# Sensor Node Localization by Three Mobile Anchors in the Wireless Sensor Networks

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**SUMMARY** For the deployment of sensor networks, the sensor localization, which finds the position of sensor nodes, is very important. Most previous localization schemes generally use the GPS signal for the sensor localization. However, the GPS signal is unavailable when there is an obstacle between the sensor nodes and satellites. Therefore, in this paper, we propose a new localization scheme which does not use the GPS signal. The proposed scheme localizes the sensors by using three mobile anchors. Because the three mobile anchors collaboratively move by themselves, it is self-localizable and can be adopted even when the sensors are randomly and sparsely deployed in the target field.

*key words:* sensor localization, sensor deployment, mobile anchor, sensor network

# 1. Introduction

PAPER

A sensor network consists of a number of sensor nodes which are randomly deployed in a field of interest. These randomly deployed sensor nodes cooperatively detect the events which a user is interested in and transmit sensing data about the event to a sink node. Accordingly, the important operation in the wireless sensor networks is for gathering not only the sensing data from the sensors but also the locations where events occur. In the case of intrusion detection, for instance, it is worthless to identify only the existence of an intruder without any information about where the intruder is. In order to obtain the location of an event, we need to know the location of sensor nodes. However, it is difficult to find the location of sensor nodes manually. Consequently, after the random deployment, a sensor network usually localizes the sensor nodes autonomously.

The localization of sensor nodes can be easily solved if all nodes know their exact locations by using a GPS-like signal. However, the GPS signal is only available when there is no obstacle between the sensor node and satellites. If a sensor node is indoors or under a tree, it cannot get the GPS signal. To overcome this problem, the neighborassisted localization approach was proposed [1], [2]. In the neighbor-assisted localization approach, a sensor node attempts to find its position by using the distance information

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with the neighbor nodes which know their location. However, this approach is not adoptable in all sensor networks. If the randomly scattered neighbor nodes are few or only few neighbor nodes precisely know their location, the neighborassisted localization which uses only the neighbor nodes in fixed locations is not very helpful. Accordingly, to fill the gap and enhance the capability of localization, the mobileassisted localization approach was proposed [3]–[12]. The mobile-assisted localization approach uses the mobile anchors which knows their positions and moves freely. The mobile anchor enables a sensor network to be localized by moving through the sensing field and measuring distances from sensor nodes.

Even in the mobile-assisted localization approach, the mobile anchor needs to know its location. The easiest way for the anchor to know its location is also to use the GPS signal. However, the mobile anchor using GPS is unworkable despite whether it is in an indoor environment such as building, factory, basement, and tunnel. Especially, when a sensor node is in the GPS-unavailable spot, the anchor node has difficulty in receiving a GPS signal because it is near the sensor node. As a result, the localization by the mobile anchor using GPS can be useless when it is needed the most.

Therefore, in this paper, we propose a new mobileassisted localization scheme which does not use the GPS signal at the mobile anchors as well as the sensor nodes. Because the proposed scheme uses only the moving and measured distance information among three mobile anchors, it is workable despite whether the sensor node is in the GPSunavailable spot. Moreover, the proposed scheme is selflocalizable since three mobile anchors move in collaboration and localize by themselves without any assistance of other nodes. Thus, the proposed scheme can be adopted even when the sensor nodes are randomly and sparsely deployed in the target field.

### 2. Background and Related Work

### 2.1 Background

Sensor network is considered as a graph consisting of a set of sensor nodes and weighted edges which represent measured distances. From the graph theory point of view, localization of sensor network is equivalent to the graph realization. Thus, a localizable sensor network has the unique graph realization [13]. In Fig. 1 (a), for instance, the graph

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which consists of 4 nodes and 4 edges has multiple realizations due to the continuous deformation. Such a graph is called flex graph. By adding one edge to the graph, we can avoid the continuous deformation as shown in Fig. 1 (b). This graph is rigid. The rigidity is a necessary condition for unique realization but not a sufficient condition. The rigid graph still has partial reflection and discrete multiple realizations as shown in Fig. 1 (b) and 1 (c). For unique realization, a graph should be redundantly rigid. The redundant rigidity is established when the graph is still rigid after the removal of any one edge. By the way, even though a graph is redundantly rigid, it may have partial reflection as shown in Fig. 1 (c). This is because three or more vertexes are collinearly laid in a straight line. To avoid this problem, a graph should have no three vertexes which are collinearly laid with in a line. We call this property as the 3-vertexconnectivity. As a result, if a graph satisfies two properties: (1) the redundant rigidity and (2) 3-vertex-connectivity, it is a globally rigid and has unique realization as shown in Fig. 1 (d). A sensor network which can be expressed by a globally rigid graph is localizable since it has unique realization.

When there are insufficient edges, a globally rigid graph cannot be constructed. Figure 2 (a) graph, for instance, does not have enough edges for satisfying global rigidity. But, by adding a node and 4 measured distances as shown in Fig. 2 (b), the graph can be globally rigid. The added node may be newly deployed sensor node or a mobile anchor as a virtual node. However, physically adding new nodes at a well-planned position is difficult without knowing the predetermined locations of other sensor nodes. Especially, it is almost impossible when a number of sensors are randomly or sparsely deployed in the field. On the contrary, the mobile anchor freely moves anywhere and can be easily placed on multiple locations. Thus, it can localize sensor networks without adding new sensor nodes. Conse-



quently, the mobile-assisted localization approach is more cost effective than the additional sensor node deployment.

## 2.2 Related Work

There are many sensor localization schemes based on various ranging techniques [22]. The distance information between sensor nodes is acquired by ranging techniques such as time difference of arrival (TDOA) of two different speed signals [14], received signal strength (RSS) measurement [1], [23], time delay measurement [24], [25], and network connectivity [15]. With these ranging techniques, [1], [2] proposed the localization algorithms which start with three fixed anchor nodes. The anchor nodes know their positions and localize the other nodes incrementally through trilateration. In [16], [17], anchor-free algorithms, which do not need anchor nodes knowing their absolute coordinates, were also introduced. They produce unique relative coordinates albeit allowing global translation, rotation, and flipping. But, all of these algorithms belong to neighborassisted localization approach. They use only the fixed neighbor nodes so that they are inapplicable to sparsely deployed sensor networks.

In [4]–[12], the mobile anchor which is equipped with GPS was used for sensor network localization. A mobile anchor broadcasts its known location and sensor nodes measure distances from it. When three or more non-collinear mobile locations and distance measurements from the mobile anchors are gathered on the sensor node, it can be localized. In these GPS-equipped schemes, the various types of moving patterns of the mobile anchor were proposed for short path length and accurate localization. In [5], to localize all sensor nodes, the linear moving pattern, which is called scan, was used. In [8], spiral trajectory was used for moving pattern. To evaluate localization accuracy, [10] compared four types of moving patterns: scan, Hilbert, circles, and s-curves. In [11], the mobility scheduling algorithm that a mobile anchor moves based on depth-first traversal was proposed. In [12], a ranging-free localization scheme by changing the transmission power was proposed. However, all of these schemes use GPS and are not workable when a sensor network is deployed in GPS-unavailable environment.

In [3], a GPS-free scheme for mobile-assisted localization was proposed. In [3], one mobile anchor which does not know its location moves around the sensor nodes and measures distances at four different locations when it enters the distance-measurable range with three sensor nodes. After measuring distances from the mobile anchor, the pairwise distances among the three sensor nodes are calculated. Through the iteration of these steps, the sensor network can be localized without GPS signal. However, the proposed scheme requires densely deployed sensor nodes. This is because all of sensor nodes should be connected by themselves and more than three sensor nodes should be seen by the mobile anchor at each position.

The localization for robots, not sensor nodes, was also

studied in the robotics field. The representative research, for instance, is the cooperative positioning system for cleaning robots [18]. The cooperative positioning system used multiple robots without GPS signal to track the moving position of the robots indoor. However, its localization algorithm requires versatile devices for measuring the angle as well as the distance. To measure angle and distance, it used an inclinometer and a laser range finder. These devices are expensive for sensor nodes and anchors. Other approaches studied in the robotics field have similar approaches. Therefore, the localization approaches for robots cannot be adopted to the sensor network which requires cheap devices for sensors.

### 3. Mobile-Assisted Localization

# 3.1 System Description

The establishment methods of sensor networks are diverse based on sensor node's characteristics such as sensing distance  $(D_s)$ , communication distance  $(D_c)$ , and ranging distance  $(D_r)$ . The  $D_s$  depends on various sensor hardwares and applications which require the different accuracy level of sensing data. The  $D_c$  depends on the radio frequency and the transmission power. In the case of the CC1000 radio module, which is used in Mica2 [19],  $D_c$  is about 150 m. In the CC2420 of MicaZ [19],  $D_c$  is about 100 m. The  $D_r$ , the maximum distance which can be measured between two sensor nodes, depends on the ranging devices and ranging techniques. In the implemented sensor nodes, the ultrasound transceiver with TDOA ranging technique is commonly used for measuring distances between sensor nodes due to cost-effectiveness and high accuracy. The  $D_r$  of the ultrasound transceiver which is used in the Cricket [14] is about 10 m. Therefore, our proposed scheme also assumes that the  $D_c$  is larger than the  $D_r$  and focuses on the variations of  $D_r$ .

In this paper, we assume that target area to be scanned is 2-dimension. For scanning 2-dimensional area, diverse moving patterns, such as scan, Hilbert, circles, s-curves, and spiral trajectory, was proposed [8], [10]. However, the basic operation of all moving patterns is the linear movement. By combining linear movements, lots of moving patterns can be created. So, in this paper, we focus on the linear movement of mobile anchors.

# 3.2 How to Use Mobile Anchors for Localization

Now, we describe how to use the mobile anchors for the localization. There are two primitive operations for mobile anchors as follows:

- A mobile anchor adds a vertex and measured edges by measuring distances from sensor nodes or other mobiles at a particular position.
- 2. After a mobile anchor moves, it can add an traveled edge between the previous position and the current position by measuring traveled distance using odometry [20]. However, the traveled edge may have more

distance measuring errors than the measured edge and localization with the distance of the traveled edge causes inaccurate localization results. Therefore, it cannot be directly used to localize the distance graph as a measured edge.

Let's find out the minimum number of mobile anchors to localize sensor networks without any density constraints. To localize sensor nodes without any constraints, the mobile anchors should be able to construct globally rigid graph themselves without other sensor nodes. This is because, when two sensor nodes are quite far from each other, mobile anchors cannot measure distance from the sensors at the same time and only mobile anchors participate to construct graph. Within this situation, a single mobile anchor cannot add any measured edges. If there are two mobiles, they only construct bilateration graph as shown in Fig. 3. The bilateration graph is rigid but 2-vertex-connected, thus it does not remove partial reflection [13]. As a result, at least three mobile anchors are required to build globally rigid graph themselves without any constraint. With three mobile anchors, when one mobile moves to a new position where the other two mobiles can be seen, on vertex, two measured edges, and one traveled edge can be added in the graph. Due to the moving error, a mobile anchor cannot track moving distance by itself and should measure distances from at least two anchors to localize its position. Therefore, the two of three mobile anchors cannot move in parallel. By iterating the step that the mobile anchors move, the graph constructed by the three mobiles becomes a trilateration graph and can be a globally rigid.

Lastly, we propose two conditions on localization with the traveled edge. The first condition is that a mobile anchor does not cross over the line connecting the other two mobile anchors. At the moment when a mobile moves across the line, there are two possible localizations by the reflection so that the mobile loses its location as shown in Fig. 4 (a). This phenomenon cannot be avoided by just stopping and localizing the mobile anchor before crossing the line. The



Fig. 3 Graph construction with two mobile anchors.





second condition is that the traveled edge is used only for avoiding partial reflection and location of a mobile anchor is calculated with two measured edges from the other anchors as shown in Fig. 4 (b). This is because distance error on the traveled edge causes the localization error among the mobile anchors.

#### 3.3 Proposed Localization Algorithm

Now, let's consider how three mobile anchors move to construct the trilateration graph efficiently. In order to construct a trilateration graph, three mobile anchors should be able to measure distances from each other. Thus, each moving distance of a mobile anchor cannot be more than  $D_r$  apart from the others. Because the trilateration graph is constructed incrementally, mobile anchors cannot move simultaneously either. Only one mobile can move at a time. In addition, a moving mobile must stop due to the constraint that the mobile anchor always sees other two mobiles located at a fixed position. Lastly, since lots of stops increase the localization time, the number of stops of mobile anchors should be minimized during localization process. With these conditions, we propose a moving algorithm of mobile anchors for efficient localization.

To reduce the number of stops, we lengthen the distance that mobile moves at a time. For simplifying the algorithm scope, we limit the algorithm to the regular sequence that each mobile moves the same distance in regular order. Within the constraint, we find the configuration of  $w_1$  and  $w_2$ in Fig. 5 (a) to minimize the number of stops. First, let's find an upper bound of moving distance in regular sequence. We define the outer mobile and the inner mobile as in Fig. 5 (a). For the inner mobile, the moving distance cannot be more than  $D_r$  far from each outer mobile anchor. And, the inner mobile cannot cross over the line connecting the outer mobiles. As shown in Fig. 5 (b), the moving distance of the inner mobile is the same as distance from the top of isosceles triangle to the base line. Therefore, the upper bound of the moving distance of the inner mobile anchor is  $D_r$ .

The upper bound of the outer mobile depends on  $w_1$ and  $w_2$  as shown in Fig. 6 (a). The moving distance of the outer mobile is limited to the length of base line of isosceles triangle as shown in Fig. 6 (b). Thus, the upper bound of the moving distance of the outer mobile can be expressed as  $2\sqrt{D_r^2 - W^2}$  where  $W = w_1 + w_2$ .

The moving distances of the regular sequence is limited by  $min(D_r, 2\sqrt{D_r^2 - W^2})$  which cannot be larger than  $D_r$ . Consequently, each mobile anchor cannot move more than  $D_r$  at each movement.

Now, we propose a moving sequence and configuration of  $w_1$  and  $w_2$  to allow mobile anchors to construct a trilateration graph and move up to  $D_r$ . In the Fig. 7, when the inner mobile follows one of the outer mobile and the moving sequence is the mobile 1, 2, and 3, they construct a trilateration graph and the upper bound of the moving distance is achieved. Hence, the configuration of  $w_2 = 0$  and



(a) Inner mobile cannot cross over the line (b) Upper bound

Fig. 5 Movement limitation with traveled edge.



(b) Upper bound

Upper bound for movement distance of outer mobile. Fig. 6



Theoretical regular triangle moving algorithm.

locate <i>MA</i> [1] at (0, 0)
locate $MA[2]$ at $(D_r/2,\sqrt{3/2}\cdot D_r)$
locate $MA[3]$ at $(D_r, 0)$
loop {
<b>for</b> $(i = 1; i \le 3; i + +)$ {
<b>move</b> $MA[i]$ to $D_r$ on the X-axis
MA[i] broadcasts radio and ultrasound to the other MAs
MA[i] gathers distance information from the other MAs
MA[i] localizes and broadcasts its position
}
} <b>until</b> (all <i>MAs</i> arrive at the destination)

Fig.8 Formal description of regular triangle moving algorithm.

 $w_1 \leq \frac{\sqrt{3}}{2} D_r$  can construct a globally rigid graph and maximize the moving distance up to  $D_r$ . The number of stop is path length divided by the moving distance. The path length is inversely proportional to the scan width which is equal to  $(2D_r + W)$ . Thus, the proposed regular triangle moving algorithm, which W is  $\frac{\sqrt{3}}{2}D_r$ , minimizes the number of stops. Figure 8 is the formal description of the proposed regular triangle moving algorithm.

### 4. Analysis

In this section, we analyze our proposed algorithm. In Sect. 3, we conclude that each mobile can move forward  $D_r$ at most and we propose the moving algorithm that maximizes the movement distance. However, in order to mini-



Fig. 9 Newly scanned area.

mize the localization time, we also consider the total moving distance as well as the number of stops in comparison with the scan width, W. The total moving distance is related to the time to move and the number of stops is related to the time to stop and restart the mobile anchor. Therefore, we will find the optimal W to minimize the localization time based on the total moving distance and the number of stops.

For analyzing the total moving distance, we first get the newly scanned area per cyclic movement of mobile anchors. The newly scanned area,  $A_n$ , is the area that three mobiles newly scan after each mobile anchor moves once. As you can see in Fig. 9, the  $A_n$  is  $D(2D_r + W)$  where D is the distance that each mobile anchor moves at a time. According to the upper bound of the moving distance of the mobile anchor, as mentioned in Sect. 3, D is as follows:

$$D = \begin{cases} D_r, & \text{if } W \le \frac{\sqrt{3}}{2} D_r; \\ 2\sqrt{D_r^2 - W^2}, & \text{if } \frac{\sqrt{3}}{2} D_r \le W < D_r. \end{cases}$$

Therefore, the moving distance of each mobile anchor per newly scanned area is  $D/A_n$  and becomes  $1/(2D_r + W)$  since  $A_n$  is  $D(2D_r + w)$ . In other words, the moving distance is decreased as W is increased up to  $D_r$ .

The number of stops of each mobile for scanning a given area,  $N_s$ , is inversely proportional to the newly scanned area,  $A_n$ . At each stop, the total localization time is increased for two reasons. First, the mobile needs more time to decelerate to stop and accelerate to move again. Second, the accurate localization after stop requires lots of time for measuring the distance many times. We define the overall delay time per stop due to acceleration, deceleration, and accurate localization as the stopping overhead time,  $T_s$ . By the way, the  $N_s$  is  $A_g$  over  $A_n$  where  $A_g$  is a given scanning area. Thus, the  $N_s$  in terms of W is as follows:

$$N_{s} = \begin{cases} \frac{A_{g}}{(2D_{r} + W)D_{r}}, & \text{if } W \leq \frac{\sqrt{3}}{2}D_{r}; \\ \frac{A_{g}}{(2D_{r} + W)2\sqrt{D_{r}^{2} - W^{2}}}, & \text{if } \frac{\sqrt{3}}{2}D_{r} \leq W < D_{r}. \end{cases}$$

Therefore, the number of stops per given area,  $N_s$ , is decreasing when W is growing up to  $\frac{\sqrt{3}}{2}D_r$ . However, it is rapidly increasing when W is growing over  $\frac{\sqrt{3}}{2}D_r$ . So, the regular triangle moving algorithm, which W is  $\frac{\sqrt{3}}{2}D_r$ , minimizes the  $N_s$ .

Finally, we look into localization time,  $T_L$ . The regular triangle moving algorithm minimizes the number of stops. But, it does not minimize  $T_L$  at all times.  $T_L$  can be divided into two parts: total moving time,  $T_M$ , and total stopping overhead time,  $T_O$ .  $T_M$  is defined as the only time to spend on moving through the path with uniform velocity, V.  $T_O$  is all the other time to spend on localization except  $T_M$ .  $T_O$  includes all  $T_s$ . Thus,  $T_M$  is  $A_g/(V(2D_r + W))$  and  $T_O$  is  $T_sN_s$ . Since  $T_L$  is the sum of  $T_M$  and  $T_O$ , we can express  $T_L$  as follows:

$$T_L = \begin{cases} \frac{A_g}{(2D_r + W)} \left(\frac{1}{V} + \frac{T_s}{D_r}\right), \\ & \text{if } W \leq \frac{\sqrt{3}}{2}D_r; \\ \frac{A_g}{(2D_r + W)} \left(\frac{1}{V} + \frac{T_s}{2\sqrt{D_r^2 - W^2}}\right), \\ & \text{if } \frac{\sqrt{3}}{2}D_r \leq W < D_r. \end{cases}$$

Therefore,  $T_L$  is minimized when  $\frac{\sqrt{3}}{2}D_r \leq W < D_r$ . According to this equation, we can find that the optimal W for minimizing  $T_L$  depends on  $T_s$ , V, and  $D_r$ . If  $T_s$  is large enough,  $T_L$  is minimized at  $W = \frac{\sqrt{3}}{2}D_r$ . However, if  $T_s$  is very small,  $T_L$  is minimized at a certain W between  $\frac{\sqrt{3}}{2}D_r$  and  $D_r$ . The small V and the large  $D_r$  has the same effect as the small  $T_s$ .

In order to get the optimal W for minimizing  $T_L$ , we have to solve the following equation:

$$\frac{dT_L}{dW} = \frac{-A_g}{V(2D_r + W)^2} + \frac{A_g T_s (2W^2 + 2D_r W - D_r^2)}{2(2D_r + W)^2 (D_r^2 - W^2)^{\frac{3}{2}}} = 0$$

According to this equation, if the optimal W for minimizing  $T_L$  is  $\frac{\sqrt{3}}{2}D_r$ ,  $T_L$ ,  $T_s$ , V, and  $D_r$  has the following relationship:

$$T_s = \frac{D_r}{2(1+2\sqrt{3})V}$$

Consequently, when  $T_s$  is greater than  $\frac{D_r}{2(1+2\sqrt{3})V}$ , the regular triangle moving algorithm in Fig. 7 minimizes  $T_L$ . In other words, the regular triangle moving algorithm minimizes the localization time when the stopping overhead time is greater than about 10% ( $\approx \frac{1}{2(1+2\sqrt{3})}$ ) of the  $D_r/V$  which is the time to move the moving distance in each step.

# 5. Implementation

We implement our mobile-assisted localization scheme on the real sensor network system. The mobile anchor consists of the Cricket [14], ER1 [21], and main controller on a laptop as shown in Fig. 10. The laptop is connected to the Cricket and the ER1 through the RS232 serial port. The Cricket is used for measuring distances and communication with other Cricket nodes. The ER1 plays a role as a mobilizer with two wheels. The ER1 provides simple APIs for



Fig. 10 Configuration of the mobile anchor.



Fig. 11 Omnidirectional ranging device.

controlling two wheels such as move, rotate, and stop. The main controller on the laptop localizes the mobile anchor with distance information from the cricket. And, it controls the ER1 to move based on the moving algorithm.

Because three mobile anchors are on the same plane, we need an omnidirectional ranging device. However, the ultrasound transmitter and receiver on the Cricket is a directional device. In [1], an omnidirectional ranging device, called Medusa, which is equipped with eight ultrasound transmitters and receivers, was introduced. But, instead of the complex Medusa, we propose a simple omnidirectional ranging device as shown in Fig. 11. For the omnidirectional ranging, we simply put solid cones on the transmitter and receiver upside down. Then, the ultrasound waves from the transmitter are reflected and spread by the reverse cone so that the receivers can detect the signal in all directions.

## 6. Experiments

In this section, we evaluate the performance of our localization scheme. We have conducted a series of experiments with the experimental parameters as shown in Table 1.

Figure 12 shows the localization result of the randomly deployment of sensor nodes. In this experiment, four sensor nodes on the left area can construct globally rigid graph by themselves but there are not enough edges to sensor nodes on the right area to localize the whole network. However, by helping mobile anchors with our localization scheme, each sensor nodes have more than three measured edges to the trilateration graph, as shown in Fig. 12 (c), so that the graph is globally rigid.

Next, we evaluated the localization accuracy by measuring locations of six sensor nodes which are located in a line and 65 cm apart from each other. Table 2 shows the localization error of each sensor nodes based on the first node. In the result, the maximum error is 2.6 cm. This is only 1.0% of the distance from the first node (260 cm). There-

 Table 1
 Experimental parameters.

Parameter	Value		
Ranging distance	75–200 cm		
Scan width/Ranging distance	0.7-0.97		
Velocity of mobile	5–50 cm/s		
Margin for flipping-free region	50 cm		



(a) Picture of sensor networks



(b) Localization results



(c) Localization graph

Fig. 12 Experiment with randomly deployed network.

Table 2 Results of location accuracy.

Node number	2	3	4	5	6
Localization error (cm)	1.7	2.1	2.3	2.6	2.5
Distance from node1 (cm)	65	130	195	260	325

fore, we can say that the localization accuracy of the proposed scheme is quite reasonable within the useful range of the ultrasound device. Localization accuracy absolutely depends on the accuracy of a ranging technique. If we use a more accurate ranging technique for the distance measurement, the localization accuracy will be increased. If we use a less accurate technique, it will be decreased. However, the comparison of accuracies of various ranging techniques is beyond the scope of this paper.

Next, we measured the localization time of our scheme to validate the analysis. Before measuring the localization time, we measured the total moving distance and the number of stops, respectively. Figure 13 shows the total moving distance and the number of stops for scanning a given area when  $D_r$  is 150 cm. As the analytical results, the total moving distance is decreased when the scan width is increased. Also, the number of stops is decreased until the scan width



Fig. 13 Total moving distance and number of stops according to scan width.

is growing up to  $\frac{\sqrt{3}}{2}D_r$  and rapidly increased after that point.

Figure 14 shows the localization time when the mobile velocity is 10 cm/s and the stopping overhead time is 6.4 sec. As you can see in the results, the localization time is minimized when the regular triangle moving algorithm, which the scan width in the ratio  $D_r$  is set to  $\sqrt{3}/2$  ( $\approx 0.86$ ), is used. This is very well accordance with the analytical result that the regular triangle moving algorithm minimizes the localization time when the stopping overhead is greater than 10% of the  $D_r/V$ . In this experiment,  $D_r$  is set to 150 cm and V is set to 10 cm/s. Thus, the minimum stopping overhead time for the regular triangle moving algorithm to minimize the localization time is 1.5 sec ( $\approx 10\% \times 150 \text{ cm}/10 \text{ cm}$ ) and it is smaller than stopping overhead time, 6.4 sec, which is used in the experiment. Therefore, the regular triangle moving algorithm used in the experiment minimizes the localization time as shown in Fig. 14.

# 7. Conclusion

In this paper, we proposed a novel mobile-assisted localization scheme. The proposed scheme does not need the GPS signal at all. Moreover, it is self-localizable by using three mobile anchors. Therefore, the proposed scheme can be adopted even when the sensor nodes are randomly and sparsely deployed.

Through the analysis and experiments, we showed that the total moving distance of mobile anchors is decreased when the scan width is increased. On the other hand, the number of stops is decreased until the scan width is grow-



**Fig. 14** Localization time vs. scan width.

ing up to  $\sqrt{3}/2$  of the ranging distance. And, it is rapidly increased after that point. As a result, if the stopping overhead is large enough, the regular triangle moving algorithm, which the ranging distance among three mobile anchors is the same and the scan width is  $\sqrt{3}/2$  of the ranging distance, minimizes the localization time.

For the future work, we will design a non-linear and irregular moving algorithm to reduce localization time. Moreover, we will find advanced movement patterns which efficiently scan target area in various environments such as shape of target space, diverse obstacles, and different system requirements. In addition, we will find more efficient localization mechanisms by using more than three mobile anchors.

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1988