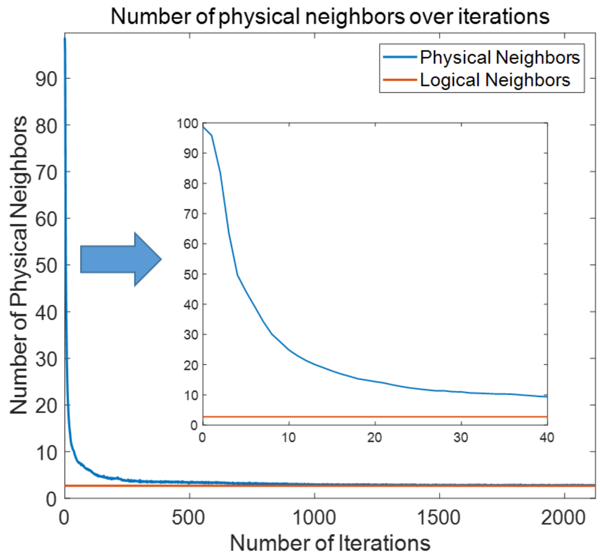


Fig. 4. Convergence of physical neighbors to logical neighbors.

One of the problems discovered was the chattering effect. As the agents pushed and pulled in compact space, there were some oscillations observed in the number of excessive physical neighbors. It can be observed that the number of physical neighbors sharply decreases at the beginning from Fig. 4. It decreased to approximately 10% of the initial value in less than 40 iterations. However, it took a lot more iterations for the physical neighbor set to completely become logical neighbor set.

VI. Conclusion

The topic of coverage enhancement is an increasingly important issue in the field of robotics due to its practical and efficient use for data collection. With recent advancements of autonomous systems, multi-agent systems can utilize decentralized method in which the robots can operate by processing local information and communicating with other robots. To increase the coverage by multi-agent system, a sparse network must be set. However, as agents only have local information, it is challenging to maintain global connectivity while generating a sparse network.

A method of topology control with potential field was suggested to address this matter. First, it calculated a sparse network while preserving global connectivity. Then, potential field was used to increase coverage and direct the robots to a region of interest while avoiding collisions. Due to the unmoving base station, the topology had to reconfigure itself regularly. Simulation of the algorithm was performed and it showed substantial increase of coverage.

References

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