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A Distributed Approach to Area Coverage for Dynamic Sensor Networks

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Abstract: In this paper a distributed solution to the area coverage problem for dynamic sensor networks is given. Collisions avoidance and communication network connectivity maintenance constraints are considered. The distributed approach, despite its lower performances with respect to the global one, shows several advantages, from reduced computational costs to lighter communication traffic and then lower energetic costs. Simulation results show some of such advantages and put in evidence the effectiveness of the proposed solution. *Copyright © 2009 IFSA.*

Keywords: Sensor networks, Dynamical configuration, Mobile sensors, Connectivity maintenance, Area coverage

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1. Introduction

Sensor networks are up to date solutions for a large number of applications where the area over which the measurements have to be taken is so much large that more sensors must be used, very often with a wireless connection for communications and data exchange. In this case, the set of sensors have to cover the maximum amount of area under detection. Then, it is easy to understand how coverage represents a key measure of the quality of service provided by a sensor network. Considering static sensors, the coverage problem has been addressed in terms of optimal usage of a given set of sensors, randomly deployed, in order to assure full coverage and minimizing energy consumption ([2, 25, 22]), or in terms of optimal sensors deployment on a given area ([19, 20, 5, 17, 26]).

The introduction of mobile sensors makes possible to develop networks in which sensors, starting from an initial random deployment, evaluate their own state and move to optimal locations ([18, 15, 8, 6, 21, 23]), where they remain fixed while operate.

Once the sensors can move autonomously in the environment, it seems reasonable that the measurements can be performed also during the motion, instead of waiting their final positions. Moreover, the final position itself can become not relevant if the measurements are achieved continuously during motion (*dynamic coverage*). In fact, under the assumption, reasonable in many applications, that synchronous or asynchronous discrete time measures are acceptable instead of continuous ones, the number of sensors can be strongly reduced making use of the measure-during-motion approach. Moreover, faults or critical situations can be faced and solved more efficiently, simply acting on the network dynamics, changing paths of the working sensors.

Clearly, coordinated motion of such *dynamic sensors network* imposes additional requirements, such as collisions avoidance or some communication preservation between sensors. In order to better motivate why and when a mobile sensor network can be a more successful choice than a static one, some considerations are reported, showing, in a first approximation, the advantages. So, given an area A_{tot} to be measured by a sensor network, and ρ_S the range of measure of each sensor (sensors are here supposed homogeneous, otherwise, the same considerations should be repeated for all the homogeneous subnets), the number N_{stat} of sensors needed for a static network must satisfy

$$N_{stat} \geq \frac{A_{tot}}{\pi \rho_S^2} \tag{1}$$

If a dynamic network is considered, the area covered by sensors is a time function and, clearly, it does not decrease as time passes. A simplified discrete time model of the evolution of the area still uncovered, at (discrete) time $t = k + 1$, by a dynamic sensor network moving with the strategy proposed hereinafter, can be given by the following differences equation

$$A_u(k+1) = \left(1 - \frac{A_N}{A_{tot}}\right) A_u(k), \tag{2}$$

where

$$\dot{A}_N = \frac{v_{max}}{2\,\rho_S} A_{tot} \left(1 - \left(1 - \frac{\pi \rho_S^2}{A_{tot}}\right)^N\right)$$

represents the area covered in the time unit by a number N of mobile sensors subject to the maximum motion velocity v_{max}. Measurement acquisition is then modeled as obtained deploying randomly N static sensors on the workspace every $\frac{2\,\rho_S}{v_{max}}$ second.

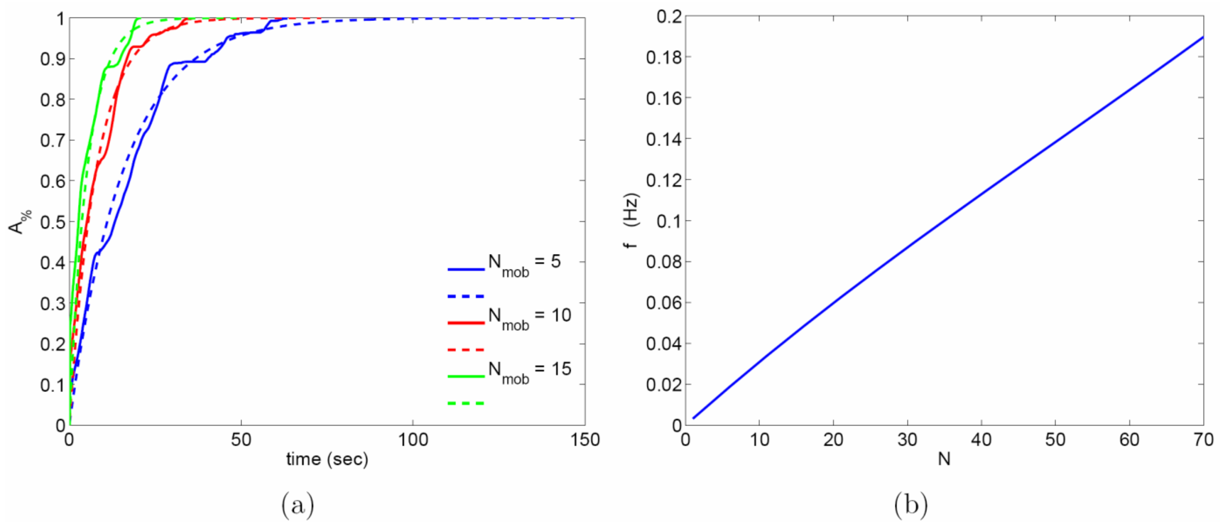
Denoting by

$$A_u(0) = A_{tot}\left(1 - \frac{\pi \rho_S^2}{A_{tot}}\right)^N$$

the initial condition for the area to be covered, at each discrete time $t = k$ the fraction of area covered is given by

$$A_{\%}(k) = 1 - \frac{A_u(k)}{A_{tot}} = 1 - \left(\frac{A_u(0)}{A_{tot}}\left(1 - \frac{A_N}{A_{tot}}\right)^k\right) \tag{3}$$

The evolution computed using (3) with $N = 5$, $N = 10$ and $N = 15$ has been compared with the results of simulations where the approach described in the sequel of the paper is applied. In Fig. 1 this comparison is reported, showing that (3) is a good model for describing the relationship between the area covered with respect to the time, using a dynamic solution.



(a) (b)

Fig. 1. (a) Comparison between coverage evolution obtained by the model (2) (*dashed*) and simulations of the proposed coverage strategy (*solid*) for different numbers of moving sensors. (b) Relationship between the number of sensors in the network (abscissa) and the rate of the area coverage (ordinate).

Referring, for fixing the ideas, to surveillance tasks, (3) can be used to evaluate the minimum number of sensors (with given ρ_S and v_{max}) required to cover a given fraction $\tilde{A}_{\%}$ of the area of interest according to a given measurement rate. In fact, it is possible to write the relation between the maximum rate at which the network can cover the $\tilde{A}_{\%}$ fraction of A_{tot} and the number of moving sensors as

$$f = \frac{\log\left(1 - \frac{A_N}{A_{tot}}\right)}{\log(1 - \tilde{A}_{\%}) - N\log\left(1 - \frac{\pi\rho_S^2}{A_{tot}}\right)} \tag{4}$$

Such a relationship between N and f is depicted in Fig. 1(b), showing, as intuitively expected, almost a proportionality between number of sensors and frequency of measurement at each point of the area A_{tot}. The motivation and the support of the dynamic solution are then evidenced by such a figure: lower is allowed to be the refresh frequency of the measurements at each point (that is higher are the time intervals between measurements) and lower can be the number of sensors required, once sensors motion is introduced.

Under the assumption of dynamic network, the area coverage problem is posed in terms of looking for optimal trajectories for the N moving sensors in presence of some constraints like communication connection preservation, motion limitations, energetic considerations and so on. In [23, 3] some results about the dynamic coverage problem for multiple sensors are reported, making use of a variational approach, in the level set framework; obstacles occlusions are considered and suboptimal solutions are proposed also in three dimensional environments ([4]). A survey of coverage path planning algorithms for mobile robots moving on the plane is presented in [7]. In [1] the dynamic coverage problem for one mobile robot with finite range detectors is studied and an approach based on space decomposition and Voronoi graphs is proposed.

In [16], a distributed control law is developed that guarantees to meet the coverage goal with multiple mobile sensors under the hypothesis of communication network connection. Collisions avoidance is considered.

Various problems associated with optimal path planning for mobile observers such as mobile robots equipped with cameras to obtain maximum visual coverage in the three-dimensional Euclidean space are considered in [24]. Numerical algorithms for solving the corresponding approximate problems are proposed.

In [10, 11, 12] a general formulation of dynamic coverage is given by the authors, a sensor network model is proposed and a centralized optimal control formulation is given. Suboptimal solution is computed by discretization. Sensors and actuators limits, geometric constraints, collisions avoidance, and communication network connectivity maintenance are considered.

In this paper a distributed approach to the dynamic coverage is proposed, following an approach previously introduced in [13, 14]. All constraints are considered including connectivity maintenance without imposing a fixed topology to the communication network.

With respect to a centralized approach, a distributed one is more efficient and can be used for online applications. However, a distributed approach is obviously less performing in terms of coverage.
In Section 2 the proposed mathematical model is shortly recalled. In Section 3 the distributed approach to the coverage problem, according to the constraints, is presented. Section 4 is devoted to the presentation of some simulation results. Some final comments end the paper.

2. Mathematical Model

In the computation of the mathematical model the assumption of homogeneous sensor devices is performed, that is all the sensors are assumed to have the same characteristics. This is done only for sake of simplicity in the notations since, clearly, the proposed approach applies also to non homogeneous sensors systems: an additional index should be added to all variables and, somewhere, sums over such an index may be required.

The model and the examples are illustrated for a motion on the plane (2D). Easy and obvious addictions should be performed for motion in the three dimensional space.

2.1. Motion

Under the simplifying hypothesis, each mobile sensor is modeled, from the dynamic point of view, as a material point of unitary mass, moving on a bi-dimensional space W, referred to as the *set of interest*, under the action of an input force named $u^{(i)}(t)$ for the i-th sensor. The motion equation is then

$$\ddot{x}^{(i)}(t) = u^{(i)}(t)\,, \tag{5}$$

where $x^{(i)}(t)$ represents the position of the i-th sensor in W at time t.

2.2. Sensing

The set of interest represents the area to be covered with sensors measurements.

Each mobile sensor at time t is assumed to take measures within a circular set of radius ρ_S around its current position $x^{(i)}(t)$. Such a set under sensor *visibility* will be denoted as

$$M^{(i)}(t) = \sigma\left(x^{(i)}(t), \rho_S^{(i)}\right) \cap W \tag{6}$$

Taking into account the whole system, it is possible to define the *generalized visibility set* as

$$M(t) = \cup_i M^{(i)}(t) \tag{7}$$

2.3. Communication

In this paper a proximity communication model is used. For every mobile sensor the communication function is given by

$$k(x^{(j)}, x^{(h)}) = \rho_C - \left|x^{(j)} - x^{(h)}\right| \tag{8}$$

If $k\left(x^{(j)}, x^{(h)}\right) \geq 0$ there is a direct link between nodes j and h. The communication network is then modeled as an Euclidean graph G and, being the nodes mobile, the graph results to be time dependent ($G(t)$). Two mobile sensors are assumed to be able to communicate each other at time t if the distance between them is smaller than a given communication radius ρ_C. It is easy to check that this communication function makes the network graph $G(t)$ undirected; in fact

$$k\left(x^{(j)}, x^{(h)}\right) = k\left(x^{(h)}, x^{(j)}\right) \forall\, i, h$$

2.4. Statement of the Coverage Problem

Given a time interval $\Theta = [0, t_f]$ and a generalized trajectory $x(t)$ for the sensor set, it is possible to define the subset of W covered by the sensors fields of measure during the motion as the union of the measure fields at every configuration $x(t)$ with $t \in \Theta$

$$M^{\Theta} = \bigcup_{t \in \Theta} M(t) \tag{9}$$

The area covered by the sensors in the time interval Θ is then the measure $A^{\Theta} = \mu(M^{\Theta})$ and the coverage problem consists of maximizing A^{Θ} according to some constraints.

3. The Distributed Approach

In this paper a distributed approach to the area coverage with moving sensors is proposed. First of all the constraints considered are to be modeled for a proper inclusion in the computation performed.

3.1. Geometric Constraints

Collisions between sensors must be avoided. Then, for any time *t*, the following relationship must be true

$$\left|x^{(i)}(t) - x^{(j)}(t)\right| \geq \rho_B$$

for $i \neq j$.

3.2. Dynamic Constraints

Physical limits on the actuators (for the motion) and/or on the sensors (in terms of velocity in the measure acquisition) suggest the introduction of the following additional constraints

$$\dot{x}(t) \leq v_{max}$$
$$u(t) \leq u_{max}$$

that introduces a maximum velocity considered acceptable for motors speed of the mobile platforms and able to guarantee enough time for a sensor detection of any field point to perform the measurements correctly.

3.3. Connectivity Maintenance

For dynamic networks, assuring continuous connectivity involves the introduction of constraints on the motion of nodes. As said before, the communication model introduced in 2.3 makes the communication graph $G(t)$ undirected. An undirected graph is connected if it contains a spanning tree.

Assuming $G(t)$ to be connected at time $t = 0$ ($G(0)$ connected), it is possible to maintain network connectivity just maintaining links that belong to a spanning tree. Let us denote by E_G the set of edges of G; setting a weight for every edge of E_G, it is possible to define the *Minimum Spanning Tree* (MST) of G as the spanning tree with minimum weight. In particular, being G an Euclidean graph, it comes natural to define the edges weights as

$$w\left(x^{(j)}, x^{(h)}\right) = \left|x^{(j)} - x^{(h)}\right|$$

and in this case the minimum spanning tree is said *Euclidean* (EMST).

If the positions of all the sensors are known, the EMST can be easily and efficiently computed by standard well known algorithms (for example Kruskal's algorithm, Prim's algorithm, etc. [8]). Indicating the EMST of $G(t)$ by $T_G(t)$, in order to maintain communication network connectivity the following constraints must be imposed to sensors positions

$$\left|x^{(j)}(t) - x^{(h)}(t)\right| \leq \rho_C \; \forall \left(\sigma_j, \sigma_h\right) \in E_{T_G(t)}, \forall t \qquad (10)$$

In this section an approximation T_G^* of T_G is computed in distributed way, making use of local information only.

Denoting by V_X the set of vertexes of the graph X in the same way as E_X denotes, as previously said, the set of edges of the graph X, the graph T_G^* is defined as

$$T_G^* = < V_{T_G^*}, E_{T_G^*} >,$$

where

- $V_{T_G^*} = V_G$;
- $E_{T_G^*} = \left\{e_{i,j} \in E_G^i \;\middle|\; e_{i,j} \in T_{G_i}\right\}$;
- G_i is the Euclidean graph that contains the node q_i and its neighbours as vertexes ($G_i \subset G$);
- T_{G_i} is a MST of G_i;
- E_G^i is the set of edges of G connected to q_i ($E_G^i \subset E_{G_i} \subset E_G$).

T_G^* is a connected sub graph of G that contains T_G; it has the same nodes of G but only a subset of its edges.

It's well known that a spanning tree T must satisfy the following property, named *cycle property*:

Property 3.1 *For any cycle C in G, if the weight of an edge $e_{i,j}$ of C is greater than the weights of other edges of C, then such an edge cannot belong to* T.

Making use of the cycle property, it is possible to prove the following theorem

Theorem 3.1 T_G^* *contains a minimum spanning tree T_G of G.*

Proof: consider an edge $e_{i,j} \in E_G^i$ that belongs to a MST T_G of G. If $e_{i,j} \notin E_{T_{G_i}}$ (and then $e_{i,j} \notin E_{T_G^*}$), there exists a cycle $C_{G_i} \subset G_i$ such that $e_{i,j} \in E_{C_{G_i}}$ and there exists another edge $e_{i,k} \in E_G^i$ such that $e_{i,k} \in E_{C_{G_i}}$ and $e_{i,k} \in E_{T_{G_i}}$ (and then $e_{i,j} \in E_{T_G^*}$).

Being T_G a MST, for the cycle property it must be true that

$$w(e_{i,j}) \leq w(e_{i,k})$$

At the same time, being T_{G_i} a MST too, for the same property also

$$w(e_{i,k}) \leq w(e_{i,j})$$

must hold. As a consequence,

$$w(e_{i,j}) = w(e_{i,k})$$

must be true.

Than is easy to see that the graph $\hat{T}_G \subset G$, obtained by T_G replacing the edge $e_{i,j}$ by the edge $e_{i,k}$ is also a MST of G and $\hat{T}_G \subset T_G^*$.

Each sensor i can then compute the constraints necessary to maintain, at every time, the edges of T_G^*, and then communication network connectivity, just knowing the position of its neighbours j such that $e_{i,j} \in T_{G_i}$.

3.4. Control

At each sample time kT_S the control input for the i-th sensor is computed according to the sensor position, the positions of its neighbours and the map coverage state

$$u^{(i)}(k) = u_C^{(i)}(k) + u_I^{(i)}(k) \tag{11}$$

3.4.1. Coverage

The first addendum of (11) describes the *virtual force* that attracts the sensors to the unmeasured cells and drives them to cover the workspace. Let us perform a uniform space discretization on W with resolution r obtaining a grid Γ_W. The set W is said to be covered if every point $p \in \Gamma_W$ is visited by one sensor, where visited obviously means that, for at least one value of i and for a time t,

$$|d_p^i| = |x^{(i)} - p| \leq \rho_S$$

Let us assume that every sensor knows the coverage status of Γ_W at each time.

Theorem 3.2 *Let*

$$\gamma_p = \begin{cases} 0 & \mathit{if\ the\ point}\ \ p \in \Gamma_W\ \mathit{has\ been\ visited} \\ 1 & \mathit{otherwise} \end{cases}$$

Applying the following control input to the i*-th sensor*

$$u_C\left(x^{(i)}\right) = \sum_{p\,\in \Gamma_W} \gamma_p \frac{d_p^i}{\left|d_p^i\right|^2}$$

the sensor network is driven to totally cover W*.*

Proof

First, notice that

$$u_i = 0 \;\Rightarrow \begin{cases} \gamma_p = 0 & \forall p, \qquad (W\ \mathit{is\ totally\ covered}) \\ \gamma_p \neq 0 & \mathit{for\ some}\ p \end{cases}$$

Let us now assume that $\gamma_p \neq 0$ for some p. If there is not any equilibrium point, the control (12) with the u_C^i term makes the sensors move. On the other hand, if there exist equilibrium points, for example for the i-th sensor, $x^{(i)} = x_e$, a small perturbation makes it move from x_e to an unmeasured point p ($\gamma_p \geq 0$). In fact, defining Δx such a perturbation, it is possible to show that there exists a neighbourhood $\mathcal{N}_e$ of x_e such that

$$\Delta x^T \sum_{p\,\in \Gamma_W} \gamma_p \frac{d_p^i}{\left|d_p^i\right|^2} > 0$$

Observing that $d_p^i = d_{p,e}^i - \Delta x$,

$$\Delta x^T \sum_{p\,\in \Gamma_W} \gamma_p \frac{d_p^i}{\left|d_p^i\right|^2} = \sum_{p\,\in \Gamma_W} \gamma_p \frac{\Delta x^T\, d_{p,e}^i - |\Delta x|^2}{\left|d_{p,e}^i\right|^2 + |\Delta x|^2 - 2\,\Delta x^T\, d_{p,e}^i}$$

Since $0 < \Delta x \ll 1$, $|\Delta x|^2 \ll \Delta x \ll 1$. Then the term $|\Delta x|^2$ can be neglected with respect to all the other terms, so giving

$$\sum_{p\,\in \Gamma_W} \gamma_p \frac{\Delta x^T\, d_{p,e}^i - |\Delta x|^2}{\left|d_{p,e}^i\right|^2 + |\Delta x|^2 - 2\,\Delta x^T\, d_{p,e}^i} \approx \sum_{p\,\in \Gamma_W} \gamma_p \frac{\Delta x^T\, d_{p,e}^i}{\left|d_{p,e}^i\right|^2 - 2\,\Delta x^T\, d_{p,e}^i} > \sum_{p\,\in \Gamma_W} \gamma_p \frac{\Delta x^T\, d_{p,e}^i}{\left|d_{p,e}^i\right|^2} = 0$$

Then, sensor i escapes from x_e and moves to points p such that $\gamma_p > 0$. Sensors stop only when $\gamma_p = 0$.

3.4.2. Interaction

The second addendum of (11) describes the *interaction virtual force*. This force depends on the distances and relative velocities between the sensor and their neighbours. Defining

$$
\begin{aligned}
d_{i,j} &= x^{(j)} - x^{(i)} \\
v_{i,j} &= \dot{x}^{(j)} - \dot{x}^{(i)} \\
\rho_{i,j} &= \left| d_{i,j} \right| \\
\dot{\rho}_{i,j} &= \frac{d_{i,j}^{T}\, v_{i,j}}{\rho_{i,j}}
\end{aligned}
$$

the functional structure of the interaction force is given by

$$
u_I^{(i)} = \sum_j \left(e^{(\rho_{i,j}-\rho_B)^{-2}} \frac{d_{i,j}}{\rho_{i,j}} + e^{\left(\dot{\rho}_{i,j}-v_B^{i,j}\right)^{-2}} v_{i,j} \right) - \sum_{y|A(i,y)=1} \left(e^{(\rho_{i,y}-\rho_C)^{-2}} \frac{d_{i,y}}{\rho_{i,y}} + e^{\left(\dot{\rho}_{i,y}-v_C^{i,y}\right)^{-2}} v_{i,y} \right),
$$

where

$$
\begin{aligned}
v_B^{i,j} &= \sqrt{u_{max}\left(\rho_{i,j} - \rho_B\right)} \\
v_C^{i,j} &= \sqrt{u_{max}\left(\rho_C - \rho_{i,j}\right)}
\end{aligned}
$$

represent the limit velocities that, considering the actuators limits, allow the system to avoid collisions (v_B) or to maintain topology (v_C). If the distance between sensors is far from critical values (ρ_B and ρ_C), the virtual force is zero and sensors can freely explore the workspace under the action of $u_C^{(i)}$. If the distance between sensors becomes close to ρ_B or ρ_C, the interaction force grows, becoming greater than $u_C^{(i)}$ and the sensor moves to avoid collisions or the breaking of network connections.

4. Simulation Results

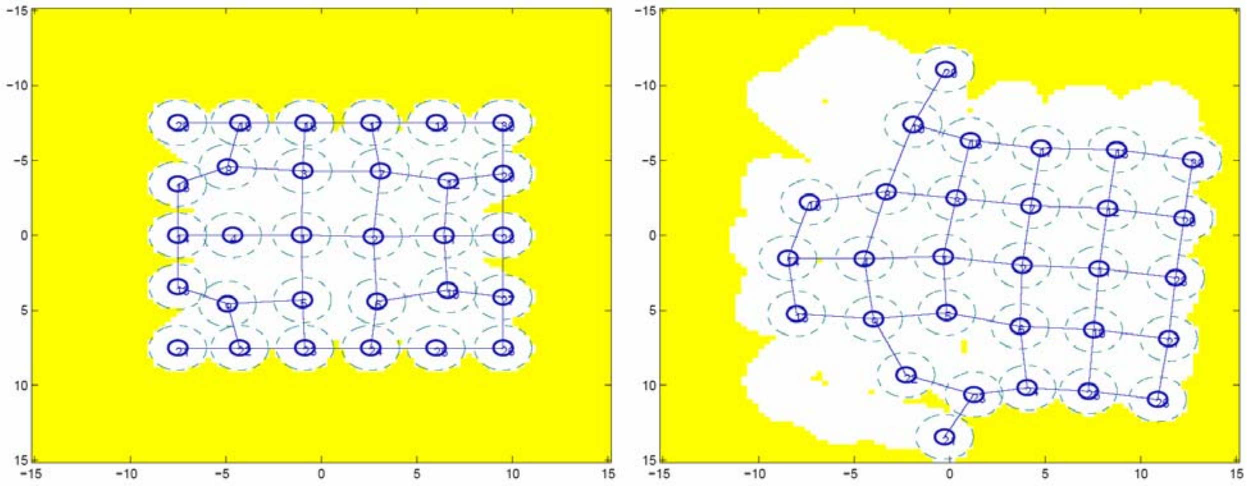
In Fig. 2 simulation results are shown for the case of a sensor network composed by 30 nodes, covering a box shaped workspace. Collisions avoidance and connectivity maintenance constraints are considered.

Collision, sensing and communication radii are

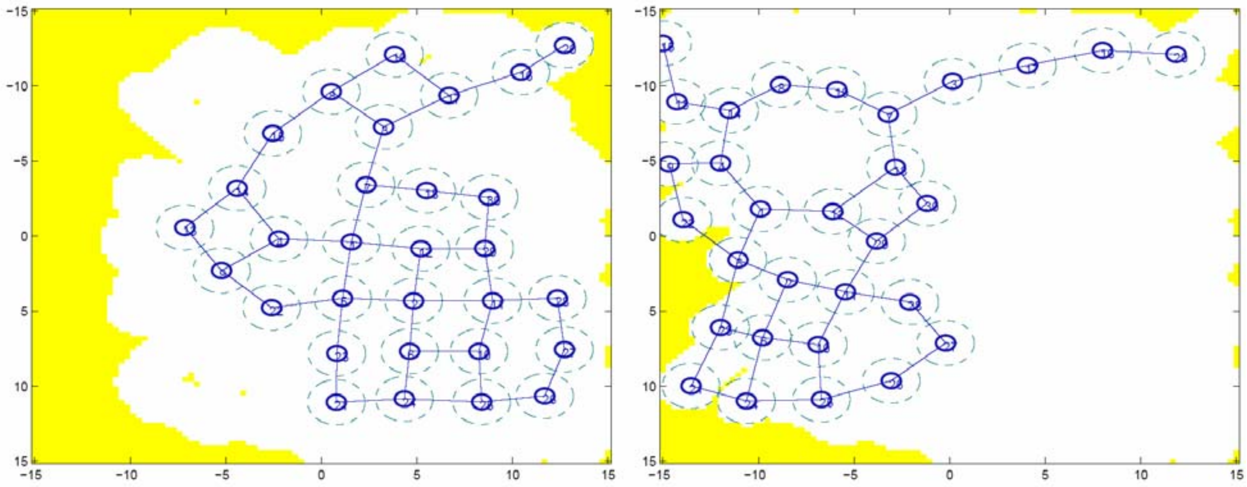
$$
\rho_B = 5, \quad \rho_S = 1.5, \quad \rho_C = 3
$$

Nodes dynamic parameters are

$$
u_{max} = 3, \quad v_{max} = 1.5
$$



(a) t=5 sec (b) t=20 sec



(c) t=40 sec (d) t=60 sec

Fig. 2. Coverage of a box shaped workspace with a dynamic sensors network. Connectivity is maintained without imposing a fixed topology to the communication network.

5. Conclusions

In this paper the area coverage problem for a mobile sensor network has been faced. The main contribution is a distributed (local) approach for motion planning of each single sensor unit. The need of distributed solutions arises from the high computation requirements, as well as the large data traffic over the network for data collection, coming from a centralized solution with great network dimension, in terms of number of sensor units.

Collision avoidance and connectivity maintenance constraints are considered. In particular a distributed strategy for connectivity maintenance is proposed that allow to handle dynamic topology for the communication graph.

The local approach has been simulated and the results show its effectiveness. Both computation and data transfer (since only local data are required) are considerably reduced with respect to global approaches, making possible the implementation for online real time applications.

Problems like the presence of obstacles in the workspace, both fixed and mobile, and the introduction in the model of the communication delays are under investigation. They are partially solved and are the subject of a coming paper.

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