An Efficient Positioning Algorithm using Ultrasound and RF

Seung Beom Kim, Chansik Park*, Dong-Youn Kang, Hee Hak Yun, Bierng-Chearl Ahn, Eun Jong Cha, and Sang Jeong Lee

Abstract: In this paper, an efficient positioning algorithm is proposed for a local positioning system using ultrasound and RF in WSN. The proposed positioning algorithm is the modified Savarese method where measurement noise characteristics are included as a weighting. Furthermore the ill-conditioned and the singularity problem occurred when all beacons are installed at the same height are removed. And the method is applicable to 2D positioning with 2 beacons only. The experiments with implemented system show the accurate seamless positioning less than 2cm error both static and dynamic experiments while the original Savarese method can not provide positions.

Keywords: Positioning, RF, ultrasound, WSN.

1. INTRODUCTION

WSN (Wireless Sensor Networks) consists of wireless network and spatially distributed sensors monitoring temperature, sound, vibration, pollutants and so on. The improvements in semiconductor and communication technology broaden the applications of WSN; smart homes, health cares, ITS (Intelligent Transportation System) and environment monitoring. If position information is available in WSN, big application areas will open.

GPS (Global Positioning System) is a de facto positioning system in navigation and location. GPS, however, is difficult to use indoors because of very weak signal level. Assisted GPS (AGPS) is applied indoors with network assistance and special hardware, but its high cost and unsatisfactory accuracy prevent an AGPS receiver from wide spreading in WSN applications. RSSI (Received Signal Strength Indication) is an inherent by-product from wireless ad-hoc network and it is already used for positioning. But RSSI is limited to the non-precise positioning applications because of large errors induced by battery level, fading and multipath. To overcome this problem, RSSI is combined with other sensors such as ultrasound, IR (Infra Red), WLAN (Wireless Local Area Network) and so on. AHLoS [1], Cricket [2], and U-SAT [3] are examples of combining RSSI and ultrasound. In these systems, besides RSSI, the arrival time difference of ultrasound and RF (Radio Frequency) signal is usually measured to provide a precise range measurement. Using the range measurements, the precise position can be found.

This paper proposes a positioning algorithm which has no limitation in installation and provides solutions even if only two beacons are available. The linearization method used in GPS is not adequate for small region applications such as WSN because small errors in initial guess can cause divergent solution. Savarese method [4] is most common algorithm in WSN because it does not require any initial guesses. However, it has the ill-conditioned and the singularity problem: when all the beacons heights are same, the matrix becomes singular. And it does not use the measurement covariance as a weight in computing position and it can't find solution when the number of beacons is less than 2. The proposed algorithm removes these drawbacks. It will increase availability of positioning and flexibility of installation.

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2. POSITIONING ALGORITHM

2.1. Ranging with ultrasound and RF

In this paper, a range measurement is obtained from the arrival time difference between RF and ultrasound. If a node transmits RF and ultrasound simultaneously, the RF signal arrives at a beacon much faster than the ultrasound. The beacon measures the interval between RF and ultrasound arrival times and converts to the range by multiplying the speed of ultrasound as shown in (1). The range ρ_i from user $\mathbf{u}=[x\ \ y\ \ z]^T$ to a beacon $\mathbf{b_i}=[X_i\ \ Y_i\ \ Z_i]^T$ can be expressed as

$$\rho_i=(t_{US}-t_{RF})v_{US}=r_i+w_i, \tag{1}$$

where t_{US} denotes the arrival time of ultrasound, t_{RF} denotes the arrival time of RF, v_{US} denotes the speed of ultrasound ($v_{US}=331.5+0.60714T_C$ m/s, and T_C represents temperature in Celsius). $r_i=\|\mathbf{u}-\mathbf{b_i}\|=\sqrt{(X_i-x)^2+(Y_i-y)^2+(Z_i-z)^2}$ is the distance between a node and a beacon i, w_i is AWGN (Additive White Gaussian Noise) measurement noise with mean 0 and a variance σ^2.

The quality of range measurements is affected by many factors: errors in ultrasound speed by temperature variations, the noises in ultrasound detection circuits and so on. The temperature influence can't be negligible because its error grows as the range increases. Fortunately, most nodes in WSN have temperature sensors and can calibrate the ultrasound speed. If there is no temperature sensor in the nodes, it is required that some beacons have temperature sensors and transmit the measured temperature to nodes using ad-hoc network.

2.2. Overview of Savarese method

By ignoring the measurement errors w_i from (1), squaring both sides to get ρ_i^2, and differencing with ρ_m^2 where m means the last beacon,

$$\begin{aligned}&\rho_i^2-\rho_m^2-\{X_i^2+Y_i^2+Z_i^2\}+\{X_m^2+Y_m^2+Z_m^2\}\\&=2[X_m-X_i\ \ Y_m-Y_i\ \ Z_m-Z_i][x\ \ y\ \ z]^T\end{aligned} \tag{2}$$

is obtained.

Equation (2) can be expressed in a simple form using vectors as

$$\rho_i^2-\rho_m^2-\mathbf{b_i^Tb_i}+\mathbf{b_m^Tb_m}=2(\mathbf{b_m}-\mathbf{b_i})^\mathbf{T}\mathbf{u}. \tag{3}$$

Equation (4) holds for the m beacons, and is represented with a simplified form as in (5). The user position can be found applying LS (Least Squares) to (5).

$$\begin{bmatrix}\rho_1^2-\rho_m^2-\mathbf{b_1^Tb_1}+\mathbf{b_m^Tb_m}\\\rho_2^2-\rho_m^2-\mathbf{b_2^Tb_2}+\mathbf{b_m^Tb_m}\\\vdots\\\rho_{m-1}^2-\rho_m^2-\mathbf{b_m^Tb_m}+\mathbf{b_m^Tb_m}\end{bmatrix}=2\begin{bmatrix}(\mathbf{b_m}-\mathbf{b_1})^\mathbf{T}\\(\mathbf{b_m}-\mathbf{b_2})^\mathbf{T}\\\vdots\\(\mathbf{b_m}-\mathbf{b_{m-1}})^\mathbf{T}\end{bmatrix}\mathbf{u}, \tag{4}$$

$$\boldsymbol{\rho}=\mathbf{Bu}. \tag{5}$$

2.3. Modified Savarese method

2.3.1 Weighted Savarese method

The measurement noise in (1) is proportional to the distance because of the temperature variation and noises in the ultrasound circuit. It implies that more precise positioning is possible using this information as weight while the original Savarese method is not. The errors in two measurements ρ_i and ρ_m are independent AWGN with zero-mean and variance σ^2. The variance of (3) is computed as

$$\begin{aligned}\sigma_{Si}^2&=\mathrm{cov}((\rho_i^2-\rho_m^2)-(r_i^2-r_m^2))\\&=6\sigma^4+4\sigma^2(r_i^2+r_m^2).\end{aligned} \tag{6}$$

Since $r_i\gg w_i$ holds, it is natural to assume that $r_i\approx\rho_i$. Now (6) becomes

$$\sigma_{Si}^2=6\sigma^4+4\sigma^2(\rho_i^2+\rho_m^2). \tag{7}$$

Using WLS (Weighted Least Squares) with weighting matrix $\mathbf{Q_S}=diag(\sigma_{Si}^2)$, the position and its covariance is found as in eqs. (8) and (9). Note WLS becomes MLE (Maximum Likelihood Estimation) since the AWGN is assumed.

$$\mathbf{u}=(\mathbf{B^TQ_S^{-1}B})^{-1}\mathbf{B^TQ_S^{-1}}\boldsymbol{\rho}, \tag{8}$$

$$\mathrm{cov}(\mathbf{u})=(\mathbf{B^TQ_S^{-1}B})^{-1}. \tag{9}$$

2.3.2 Elimination of singularity problem

When all beacons are installed on the same height, the last column of matrix $\mathbf{B}$ becomes 0, so the inverse of $(\mathbf{B^TB})$ or $(\mathbf{B^TQ_S^{-1}B})$ can not be found. Even though all beacons are installed in different heights, $(\mathbf{B^TB})^{-1}$ or $(\mathbf{B^TQ_S^{-1}B})^{-1}$ become ill-conditioned matrix if the height difference is not so large. When beacons are installed inside buildings, it is very hard to make a large height difference. To solve this singularity and ill-conditioned problem, this paper presents an alternative positioning method using (10) instead of (2).

$$\begin{aligned}&\rho_i^2-\rho_m^2-(X_i^2+Y_i^2)+(X_m^2+Y_m^2)\\&=2\left[X_m-X_i\ \ Y_m-Y_i\right][x\ \ y]^T.\end{aligned} \tag{10}$$

Equation (11) can be obtained in similar manner used in (5) where $\mathbf{u_{XY}}=[x\ \ y]^T$ is 2 dimensional user position, $\boldsymbol{\rho}_\mathbf{XY}$ is $(m-1)\times1$ measurement vector with ith element of $\rho_i^2-\rho_m^2-(X_i^2+Y_i^2)+(X_m^2+Y_m^2)$ and $\mathbf{B_{XY}}$ is $(m-1)\times2$ matrix with ith row of $2[X_m - X_i \quad Y_m - Y_i]$.

$$\boldsymbol{\rho}_{\mathbf{XY}} = \mathbf{B}_{\mathbf{XY}} \mathbf{u}_{\mathbf{XY}} \tag{11}$$

Applying WLS to (11), the horizontal position (x, y) is found without a singularity problem. The estimator of height z is calculated using (12) with the fixed (x, y). The higher accurate height can be found by averaging the estimators of height from all beacons.

$$(Z_i - z)^2 = \rho_i^2 - (X_i - x)^2 - (Y_i - y)^2 \tag{12}$$

Note the matrix $\mathbf{Q_S} = diag(\sigma_{Si}^2)$ defined in (7) can be used as a weighting matrix without modification, and covariance of position is $\mathrm{cov}(\mathbf{u_{xy}}) = (\mathbf{B_{xy}^T Q_S^{-1} B_{xy}})^{-1}$.

2.3.3 Modified Savarese method in 2D

The available beacons are frequently less than 4 because of obstacles. If only 2 beacons are available, it is impossible to find positions. In this case by assuming that height is fixed as z_F, horizontal 2D position can be found. Because the height of a node remains constant on a flat floor usually, this assumption is reasonable. The height can be fixed to an estimated value when more than 3 beacons are available or an assumed value such as a height of a vehicle or a human. With fixed height, (2) is expressed as

$$\rho_i^2 - \rho_m^2 - \left\{X_i^2 + Y_i^2 + Z_i^2\right\} + \left\{X_m^2 + Y_m^2 + Z_m^2\right\} -2(Z_m - Z_i)z_F = 2[X_m - X_i \quad Y_m - Y_i][x \quad y]^T. \tag{13}$$

When more than 2 beacons are available, the 2D position is found using (14) where $\boldsymbol{\rho}_{\mathbf{2D}}$ is $(m-1)\times 1$ measurement vector with ith element of $\rho_i^2 - \rho_m^2 - \left\{X_i^2 + Y_i^2 + Z_i^2\right\} + \left\{X_m^2 + Y_m^2 + Z_m^2\right\} - 2(Z_m - Z_i)z_F$. The covariance is $\mathrm{cov}(\boldsymbol{\rho}_{\mathbf{2D}}) = \mathbf{Q_{2D}} = diag(\sigma_{Si}^2 + \sigma_{Fi}^2)$ where $\sigma_{Fi}^2 = 4(Z_m - Z_i)^2 \sigma_{z_F}^2$ and the error of a fixed height is assumed AWGN with zero mean and $\sigma_{z_F}^2$ variance.

$$\boldsymbol{\rho}_{\mathbf{2D}} = \mathbf{B_{xy}} \mathbf{u_{xy}} \tag{14}$$

Note (14) also can have singularity problem if $X_m = X_i$ or $Y_m = Y_i$ holds for all beacons, i.e. all beacons are in a line. The singularity problem is eliminated by using the similar method described in the previous section. If just 2 beacons are available, it is impossible to find 2D position with (14) because 2 unknowns can not be found with a scalar $\boldsymbol{\rho}_{\mathbf{2D}}$. A minimum norm estimator can be applied but the result is not reliable. When just 2 beacons are available, in this paper, (15) which is a direct expansion of (13) is used.

$$y = ax + b, \tag{15}$$

where $a = -(X_1 - X_2)/(Y_1 - Y_2)$ and

$$b = \frac{-\rho_1^2 + \rho_2^2 + X_1^2 - X_2^2 + Y_1^2 - Y_2^2 + (Z_1 - z_F)^2 - (Z_2 - z_F)^2}{2(Y_1 - Y_2)}.$$

By inserting (15) and $z = z_F$ into (12), a quadratic equation is obtained as

$$x^2 + \alpha_i x + \beta_i = 0, \tag{16}$$

where $\alpha_i = -2(X_i + a(Y_i - b))/(1 + a^2)$ and $\beta_i = (X_i^2 + (Z_i - z_F)^2 - \rho_i^2)/(1 + a^2)$ for $i = 1, 2$. From (16), 2 x-candidates are found and a proper one is chosen based on the known beacon coordinates; the candidate not in the interval $[X_1, X_2]$ is discarded.

3. EXPERIMENTAL RESULTS

Three experiments are performed to evaluate the proposed algorithm. The first is static experiments to show the ill-conditioned problem, the second is static experiments to show the effect of the number and geometry of beacons, and the third is dynamic experiments using a line-tracer.

3.1. System implementation

An ultrasound transmitter and a receiver circuit are added to Crossbow MICAz which uses ZigBee as wireless communication. The overall hardware is consisted of a RF, an ultrasound circuit and a microcontroller. A RF is made with Chipcon's CC2420 for ZigBee and AT/R40-10P of KOMAN TECHNICS for an ultrasound transmitter and receiver. An Atmel's AVR ATmega128 is used as a microprocessor. A node makes the 40 kHz frequency pulse to drive ultrasound transducer using PWM (Pulse Width Modulation) controller in ATmega128. An ultrasound receiver is in a beacon fixed at a known position and an ultrasound transmitter is in a mobile node. To transmit an ultrasound signal to all beacons in a test bed directly, both transmitter and receiver use ultrasound sensors with a wide beam pattern of 100 degree. By removing the cap of ultrasound transducer and trimming the gain of amplifier, the coverage becomes wider. Note in this paper we implemented an active mobile structure for convenience but the proposed positioning algorithm can be used in a passive mobile structure also.

To synchronize between RF and ultrasound, the SFD (Start of Frame Delimiter) signal from CC2420 is used. SFD signal is generated when a data frame is transmitted or received using ZigBee communication, therefore by using the SFD signal to transmit ultrasound, synchronization is done. At a beacon, the activation of SFD means the arrival of RF signal. By starting a timer when the SFD activates and stopping a timer when an ultrasound arrives, the time interval between RF and ultrasound is measured.

3.2. Static experiments with different heights

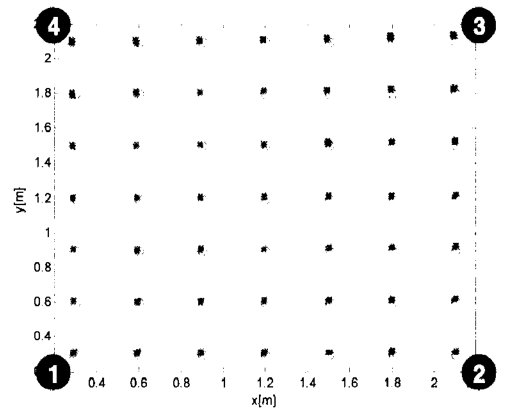
Four beacons are installed at the corners of a test bed in (0m, 0m, 2.4m), (2.4m, 0m, 2.425m), (0m, 2.4m, 2.450m), (2.4m, 2.4m, 2.475m). 500 range measurements are gathered and saved at each 49 reference points. The referenced points are on the bottom of test bed with 30cm grid.

With 4 beacons, there is no difference between the Savarese method and weighted Savarese method as can be seen in (8) where $(\mathbf{B}^T\mathbf{Q}_S^{-1}\mathbf{B})^{-1}\mathbf{B}^T\mathbf{Q}_S^{-1} = (\mathbf{B}^T\mathbf{B})^{-1}\mathbf{B}^T = \mathbf{B}^{-1}$ holds. The horizontal and vertical trajectories using the Savarese methods are shown as Fig. 1. Red o is a true position; blue x is an estimated position in Fig. 1. Note the Savarese method has the high accuracy of horizontal positions but the large error of vertical positions because of the ill-conditioned matrix problem caused by small difference in height. From (5), in the center of the test bed

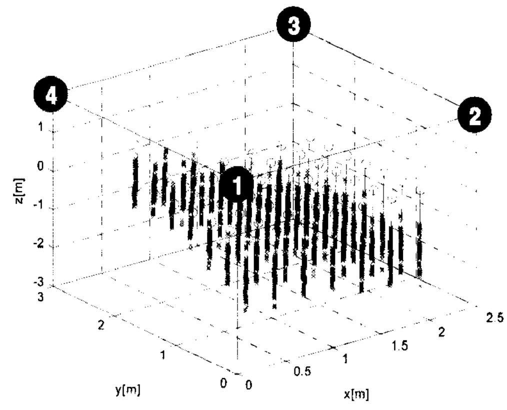
$$(\mathbf{B}^T\mathbf{B})^{-1}\mathbf{B}^T = \begin{bmatrix} 0.1042 & -0.1042 & -0.1042 \\ -0.1042 & 0.3125 & -0.3125 \\ 10.0000 & -10.0000 & 10.0000 \end{bmatrix}$$

and the third row related to the vertical position is about 100 times larger than the other rows. So the height is more influenced by the error of the range measurements. Fig. 2 shows the results using the modified Savarese method in (11).

The horizontal and vertical RMS errors of both methods at 49 points are summarized in Table 1. It shows dramatic reduction of vertical error. However, the horizontal error becomes large because in this method the height of all beacons are assumed same and this error is propagated into the horizontal error. To get more accurate position with the proposed method, the height of beacons should be same.

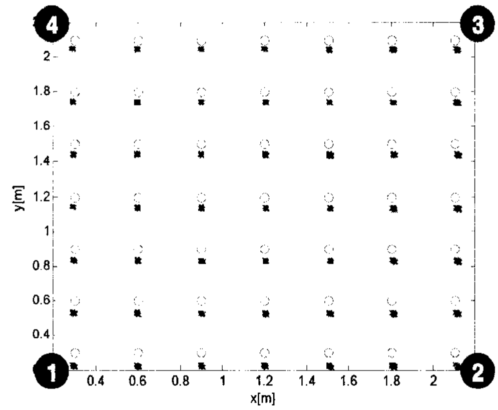


(a) Horizontal trajectory.

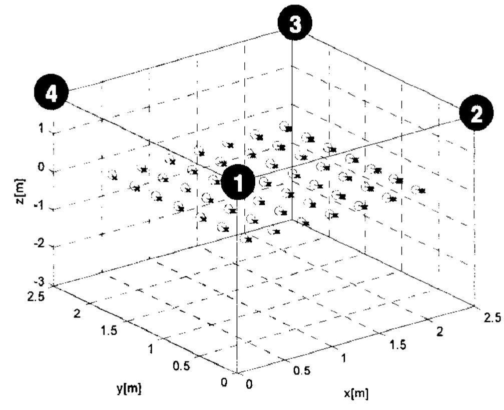


(b) Vertical trajectory.

Fig. 1. Horizontal and vertical trajectory using the Savarese method.



(a) Horizontal trajectory.



(b) Vertical trajectory.

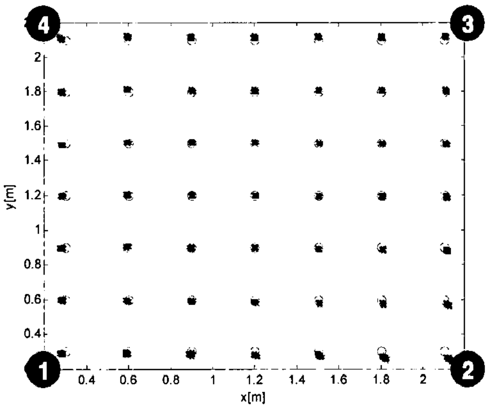
Fig. 2. Horizontal and vertical trajectory using the modified Savarese method.

Table 1. RMS errors using the Savarese and modified Savarese method.

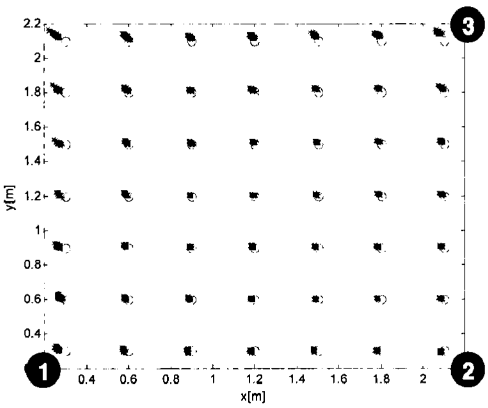
Result \ Algorithm		Savarese	Modified Savarese
Horizontal RMS	Mean	1.82cm	6.78cm
	Max	4.11cm	8.17cm
	Min	0.99cm	5.51cm
Vertical RMS	Mean	103.42cm	1.91cm
	Max	184.06cm	4.28cm
	Min	26.49cm	0.22cm

3.3. Static experiments with same heights

In this experiment, configurations of the test bed are same as the previous section except four beacons are installed at the same height of 2.4m. With this configuration the Savarese method diverges, therefore the results of the modified Savarese method only are given in this section. To see the effect of number of beacons and its geometry, some beacons are intentionally removed during the processing. If more than 3 beacons are available, 3D position is found. When only 2 beacons are available, the modified Savarese method in 2D is used to find 2D position.

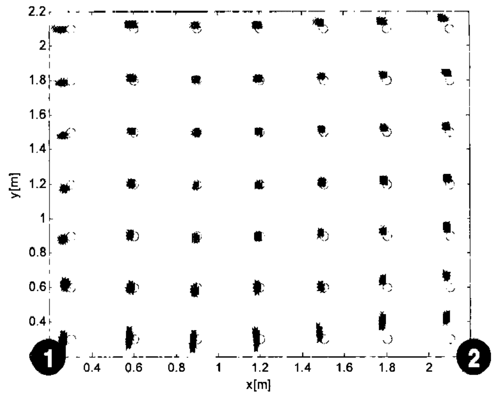


(a) 4 Beacons (1, 2, 3, 4).

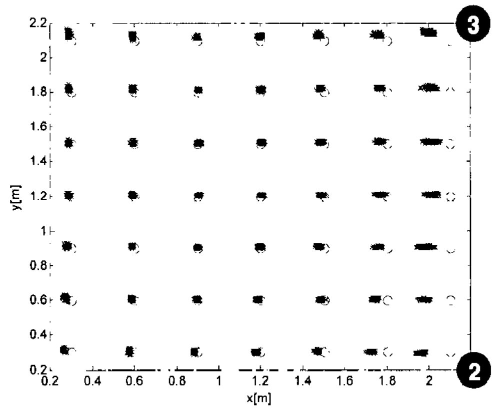


(b) 3 Beacons (1, 2, 3).

Fig. 3. Horizontal Trajectory using the 3D modified Savarese method with 4 and 3 beacons.

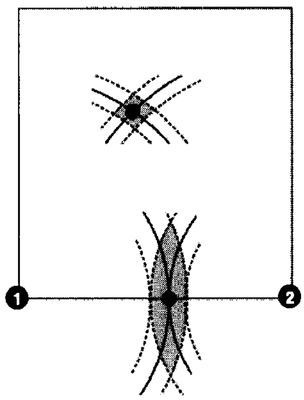


(a) 2 Beacons (1, 2).

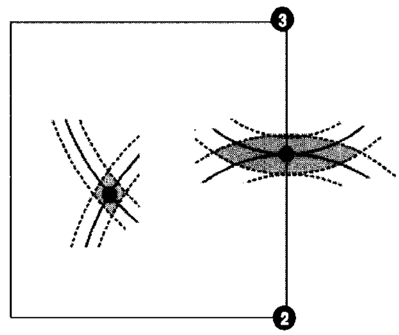


(b) 2 Beacons (2, 3).

Fig. 4. Horizontal Trajectory using the 2D modified Savarese method with only 2 beacons.



(a) Beacon 1 and beacon 2.



(b) Beacon 2 and beacon 3.

Fig. 5. Relative geometry and dilution of precision with 2 beacons.

Table 2. RMS errors using modified Savarese method in 3D and 2D.

Result \ Algorithm		Modified Savarese		
		3D		2D
		4 Beacons	3 Beacons	2 Beacons
Horizontal RMS	Mean	1.85cm	3.33cm	4.01cm
	Max	5.25cm	7.18cm	11.15cm
	Min	0.40cm	1.93cm	1.96cm
Vertical RMS	Mean	0.64cm	1.06cm	-
	Max	2.06cm	4.42cm	-
	Min	0.28cm	0.28cm	-

The positioning results with the 3D modified Savarese method are shown in Fig. 3. The mean horizontal error is 1.85cm (RMS) with 4 beacons while 3.33cm with 3 beacons. The left upper corner of Fig. 3(b) clearly shows the effect of absence of beacon 4. The positioning results with the 2D modified Savarese method are shown in Fig. 4. It also clearly shows the effect of the number and geometry of beacons. The error patterns in Fig. 4 are explained with Fig. 5. The position is determined in the intersection area of two circles where the covariance of measurement error represents the width of arc, and the area of intersection of two circles is the uncertainty in position. The position accuracy is affected by not only the measurement error but also the relative geometry of a node and beacons. It is analogous to the concept of DOP (Dilution of Precision) in GPS [5].

The horizontal and vertical RMS errors are summarized in Table 2. It shows the more beacons are installed, the higher accuracy is obtained. And it is possible to find an accurate position at the cm level if at least 2 beacons are available.

3.4. Dynamic experiments

A line-tracer as a mobile robot is made to evaluate the performance of the implemented system in dynamic environments. The ultrasound transmitter in the line-tracer is installed at 15.5cm height. The test bed, beacon and node are shown in Fig. 6, the total length of the track is 8.23m. The speed of the line-tracer is 13.8cm/sec and it takes one minute to run the track. 1826 measurements are taken while the line-tracer runs 5 times with the 6Hz output rate. During the processing 3 scenarios are assumed; scenario 1 uses all 4 beacons for the first 700 epochs, scenario 2 uses beacon 3 and 4 only for 701~1126 epochs and scenario 3 uses beacon 1 and 2 only for 1127~1826 epochs.

The horizontal trajectory of the line-tracer is shown in Fig. 7. Blue solid line x is the result using 3D modified Savarese method at scenario 1. Red dashed line + and green dash-dot line * are the results using 2D modified Savarese method at scenario 2 and 3 respectively. Fig. 7(b) shows the zoomed result. The results of scenario 1 show the accuracy less than 2cm. The results of scenario 2 and 3 show a shift along the y-axis. The results with beacon 1 and 2 are opposite to the results with beacon 3 and 4. It is influenced by the geometry as explained in Fig. 5.

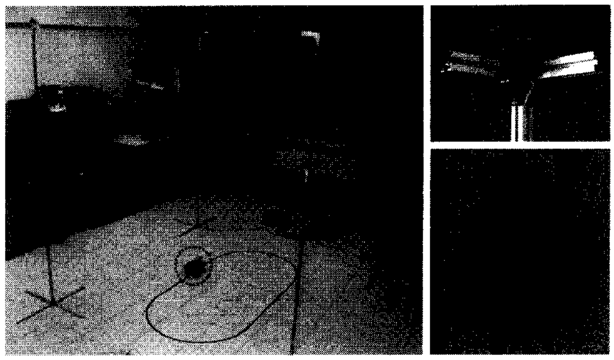
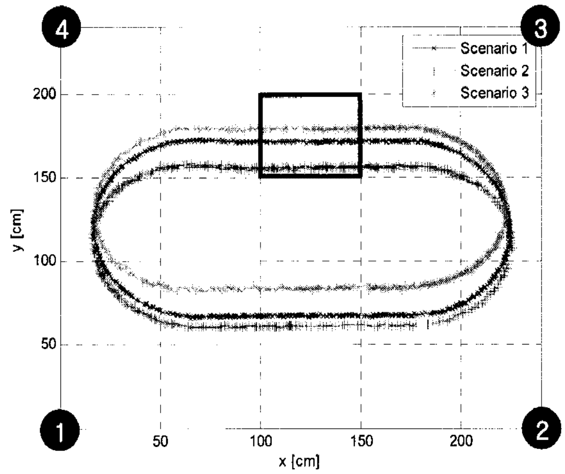
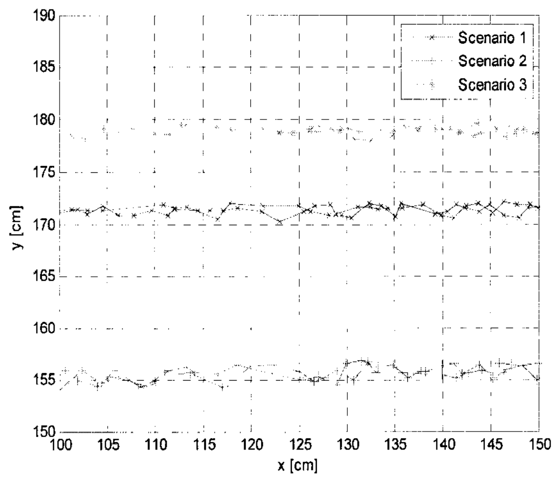


Fig. 6. Test bed: 2.4m×2.4m×2.4m (W×D×H).



(a) Horizontal trjectories from 3 scenarios.



(b) Zoomed trajectory [100~155].

Fig. 7. Horizontal trajectory of dynamic experiment.

4. CONCLUSIONS

This paper proposed an efficient positioning algorithm using ultrasound and RF in WSN. By modifying the Savarese method, the proposed algorithm improves accuracy, availability and flexibility; the error covariance of range measurements is derived and used in WLS as a weighting matrix to get higher accuracy, the ill-conditioned and the singularity problem are solved so that all beacons can be installed at the same height and 2D positioning is possible with 2 beacons only. From the static and dynamic experiments with the implemented system, the seamless positioning with the accuracy less than 2cm error is possible while the Savarese method diverges. The proposed method is expected to be easily adopted in many WSN applications such as smart homes, health cares, ITS, environmental monitoring and mobile robots.

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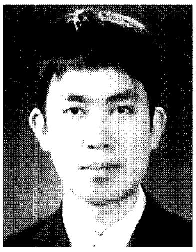

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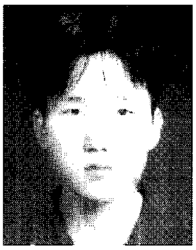

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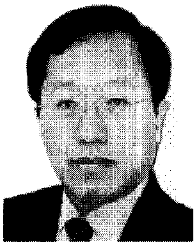

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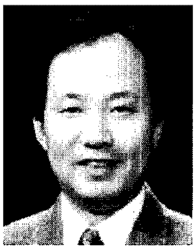

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