Proceedings of the 7th
World Congress on Intelligent Control and Automation
June 25 - 27, 2008, Chongqing, China

A decentralized control for mobile sensor network effective coverage

Hua Wang and Yi Guo

***Abstract*— This paper investigates the effective coverage problem over an $n-$dimensional space of a mobile sensor system. We assume the sensor agent in the system has limited sensing range and communication range. We define the effective coverage problem as to achieve the maximum coverage and total communication distance minimized. We proposed decentralized control law to deploy mobile sensors achieve coverage goal based on gradient approach. Furthermore, the deploying control law avoids potential collision between agents.**

I. Introduction

Nowadays, sensor network has a broad application in environmental sampling, ecosystem monitoring, and military surveillance, which call for effective network control methods and coordination tools to achieve specific performances. Especially in term of sensor network coverage, the following questions need to be addressed, how to deploy a sensor network, how to setup proper protocols among sensor agents to control the information flow, and how to efficiently maximize the coverage area with service quality ensured.

Low-power embedded system and network control system have boosted the sensor network into a more flexible fashion with controllable mobility. Mobile sensor network, comparing to the static sensor network, has the following promising advantages. First, it offers the flexibility and convenience for the network to reorganize according to dynamic changes; for example, once a suspicious target is found, the whole mobile sensor network is able to rearrange its layout according to the detection. Second, mobility facilitates the sensor carriers loading with highly accurate and precise sensors, which provides insight into the trade-off between rich information and limited computation capability/expense budget. Third, mobile sensor network provides utility maintain service. Once a sensor is out of battery or out of order, the sensor can be recharged or repaired. More, it is environmentally friendly. For the static sensor network, once the sensor's battery dies out, it is an extremely tedious and tough job to collect the sensors remained on the field. And furthermore, it may cause undesired environmental pollution. On the other hand, the scheme of mobile sensor network provides the green recycle option to alleviate the environmental contamination.

Hua Wang and Yi Guo are with the Electrical and Computer Engineering Department, Stevens Institute of Technology Hoboken, NJ 07030, USA hwang, Yi.Guo@stevens.com

The coverage problem is a fundamental issue of a sensor network system. Researchers have proposed various solutions to a lot of interesting sensor network coverage problems. In [9], a coverage problem called "best coverage problem" is defined as to find a path connecting two point in a given area, which maximizes the smallest observability of all points on the path. In [8], a coverage related problem called "worst coverage problem" is defined as to find the path that maximizes the distance of the path to all sensor nodes. In [3], Du et. al. introduce the centroidal Voronoi tessellations as a comprehensive solution to a series of partition problems which sheds light on the sensor coverage problem, and also provide a centralized algorithms under deterministic and probabilistic domains. Cortés [1] proposes a decentralized control law to encode a group of vehicles to partition an area into a Voronoi diagram, in the sense that the group of vehicles covers the area. In [5], Hussein et al. address the dynamical coverage control law over a given bounded region, given the fleet fully connected, it may reach "effective" coverage with collision avoidance under different sensing models and parameters. In [7], W. Li etc propose a distributive coverage control scheme based on a probabilistic sensing range model to maximize the joint detection probability and minimize the communication cost.

And in this paper, we will consider the coverage problem by deploying mobile sensor agents with limited sensing region to cover an area most "efficiently" without collisions between agents. Based on the gradient descent method, we propose control scheme to deploy mobile sensors over a uniform field. We will show some simulation results which shows satisfactory performances.

II. Problem setup

Consider a networked sensor system I with N agents forming an unordered communicating topology G, we take the dynamics as

$$\dot{q}_i = u_i \tag{1}$$

where q_i is the n-dimension state vector of ith agent, $q_i = [q_{ix_1} \dots \; \dots \; q_{ix_n}] \in \mathbb{R}^n$, and u_i is corresponding n-dimension input $u_i = [u_{ix_1} \; \dots \; u_{ix_n}]$. In all, we can denote the system state vector q as $q = [q_1 \dots \; \dots q_N]^T \in \mathbb{R}^{Nn}$.

In order to study the coverage problem, we need to setup the following sensor network property assumptions.

978-1-4244-2114-5/08/$25.00

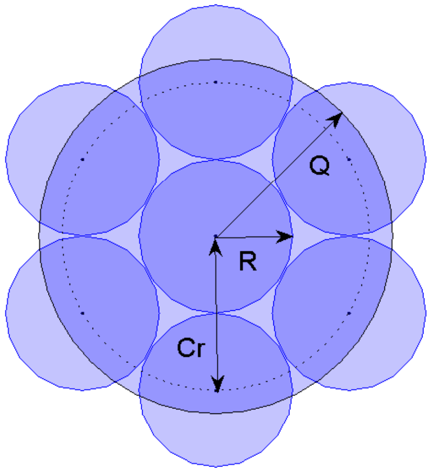

Fig. 1. An example of effective coverage by maximizing the coverage area and minimizing the total communication range

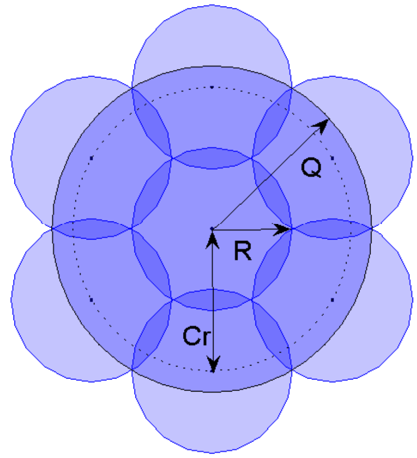

Fig. 2. Another example of effective coverage by completely covering the area with overlap

Assumption 1: The sensor network system I is homogeneous. Each agent in the system utilizes its sensing capability to monitor and collect data from environment world; and uses the communication capability to share information with its neighbors.

Assumption 2: Each sensor has limited communication range Q. We define the neighborhood N_i of agent i as

$$N_i = \{j : \|q_i - q_j\| < Q\} \tag{2}$$

Since the system is homogeneous, the communication topology is undirected. Therefore, j is in the neighborhood of i, if and only if i is in the neighborhood of j, denote as $i \in N_j \Longleftrightarrow j \in N_i$.

Assumption 3: Each sensor has limited and equal sensing range R in all directions. The sensing domain Φ_i is

$$\Phi_i = \{\phi : \|q_i - \phi\| \leq R\} \tag{3}$$

More, in Φ_i, every point has equal sensing intensity. In 2-D dimension case, a sensor has a circular sensing shape with even intensity.

In this paper, we consider the system with *initial conditions* as following.

I1 In the system, no two agents initially overlap with each other.

$$\|q_i^{\text{init}} - q_j^{\text{init}}\| > 0, \forall i, j \in N_i \tag{4}$$

I2 The initial communication topology G^{init} is connected on topological space.

$$\{G^{\text{init}} \text{ is connected.}\} \tag{5}$$

Based on the assumptions and the initial condition setup of the dynamic sensor network system, we introduce two scenarios of coverage structure. In figure 1, we illustrate a coverage case where Q, R, C_r are the communication range, sensing range and critical distance of the system respectively. The coverage area $\bigcup_{i\in I} \Phi_i$ of the system is maximized and the total communication distance $\sum_{i,j\in N_i} \|q_i - q_j\|$ is minimized. And the critical distance of the system is two times the sensing range. In figure 2, we illustrate another coverage scenario that the area is completely covered without gap. on the other hand, there is boundary area overlapped among agents. And in this case, the critical distance C_r is $\sqrt{3}R$. These two cases are both effective according to different coverage requirement, and the critical distance C_r of the system is a key parameter tuning the coverage quality. Now we will define our generalized "effective coverage" problem as follows.

Problem 1: (effective coverage) Given the *initial conditions* satisfying I1 and I2, the effective coverage over a mobile sensor network system I is a desired configuration that the distance between agents attains C_r so that the coverage area and the total communication distance are optimized.

The coverage defined is effective since it balances the sensor system coverage and the communication quality. It is always a tradeoff between coverage area and communication distance. On one hand, the distance between agents has to stretch out enough to make sure the coverage area is maximized; on the other hand, the distance between agents must be within the communication range to ensure communication energy consumption and robustness.

Note that the sensing range R and communication range Q need to be adjusted to achieve the effective coverage. In [12], Zhang and Hou analyzed the relationship between sensing range and communication range, which will not be covered in this paper. Generally, the value for C_r varies from different applications(complete coverage or optimal coverage with certain quality of service guaranteed etc), and we assume the critical distance C_r between agents is known. In the following, we will develop control law to deploy mobile sensor network to achieve "effective coverage".

III. Deployment control scheme with collision avoidance

In this section, we will design the decentralized deployment control law with collision avoidance, under the scenario that the area to be deployed is uniform.

For a given area to be monitored on a n-dimensional Euclidean space space M^n, the state space of the N-agent system on M^n is on $\mathbb{R}^{Nn}$. We define a map $\{\delta(q) : \mathbb{R}^{Nn} \to \mathbb{R}^{Nn\times Nn}\}$ of the local distance.

$$\delta_{ij} \equiv \begin{cases} q_i - q_j = [q_{i1}-q_{j1} \quad q_{i2}-q_{j2} \dots q_{in}-q_{jn}], & \forall j \in N_i; \\ \text{Not defined}, & \text{otherwise.} \end{cases} \tag{6}$$

Its Euclidean norm is

$$\|\delta_{ij}\| = \begin{cases} \sqrt{(q_{i1}-q_{j1})^2 + \ldots + (q_{in}-q_{jn})^2}, & \forall j \in N_i; \\ \text{Not defined}, & \text{otherwise.} \end{cases} \tag{7}$$

Furthermore, we have the partial derivative of $\|\delta_{ij}\|$ as

$$\frac{\partial \|\delta_{ij}\|}{\partial q_k} = \begin{cases} \left[\frac{q_{i1}-q_{j1}}{\|\delta_{ij}\|} \dots \frac{q_{in}-q_{jn}}{\|\delta_{ij}\|}\right] = \frac{q_i - q_j}{\|\delta_{ij}\|}, & \text{if } k = i; \\ -\left[\frac{q_{i1}-q_{j1}}{\|\delta_{ij}\|} \dots \frac{q_{in}-q_{jn}}{\|\delta_{ij}\|}\right] = \frac{q_j - q_i}{\|\delta_{ij}\|}, & \text{if } k \in N_i; \\ \text{Not defined}, & \text{otherwise.} \end{cases} \tag{8}$$

Let the decentralized dynamic control as

$$u_i = -\sum_{j\in N_i} \frac{\delta_{ij}\cdot(\|\delta_{ij}\| - C_r)}{\|\delta_{ij}\|^4} \tag{9}$$

in which the control law on agent i is associated with the state information of itself and its neighbors j.

Define the potential function $V(\delta)$ as

$$V(\delta) = \sum_i \sum_{j\in N_i} \frac{1}{2}\left(1 - \frac{C_r}{\|\delta_{ij}\|}\right)^2 \tag{10}$$

in which δ_{ij} is the local distance between agent i and j, C_r is the desired distance between agents to achieve effective coverage. It is obvious to see that $V(\delta)$ is positive semi-definite at least in the neighborhood of $\{\delta_{ij} = C_r, \forall i, j \in N_i\}$. And its minimum energy point can be reached only when the distance δ_{ij} between any agents i and j goes to the critical value C_r, in the sense that the effective coverage can be attained ideally.

Lemma 1: Given the initial conditions at t_0 as $I1$ and $I2$, then, the set $\Omega_M = \{q \in \mathbb{R}^{Nn} : V(\delta(t)) \le V(\delta(t_0))\}$ with regard to the system (1) is an invariant set.

Proof: Since the initial communication topology G^{init} is connected, one has

$$\|\delta_{ij}^{\text{init}}\| < Q, j \in N_i \tag{11}$$

More, since no overlap between agents in the system, one has

$$\|\delta_{ij}^{\text{init}}\| > 0, \forall\, i, j \in N_i \tag{12}$$

Therefore, we can define a set Ω_{init} for any given initial condition:

$$\Omega_{\text{init}} = \{q(t_0) \in \mathbb{R}^{Nn} : \delta_{ij}(t_0) \in (0, Q), \forall\, i, \exists j \in N_i\} \tag{13}$$

On the other hand, we have the potential function $V(\delta)$ defined in (10) is a positive definite function. And one can evaluate the first time derivative of potential function as:

$$\begin{aligned} \dot{V}(\delta) &= \sum_i \sum_{j\in N_i} (1 - \frac{C_r}{\|\delta_{ij}\|}) \cdot \frac{C_r}{\delta_{ij}^2} \cdot (\frac{\partial \delta_{ij}}{\partial q_i} \cdot \dot{q}_i + \frac{\partial \delta_{ji}}{\partial q_i} \cdot \dot{q}_i) \\ &= \sum_i \sum_{j\in N_i} (1 - \frac{C_r}{\|\delta_{ij}\|}) \cdot \frac{C_r}{\delta_{ij}^2} \cdot \frac{2\partial \delta_{ij}}{\partial q_i} \cdot \dot{q}_i \\ &= \sum_i \sum_{j\in N_i} (1 - \frac{C_r}{\|\delta_{ij}\|}) \cdot \frac{C_r}{\delta_{ij}^2 \cdot \|\delta_{ij}\|} \cdot 2 \cdot (q_i - q_j) \cdot \dot{q}_i \\ &= \sum_i \sum_{j\in N_i} 2C_r \frac{(q_i - q_j)\cdot(\|\delta_{ij}\| - C_i)}{\|\delta_{ij}\|^4} \cdot \dot{q}_i \\ &= -\sum_i \sum_{j\in N_i} 2C_r \left(\frac{\delta_{ij}\cdot(\|\delta_{ij}\| - C_i)}{\|\delta_{ij}\|^4}\right)^2 \\ &\le 0 \end{aligned} \tag{14}$$

Thus, the first derivative of potential function is negative semi-definite $\dot{V}(\delta) \le 0$.

Therefore, we have $V(\delta)$ is positive semi-definite on Ω_{init}, and the time derivative $\dot{V}(\delta)$ is non-positive. So as t increases, the potential function is non-increasing. For any trajectory $q(t)$ starts from Ω_{init} at t_0, through the map $\{\delta(t) = \delta(q(t)) : q \to \delta\}$, we have $V(\delta(t)) \ge V(\delta(t_0))$ for any $t \ge t_0$. So any trajectory initiating in Ω_{init} tends to the set $\Omega_M = \{q \in \mathbb{R}^{Nn} : V(\delta(t_0)) \ge V(\delta(t))\}$, for any $t \ge t_0$. Therefore, Ω_M is an invariant set for the system defined in (1). ■

Remark 1: Note that the collision case $\delta_{ij} \to 0$ is avoided in the process of the trajectory tends to stay in Ω_M, because the collision case $\delta_{ij} \to 0$ is excluded from the largest invariant set Ω_M, since $\dot{V}(\delta) \to \infty$, as $\delta_{ij} \to 0$ conflicts with $\dot{V}(\delta) \le 0$. Thus, the control law is collision free.

From lemma 1, we know that $V(\delta)$ is positive definite, and $\dot{V}(\delta) \le 0$. More, $\Omega_M = \Omega_{init} = \{q \in \mathbb{R}^{N\times n} : \delta_{ij}^M \in (0, Q), \forall\, i, \exists j\}$ is an invariant set, any trajectory will tend to be in it along the direction of gradient descent of the potential function $V(\delta)$ according to the control law developed in (9).

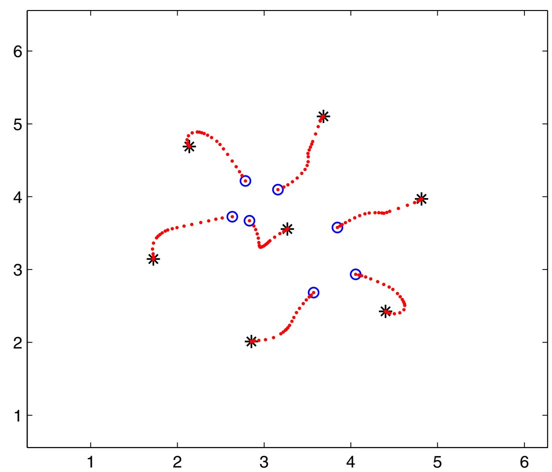

Fig. 3. The trajectory of a 7-agent mobile sensor system achieving effective coverage

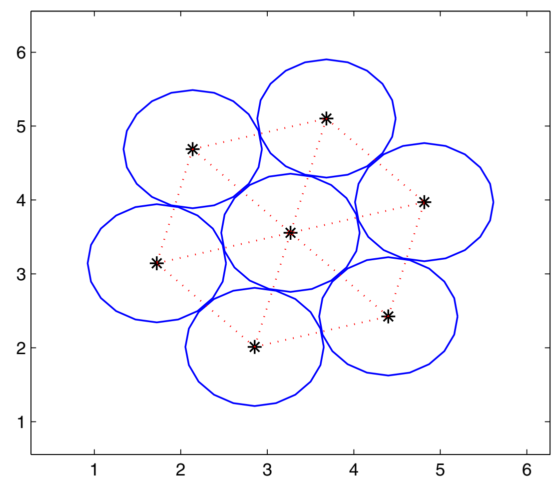

Fig. 4. The final coverage configuration of a 7-agent mobile sensor system

Then From (14), we know that $\dot{V} = 0$ only for the distance between any communicating pair i and j approaching $\delta_{ss} = \{\delta : \sum_{\forall i, \exists j \in N_i} (\|\delta_{ij}\| - C_r)^2 = 0\}$, so the distance vector will converge to δ_{ss}. And the centroid $\bar{q}$ of state vector q is static.

$$\begin{aligned} \frac{d\bar{q}}{dt} &= \frac{d(\sum_i q_i/N)}{dt} = \frac{1}{N}\sum_i \frac{dq}{dt} \\ &= \frac{1}{N}\sum_{\forall i, \exists j \in N_i} \frac{(q_i - q_j)\cdot(\|\delta_{ij}\| - C_r)}{\|\delta_{ij}\|^4} \\ &\quad + \frac{(q_j - q_i)\cdot(\|\delta_{ij}\| - C_r)}{\|\delta_{ij}\|^4} \\ &= 0 \end{aligned}$$

Since the centroid derivative is zero, the centroid of the system keeps itself once the initial state is setup.

IV. Simulation

In this section, we provide two sets of simulation results of the sensor network deploying scheme over a 2-D area.

In figure 3, 4, 5, we consider a homogeneous sensor system of 7 agents achieving an effective coverage configuration, as shown the sensing range of the system is 0.8, the communication range between any two agents are 1.85, and the critical distance C_r is 1.6.

As illustrated in figure 3, the small circles demonstrate the initial positions, the asterisks denote the steady state positions, and the dotted curves are the trajectory of mobile sensor system under deploying control law. Figure 4 shows the final coverage configuration. And obviously, the distance between any adjacent pair of agents is the critical distance C_r.

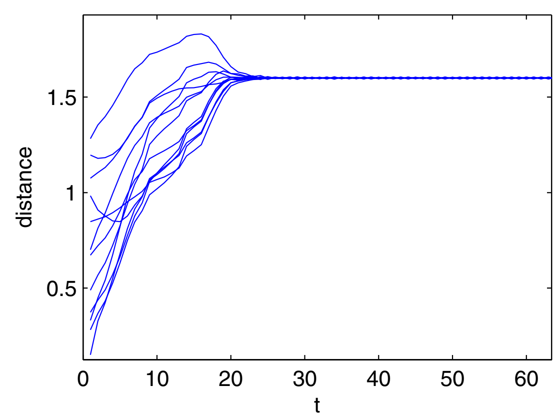

Fig. 5. Local distance between communicating pairs converging to the critical distance $C_r = 1.6$ along time

Figure 5 shows the local distance between any communicating two agents versus time. We can see that finally, the distance achieves the critical value C_r, and the local distance avoids achieving zero through the whole process, which, therefore, illustrates control law is collision-free.

In figure 6, 7, 8, we consider a system of 10 agents achieving effective(complete) coverage. The sensing range R of the system is 1, the communication range Q between agents is 1.15, and the critical distance C_r is 1.732.

In figure 6, the small circles stand for the initial positions, the asterisks denote the steady state positions, and the dotted curves are the trajectory of mobile sensor system under deploying control law. Figure 7 illustrates the finial configuration, we can see that there is no gap between each

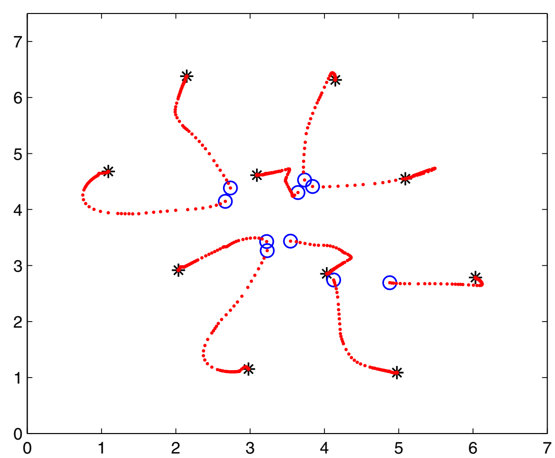

Fig. 6. The trajectory of a 10-agent mobile sensor system achieving effective coverage

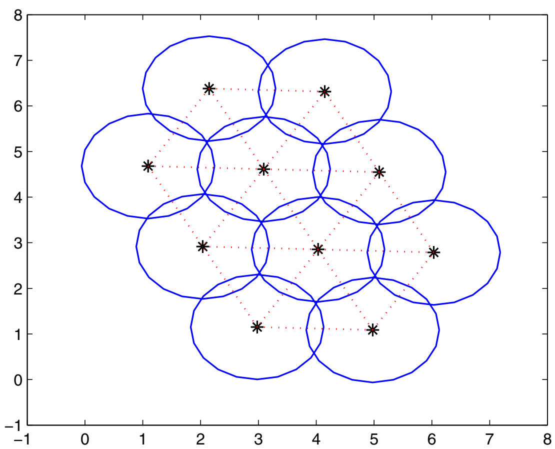

Fig. 7. The final coverage configuration of a 7-agent mobile sensor system

sub-sensing area, which achieves the full coverage. And on the other hand, there is overlap among the coverage area. In figure 8, we plot the centroid of the system versus time. It is clear that the centroid of the system stays still at 3.6479.

V. CONCLUSION

In this paper, we proposed an effective coverage goal as to optimize the coverage area and total communication distance. We design a decentralized deploying control law to achieve the coverage goal for uniform area through gradient-based method. More, the decentralized control law is with collision-free between agents. And we provide some simulation results to support the feasibility of the control scheme proposed.

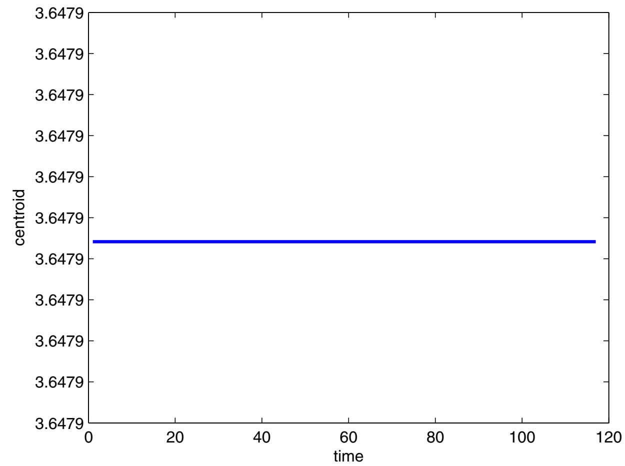

Fig. 8. The centroid of the system vs time

ACKNOWLEDGEMENT

The work was supported in part by US Army contract W15QKN-05-D-0011.

REFERENCES

[1] J. Cortes, S. Martinez, T. Karatas, and F. Bullo. Coverage control for mobile sensing networks. *Robotics and Automation, IEEE Transactions on*, 20(2):243–255, April 2004.

[2] Dimos V. Dimarogonas and Kostas J. Kyriakopoulos. An inverse agreement control strategy with application to swarm dispersion. *Decision and Control, 2007 46th IEEE Conference on*, pages 6148–6153, 12-14 Dec. 2007.

[3] Q. Du, Vance Faber, and Max Gunzburger. Centroidal voronoi tessellations: Applications and algorithms. *SIAM Rev.*, 41(4):637–676, 1999.

[4] I. I. Hussein. and M. A. Demetriou. Estimation of distributed processes using mobile spatially distributed sensors. *American Control Conference, 2007. ACC '07*, pages 2756–2761, 9-13 July 2007.

[5] I. I. Hussein and D. M. Stipanovic. Effective coverage control for mobile sensor networks with guaranteed collision avoidance. *Control Systems Technology, IEEE Transactions on*, 15(4):642–657, July 2007.

[6] M. Ji and M. Egerstedt. Distributed coordination control of multiagent systems while preserving connectedness. *Robotics, IEEE Transactions on [see also Robotics and Automation, IEEE Transactions on]*, 23(4):693–703, Aug. 2007.

[7] W. Li and C.G. Cassandras. Distributed cooperative coverage control of sensor networks. *Decision and Control, 2005 and 2005 European Control Conference. CDC-ECC '05. 44th IEEE Conference on*, pages 2542–2547, 12-15 Dec. 2005.

[8] S. Meguerdichian and F. Koushanfar etc. Exposure in wireless ad-hoc sensor networks. In *MobiCom '01: Proceedings of the 7th annual international conference on Mobile computing and networking*, pages 139–150, New York, NY, USA, 2001. ACM.

[9] S. Meguerdichian, F. Koushanfar, M. Potkonjak, and M. B. Srivastava. Coverage problems in wireless ad-hoc sensor networks. In *INFOCOM*, pages 1380–1387, 2001.

[10] G. Notarstefano, K. Savla, F. Bullo, and A. Jadbabaie. Maintaining limited-range connectivity among second-order agents. *American Control Conference, 2006*, pages 2124–2129, 14-16 June 2006.

[11] X. Wang, G. Xing, Y. Zhang, C. Lu, R. Pless, and C. Gill. Integrated coverage and connectivity configuration in wireless sensor networks. In *SenSys '03: Proceedings of the 1st international conference on Embedded networked sensor systems*, pages 28–39, New York, NY, USA, 2003. ACM.

[12] H. Zhang and J. C. Hou. Maintaining sensing coverage and connectivity in large sensor networks. *Ad Hoc and Sensor Wireless Networks*, 12(1-2):89–124, January 2005.