A Comparison of Cooperative Localisation Techniques for Wireless Mobile Sensor Networks

Frank Engel and Mark Hedley
CSIRO ICT Centre, Sydney, Australia
E-mail: {frank.engel, mark.hedley}@csiro.au

***Abstract*— Sensor networks allow monitoring, tracking, and controlling various aspects of the physical world. Any data retrieved or generated is only useful if considered in relation to its time and space coordinates.**

CSIRO's ICT Centre is currently developing a platform for distributed ad-hoc sensor networks. This paper describes the evaluation of various cooperative localisation techniques and their suitability for this sensor networks platform. Simulation results comparing different algorithms are presented and discussed.

I. Introduction

Sensor networks are developed to sense data or information about the environment. Typical data comprises temperature, pressure, sound, object movement, etc. Thus the applications are manifold. Their range encompasses environment monitoring and control for agricultural purposes as well as habitat protection, object tracking or routing, disaster relief, forest fire monitoring, or medical applications [1]–[11].

A. Characteristics

Although the application spectrum is broad a set of characteristics for sensor networks can be summarised:

- The number of sensor devices in a network is often very high.
- Sensor devices are randomly deployed with a high but varying density.
- Sensor devices need to be small, cheap, and robust so they can easily deployed.
- Sensor devices are limited in power, processing capabilities,and memory.
- Sensor devices manly use a broadcast communication paradigm.
- Network topologies vary as cases arises. They often even change within a particular case.
- Sensor networks should be scalable, self-organising, fault-tolerant, and work unattended with minimal configuration requirements.
- To scale well a sensor node itself is responsible for determining its position.
- No special deployment planning should be required.

In general a system is desired which can be deployed within a reasonable amount of time and effort wherever needed, operates for a long period, and copes with environmental harshness [5], [12].

B. Localisation

The process of estimating the spatial relationship between objects is called *localisation* [12]. Here two types of relationship can be distinguished. Those which are based on a global coordinate system like GPS and those which create a local coordinate system based on arbitrary reference points within the covered area. The first one is referred to as *anchor based* and provides position coordinates while the later one as *anchor free* stating distances and directions between sensor nodes. *Anchors* are sensor nodes with an a-priori known position serving as reference points. All other sensor nodes are simply referred to as *mobile nodes* in this paper.

Sensor devices use wireless communication to establish links to other devices within a neighbourhood. This communication is used for exchanging data and to measure inter-device distances. CSIRO's hardware platform for wireless sensor devices uses *TOA (Time of Arrival)*. Other techniques for radio range measurement are *AOA (Angle of Arrival)* and *RSSI (Receive Signal Strength Indication)* [4]. Another group of localisation techniques does not use direct range measurements. They are referred to as *range free*. Here distance relations are determined by assuming an average value or by local coverage areas. This often leads to coarse estimates or requires a-priori knowledge of the network [3], [10].

The way positions are calculated is divided into centralised and distributed approaches. In a *centralised* scheme all data is forwarded to a powerful computation facility outside the sensor network area (e.g. MDS-C [13]). While in a *distributed* one the calculation is done within the sensor network. Here each node works out its own position (e.g. TERRAIN [14]).

C. Objective

This article describes an investigation into cooperative localisation techniques for mobile wireless sensor networks. Different existing approaches are investigated. The aim is to identify a candidate to be implemented on CSIRO's mobile sensor devices platform – the next step towards an ad-hoc wireless sensor network.

II. Project Description

The goal of the overall project is to build a demonstrator application – a mobile wireless sensor network which is capable of locating objects and/or persons inside a building.

In stage one a system has been developed which tracks the movement of an object at close range. A minimum set of four

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anchors and one mobile node is used. All anchors are within range of each other and the mobile node. Thus, full coverage exists. All devices communicate via a wireless link to perform TOA range measurements and to exchange data [15].

A. System Requirements

There is already a broad range of techniques for position location in sensor networks available. To select potential algorithms a set of system requirements is defined:

- 25 sensor devices will be available.
- Each device is capable of acting as an anchor or as a mobile node.
- The indoor radio range of those devices is about 100 m.
- Range measurements have an error which is range dependent.
- A minimum inter-node distance of 2 m is assumed.
- Anchors will be placed at the boundaries of the covered area.
- A minimum of four anchors is deployed.
- Nodes move freely within the covered area.
- No guarantee is given that anchors are within radio range of each other, and/or mobile nodes have direct links to anchors.
- No central processing unit (e.g. laptop) is available. All processing is executed in a distributed fashion.
- The covered area will be no larger than 125 x 125 m.

To determine the size of the area which could be covered by our demonstrator network an estimate of the device density within the network is necessary. A survey of articles about position locationing techniques led to the conclusion a minimum inter-node connectivity of eight is necessary to achieve good results [13], [16], [17]. Simulations of random network topologies show an area of about 125x125 m is realistic.

III. Algorithm Selection

The above system requirements lead to the following algorithm requirements:

- No a-priori information about the network and/or area is available.
- Nodes calculate their own position using information from anchors and direct neighbours. Thus, the algorithm has to be distributed.
- An anchor based approach is used.
- The algorithm should take advantage of the TOA distance measurements.
- Estimates of multi-hop distances are required.
- The algorithm needs to scale with the network size.

Position calculation is an optimisation process. It starts with an estimate for an initial position for each mobile node. This step is followed by an optimisation (*refinement*) in which each mobile node n_i tries to minimise the differences between the measured distances d_{ij} to its neighbours n_j ($j:1..M_i$) and the calculated ones r_{ij} based on those initial position estimates. A set of equations (2) based on (1) is solved at each mobile node.

$$f_i(x_i, y_i) = d_{ij} - \sqrt{(x_i - x_j) + (y_i - y_j)} \quad (1)$$

$$F(x_i, y_i)\,|_{\min} = \sum_{j=1}^{M_i} f(i)^2 \quad (2)$$

A. Initial Position Estimate

To calculate an initial position estimate a mobile node needs to estimate the distance to each of the anchors. Once those distances are known the mobile node uses the same set of equations as shown in (1) to solve its initial position estimate. This step is referred to as *Multilateration* [4].

The quality of an algorithm for initial position estimation is measured by its ability to approximate multi-hop distances between anchors and mobile nodes as accurate as possible.

1) DV-Hop: The first candidate is DV-Hop. It is the most basic scheme. Here all anchors calculate their Euclidean distance r_{ij} to all other anchors by exchanging position information. Furthermore each anchor n_i determines the shortest hop count h_j to all anchors n_j. Based on this information each anchor estimates an average hop distance c_i (3).

$$c_i = \frac{\sum r_{ij}}{\sum h_i} \quad (3)$$

Mobile nodes use the average hop distance estimate c_i of their nearest anchor to calculate the distance to all anchors in the network: shortest hop count multiplied by c_i [4].

2) DV-Distance: This method is similar to DV-Hop. But mobile nodes use their measured inter-node distances instead of an average hop distance estimate. Thus the distance to an anchor is determined by the accumulated measured inter-node distances along the shortest path to an anchor. This approach is less coarse than the previous one, but affected by measurement errors [4].

3) N-Hop: Similar to DV-Distance this algorithm determines the shortest multi-hop distance to all anchors. The value is applied as constraints to the X and Y coordinates of the mobile node. A bounding box with a minimal area is formed and its centre used as initial position estimate [18], [19].

4) TERRAIN: With this technique each anchor forms its own local coordinate system and spreads it through the network by solving a position for each mobile node. This way each mobile node calculates its distance to the anchor as Euclidean distance. The anchor n_0 itself is located at the centre $(0,0)$ of the local coordinate system. To establish its coordinate system the anchor picks one of its neighbours and assigns it a position on the X-axis n_1: $(d_{01}, 0)$. The location of the second neighbour n_2 is given the constraint that its

Y-coordinate is positive ($x_2, y_2 \geqslant 0$). Now there are only two unknowns remaining:

$$x_2 = \frac{d_{01}^2 + d_{02}^2 - d_{12}^2}{2d_{01}} \qquad y_2 = \sqrt{d_{02}^2 - x_2^2} \tag{4}$$

For this point on a standard triangulation algorithm is used to solve positions for all other mobile nodes while flooding trough the network [14].

The algorithm calculates direct distances to anchors but requires a high connectivity to reach each mobile node. It is also sensitive to distance measurement errors.

B. *Refinement*

Once initial positions for all mobile nodes are available, an optimisation step (refinement) may follow to improve the position accuracy. As mentioned earlier each mobile node tries to align the measured distances d_{ij} to its neighbours with the calculated Euclidean distances r_{ij} derived from actual position values (1), (2). The more distance measurements with its neighbours a mobile node has the better this optimisation performs.

Synchronisation is needed between all nodes in the network. After a mobile node has finished updating its position estimates, it waits until all other nodes in the network have finished as well. Otherwise some mobile nodes would broadcast new positions while others are still calculating. This could lead to "local oscillating" [18].

1) Minimum Mean Square Estimate (MMSE): The easiest refinement technique is a linear approximation of the non-linear set of equations in (2). Here one of the equations is used to eliminate the quadratic terms x_i^2 and y_i^2. It leads to a linear system of equations of the form $a = b\,M$ with the well known solution [4]:

$$b = (M^T\,M)^{-1}\,M^T\,a \tag{5}$$

2) Mass-Spring Optimisation (MSO): Mass-Spring Optimisation adopts the model of masses (anchors + nodes) connected by springs ($d_{ij} - r_{ij}$). The system comes to rest when all masses stop moving – means the energy on each of the masses reached its minimum [20].

Again each node calculates its position based on inter-node measurements d_{ij} and Euclidean distances r_{ij} derived from current position estimates. The difference between d_{ij} and r_{ij} is represented by a force $\vec{F}_{ij}$ (6). v_{ij} is a unit vector into the direction from node n_i to neighbour n_j.

$$\vec{F}_{ij} = v_{ij}(d_{ij} - r_{ij}) \qquad \vec{F}_i = \sum_{ij} \vec{F}_{ij} \tag{6}$$

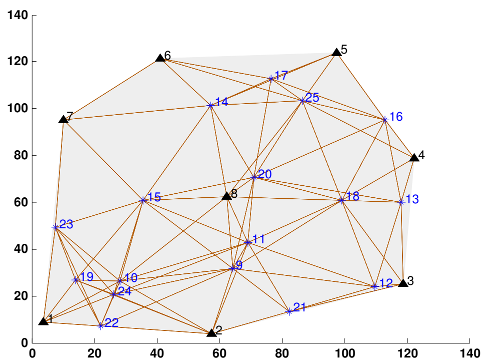


Fig. 1. Example of a Network (Anchors: 7+1, Avg. Connectivity: 8)

The total energy E_i of a node n_i is the sum of the squares of the magnitudes of all forces to its neighbours (7):

$$E_i = \sum_j^{M_i} E_{ij} = \sum_j^{M_i} (d_{ij} - r_{ij})^2 \tag{7}$$

Moving into the direction of the resultant force $\vec{F}_i$ reduces the energy E_i on mobile node n_i. The resolution of the movement (step width) is $|\vec{F}_i|/(2M_i)$ with M_i being the number of n_i's neighbours [17].

IV. Simulation

Matlab is used as simulation environment. The goal of this investigation is to identify a combination of an initial position algorithm and a refinement technique which together achieve position estimates as close to the real positions as possible. Furthermore the algorithms need to cope with distance measurement errors, various anchor configurations, and different average inter-node connectivity (network density).

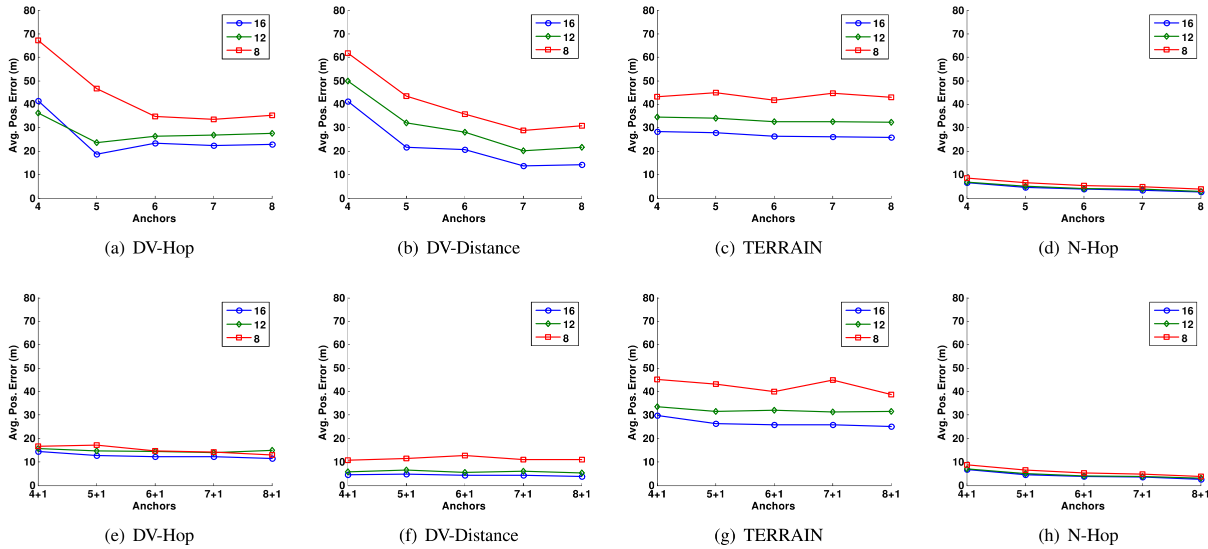
A. *Simulation Setup*

Experiments on the sensor device platform showed that the error on TOA measurements is dependent on the inter-node distance [15]. To simulate the effect zero mean Gaussian noise is added to the Euclidean distance r_{ij}. This error increases with distances greater than 10 m (8).

$$d_{ij} = r_{ij} + 0.3 \cdot \max(1,\ r_{ij}/10) \cdot \mathrm{randn}(1) \tag{8}$$

Based on the system requirements stated in Sec. II-A 100 random network topologies with four anchors at the boundaries inside a 125x125 m area were generated. This configuration has an average inter-node connectivity of eight. To determine the robustness and performance of the techniques the following questions were investigated:

- Do additional anchors improve position accuracy?
- Does an additional anchor at the centre help?
- How does inter-node connectivity affect the algorithms?



(a) DV-Hop (b) DV-Distance (c) TERRAIN (d) N-Hop

(e) DV-Hop (f) DV-Distance (g) TERRAIN (h) N-Hop

Fig. 2. Avg. Position Error after Initial Positioning Algorithms (Sorted by Algorithm, Parameter: Connectivity)

Based on those questions a set of network configurations is used. Table I gives an overview. 100 random topologies per configuration were simulated. A configuration is a combination of a particular anchor number and an average connectivity. Fig. 1 shows an example.

TABLE I

NETWORK CONFIGURATION PARAMETERS

Anchors / Nodes	4 / 21, 5 / 20, 6 / 19, 7 / 18, 8 / 17
Anchors+Centre / Nodes	4+1 / 21, 5+1 / 20, 6+1 / 19, 7+1 / 18, 8+1 / 17
Avg. Connectivity / Area (m)	8 / 125x125, 12 / 100x100, 16 / 90x90

As a metric to evaluate the algorithms the average position error ERR is used, see (9). The average is calculated over all mobile nodes N_k in a network (err_k) and over all 100 topologies of a configuration.

$$
\begin{aligned}
err_k &= \frac{1}{I}\sum_{i=1}^{N_k}\sqrt{(x_i - x_i^{'}) + (x_i - x_i^{'})} \\
ERR &= \frac{1}{100}\sum_{k=1}^{100} err_k
\end{aligned}
\tag{9}
$$

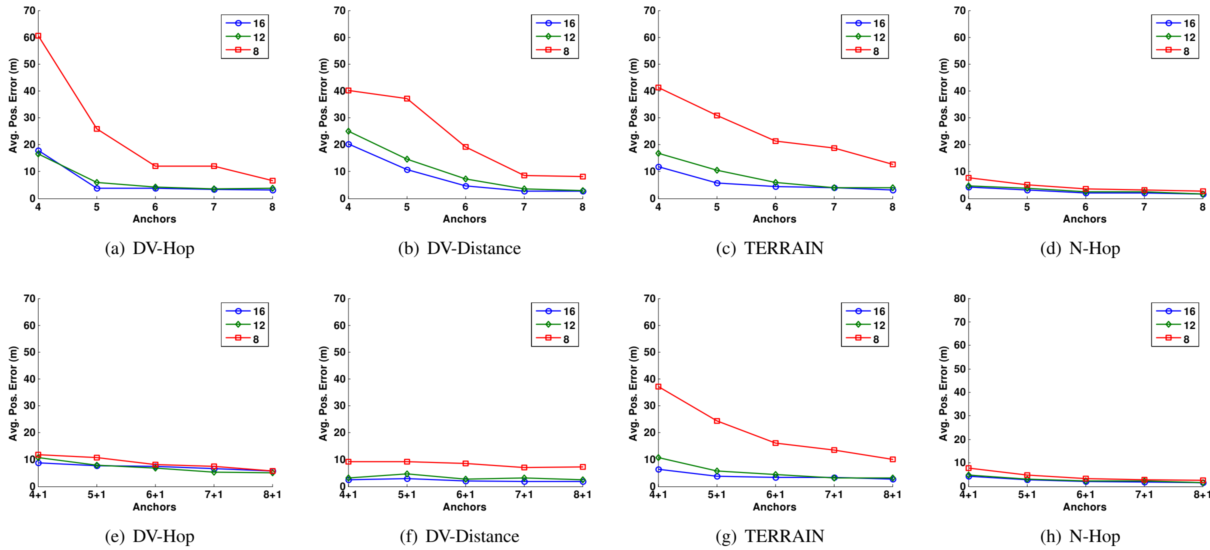
B. Initial Position Algorithms

Fig. 2 depicts the results of the simulations of the initial position algorithms from Sec. III-A.

DV-Hop and *DV-Distance* use similar approaches. Thus, they have similar behaviour. DV-Hop as the simplier of the two shows slightly worst graphs. This is due to the fact that the more multi-hops between anchors, and between nodes and anchors exist, the less accurate is the use of an average inter-node distance on all hops. DV-Distance's better performance is related to the fact that it uses distance measurements instead of an average value. But both algorithms profit from an additional anchor at the networks centre. The reason is the reduced hop-count of mobile nodes close to the network's centre. It allows more accurate inter-node distance estimates. DV-Hop achieves an average position error of 15 m and DV-Distance of 5 m (inter-node connectivity ≥ 12) if an additional centre anchor is available.

TERRAIN is robust across all configurations but performs worst compared to all other algorithms. It seems TERRAIN is strongly affected by the measurement errors. Simulations with error-free distances showed always perfect matches with the real positions. Another problem is the flooding scheme which means reference points are at one end only rather than spread across the network's boundaries. Simulations of networks with anchors concentrated in one area using DV-Distance or N-Hop showed a decrease in their performance, hence verifying the effect. Additionally, TERRAIN needs high inter-node connectivity to reach all mobile nodes in the network. The authors of TERRAIN recommend an average connectivity of 15 or higher [14].

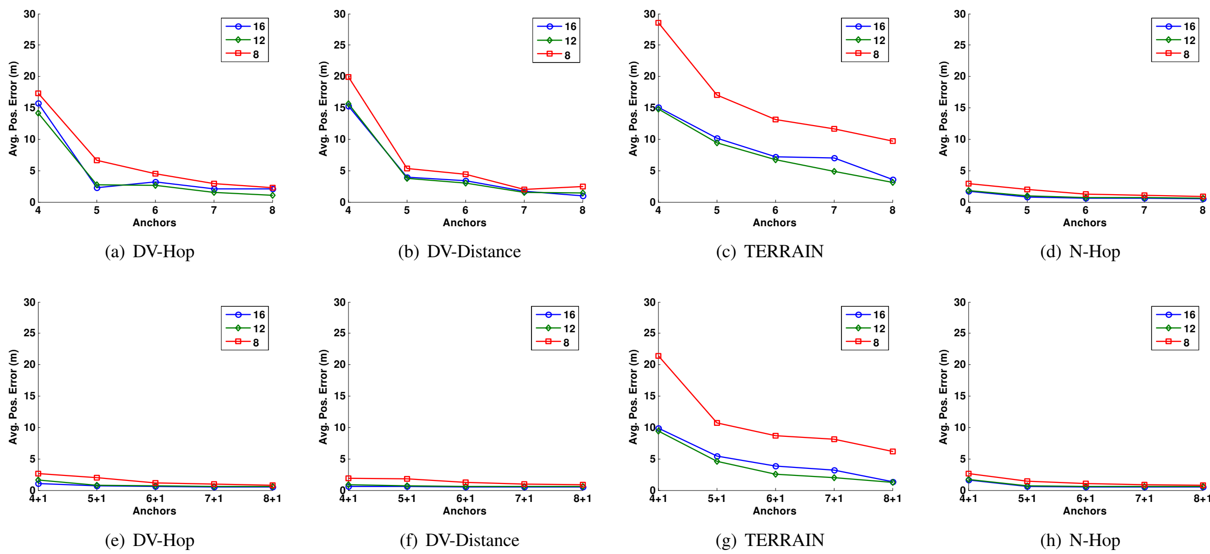
N-Hop shows the best performance and stable results across varying connectivity and anchor count. It has an average position error of about 5 m across any simulated network configuration. Anchors inside the network (e. g. at the centre) should be skipped by the algorithm. They might decrease the accuracy especially in low anchor count situations.



(a) DV-Hop (b) DV-Distance (c) TERRAIN (d) N-Hop

(e) DV-Hop (f) DV-Distance (g) TERRAIN (h) N-Hop

Fig. 3. Avg. Position Error after MMSE (Sorted by Init. Algorithm, Parameter: Connectivity)



(a) DV-Hop (b) DV-Distance (c) TERRAIN (d) N-Hop

(e) DV-Hop (f) DV-Distance (g) TERRAIN (h) N-Hop

Fig. 4. Avg. Position Error after MSO (Sorted by Init. Algorithm, Parameter: Connectivity)

C. Refinement Algorithms

Fig. 3 and Fig. 4 depict graphs of final average positioning errors after MMSE and MSO on all four initial positioning algorithms. The results show that a minimum connectivity of 12 is required and the number of anchors should be 6 or 5+1 at least. MSO achieves accuracies of about 0.5 m while MMSE reaches only 2.5 m. In both cases N-Hop gives the best initial positions (Sub-Fig. (d) & (h)) for refinement.

TERRAIN should be rejected as initial positioning algorithm. Only in combination with MMSE and an additional anchor at the network's centre the results are acceptable (Fig. 3(g)). TERRAIN does not provide good starting points (Fig. 2(c)+(g)) for refinement. Or if it does, it comes at a high cost (connectivity > 16, anchors > 8). A resolution of 5 m can be expected. Furthermore TERRAIN may be unable to calculate initial positions for all mobile nodes which is an explanation for its bad graphs at a connectivity of eight (Sub-Fig. (c) & (g) in Fig. 3 & 4).

As a general guideline any anchor inside the network will help the refinement algorithm to calculate better final positions. The figures show MSO could be combined with DV-Hop, DV-Distance or N-Hop to achieve resolutions below 1 m. Table II lists the resolutions of all the depicted algorithm combinations.

TABLE II
ACHIEVABLE FINAL RESOLUTIONS (MIN. AVG. POS. ERRORS)

	DVH	**DVD**	**TER**	**NHP**
MMSE	3.5 m	3.5 m	5.0 m	2.5 m
MSO	1.5 m	1.5 m	4.0 m	0.7 m
w/ Anchor				
MMSE	5.0 m	3.0 m	3.0 m	2.5 m
MSO	0.8 m	0.6 m	1.3 m	0.5 m

To summarise, a combination of N-Hop and Mass-Spring Optimisation provides the best performance for cooperative localisation under the simulated conditions.

V. FUTURE WORK

The next step is implementing DV-Hop, DV-Distance, N-Hop and Mass-Spring Optimisation (MSO) on the sensor devices platform. Experiments are necessary to validate the simulation results presented in this paper.

As stated in [17] the step width used to minimise the total energy E_i per node is selected empirically. Investigations into a modified step width might improve results.

VI. CONCLUSIONS

In this paper an analysis of current algorithms for cooperative localisation has been presented. Candidates for initial positioning as well as refinement have been selected to be implemented on CSIRO's hardware platform for wireless sensor devices in the near future. According to the findings in this paper a position accuracy of the system of about 0.5 m can be expected.

REFERENCES

[1] Nirupama Bulusu, John Heidemann, and Deborah Estrin, "GPS-less low-cost outdoor localization for very small devices," in *IEEE Personal Communication Magazine*. Oct. 2000, vol. 7, pp. 28–34, IEEE Communications Society.

[2] Pratik Biswas and Yinyu Ye, "Semidefinite programming for ad hoc wireless sensor network localization," in *IEEE Information Processing in Sensor Networks (IPSN)*, Berkeley, CA, USA, 26–27Apr. 2004, pp. 46–54, 3rd International Symposium.

[3] Dragos Niculescu and Badri Nath, "Ad hoc positioning system (APS)," in *IEEE Globecom*, San Antonio, TX, USA, 25–29 Nov. 2001, pp. 2926–2931.

[4] Andreas Savvides, Chih-Chieh Han, and Mani B. Strivastava, "Dynamic fine-grained localization in ad-hoc networks of sensors," in *7th ACM Annual International Conference on Mobile Computing and Networking (ACM MobiCom)*, Rome, Italy, 16–21 July 2001, ACM SIGMOBILE.

[5] Ian F. Akyildiz, Weilian Su, Yogesh Sankarasubramaniam, and Erdal Cayirci, "A survey on sensor networks," *IEEE Communications Magazine*, pp. 102–114, Aug. 2002.

[6] R. Nagpal, H. Shrobe, and J. Bachrach, "Organizing a global coordinate system from local information on an ad hoc sensor network," in *IEEE Information Processing in Sensor Networks (ISPN)*, Palo Alto, CA, USA, 22–23 Apr. 2003, pp. 333–348.

[7] Wen-Hwa Liao and Yu-Chee Lee;, "A lightweight localization scheme in wireless sensor networks," in *International Conference on Wireless and Mobile Communications (ICWMC)*, Bucharest, Romania, 29–31 July 2006.

[8] Xiang Ji and Hongyuan Zha, "Robust sensor localization algorithm in wireless ad-hoc sensor networks," in *12th International Conference on Computer Communications and Networks (ICCCN)*, Dallas, TX, USA, 20–22 Oct. 2003, pp. 527–532.

[9] Jeffrey Hightower and Gaetano Borriello, "Location systems for umbiquitous computing," *IEEE Computer*, pp. 57–66, Aug. 2001.

[10] Tian He, Chengdu Huang, Brian M. Blum, John Stankovic, and Tarek Abdelzaher, "Range-free localization schemes for large scale sensor networks," in *ACM Annual International Conference on Mobile Computing and Networking (ACM MobiCom)*, San Dieago, CA, USA, 14–19 Sept. 2003.

[11] Kui Wu, Chong Liu, and Valerie King, "Very low cost sensor localization for hostile environments," in *IEEE International Conference Communications (ICC)*, Seoul, Korea, 16–20 May 2005, vol. 5, pp. 3197–3101.

[12] Nirupama Bulusu, John Heidemann, Deborah Estrin, and Tommy Tran, "Self-configuring localization systems: Design and experimental evaluation," *ACM Transactions on Embedded Computing Systems*, vol. 3, no. 1, pp. 24–60, Feb. 2004.

[13] Yi Shang, Wheeler Rumi, Ying Zhang, and Markus Fromherz, "Localization from connectivity in sensor netwroks," *IEEE Transaction on Parallel and Distributed System*, vol. 15, no. 11, pp. 961–974, Nov. 2004.

[14] Chris Savarese, Jan M. Rabaey, and Jan Beutel, "Locationing in distributed ad-hoc wireless sensor networks," in *IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*, Salt Lake City, UT, USA, May 2001.

[15] Mark Hedley, Phil Ho, David Humphrey, Alija Kajan, Alex Grancea, and Joseph Pathikulangara, "A platform for radio location research in ad hoc and sensor networks," 2007, submitted to ISCIT'0700.

[16] Chris Savarese, Jan M. Rabaey, and Koen Langendoen, "Robust positioning algorithms for distributed ad-hoc wireless sensor networks," in *USENIX Annual Technical Conference*, Monterey, CA, USA, 2002.

[17] Nissanka B. Priyantha, Hari Balakrishnan, Erik Demaine, and Seth Teller, "Anchor-free distributed localization in sensor networks," Tech. Rep. 892, MIT LCS Technical Report, Apr. 2003.

[18] Andreas Savvides, Heemin Park, and Mani B. Srivastava, "The bits and flops of the n-hop multilateration primitive for node localization problems," in *1st ACM International Workshop on Wireless Sensor Networks and Application (WSNA)*, 28–28 Sept. 2002, pp. 112–121, In Conjunction with ACM MOBICOM.

[19] Andreas Savvides, Heemin Park, and Mani B. Srivastava, "The n-hop multilateration primitive for node localization problem," *Mobile Networks and Applications*, vol. 8, no. 4, pp. 443–451, Oct. 2003, Publisher: Kluwer, now Springer Netherlands.

[20] Neal Patwari, Joshua N. Ash, Spyros Kyperountas, Alfred O. Hero III, Randolph L. Moses, and Neiyer S. Correal, "Locating the nodes," *IEEE Signal Processing Magazine*, July 2005.