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Error Compensation for Cricket Indoor Location System

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***Abstract*—Cricket is a fine-grained indoor location system utilizing beacons transmitting both ultrasound and radio wave signals. However, the system accuracy is greatly impacted by the relative angle and distance between the beacon and listener. This paper proposes a low cost method to improve the system precision by means of incremental error compensation. The ultrasonic detecting error, which directly affects the accuracy of time-difference-of-arrival (TDOA), is first analyzed and verified via experiments. Then an error compensation method is designed based on total least squares (TLS) to further improve the Cricket's localization performance. Experimental results show that the average error of localization is reduced to 5.60cm with compensation, compared with 9.06cm of the original Cricket method. The standard deviation of the errors is reduced from 7.80cm to 3.99cm. This method lays a foundation for further improving the existing ultrasound-related distance measurement method.**

Keywords-Cricket indoor location system; error compensation; total least squares

I. INTRODUCTION

Cricket system [1, 2] is a platform for the indoor positioning, which measures the distance based on the principle of TDOA [3] and then calculates the coordinate based on triangulation [4].

Cricket has a fine positioning precision (about 10cm on average) and it is commercially available. Thus, it is widely used in many location-aware applications [1, 5-8] such as human positioning and tracking, robots path planning, interactive virtual games and location-aware sensor networks. However, in our effort for positioning indoor fire robots in building safety related research, the available localization precision of the original Cricket (10cm on average) is not fully satisfactory.

In this paper, we propose an error compensation method to improve the localization precision of Cricket based on error analysis and experiments. The positioning results of the modified Cricket are compared with that of the original results to verify the effectiveness of our compensation method. The results showed that our method significantly improved the positioning accuracy of the Cricket: the average value of the absolute error is reduced to 5.60cm from 9.06cm (38% improved), and the standard deviation of the absolute error is reduced to 3.99cm from 7.80cm (49% improved).

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The remainder of this paper is organized as follows. The basic principles of distance measurement and coordinate localization and the analysis of the error sources are introduced in Section II. Section III describes the verification of the relationships between the ultrasonic detecting error and its causes. In Section IV, our compensation method is described in detail. The effects of the compensation method are verified and the results are discussed in Section V and the summary and conclusion are presented in Section VI.

II. PRELIMINARIES

A. Basic principles for Cricket to measure distance

The main hardware components of Cricket are the ultrasonic and radio frequency (RF) transceivers, micro controller unit (MCU) Atmegal128L, and other necessary peripherals. When measuring distance, the sender first sends out an ultrasonic signal and an RF signal simultaneously, and then the receiver detects the arrival of the two signals and calculates the time difference of their arrival. Based on the TDOA, the distance can be calculated.

Suppose the velocity of the ultrasonic signal and the RF signal is v_1 and v_2, respectively, and the distance between the sender and the receiver is d. Obviously, $v_1 < v_2$ is satisfied. When both of these signals are sent simultaneously, the time difference of arrival Δt can be calculated by (1).

$$\frac{d}{v_1} - \frac{d}{v_2} = \Delta t \tag{1}$$

Cricket detects the arrival of the two signals and calculates the Δt, and then the distance can be obtained as (2).

$$d = \frac{\Delta t}{\left(\frac{1}{v_1} - \frac{1}{v_2}\right)} \tag{2}$$

B. Basic priciples for Cricket to find coordinates

Fig.1 shows the configuration for an indoor Cricket location system. The Cricket beacons are deployed on the ceiling and their coordinates are determined and preset. A listener is placed on the floor at the points of intersection to get the samples.

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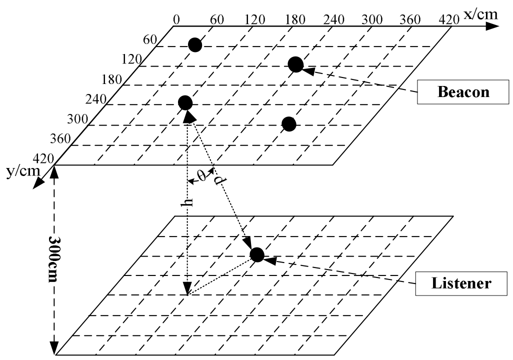

Figure 1. The scenario for measuring the Cricket positioning accuracy. The beacons are deployed on the ceiling and the listener is placed on the floor in parallel with the plane containing the beacons. The distance samples are collected from the listener when it is placed at the intersection points.

During the experiment, the listener receives the signals from each beacon and measures the distance according to (2). Then the coordinates are calculated based on the measured distances.

As Fig.1 shows, suppose the coordinate of the listener is (x, y) and it needs to be positioned by Cricket. Beacon 1 to Beacon n are deployed on the ceiling and their coordinates are determined, which are (x_1, y_1) , (x_2, y_2) ,$\cdots$, (x_n, y_n) , respectively. Based on their geometric relationship, formula (3) is obtained, where, h represents the distance between the floor and the ceiling (as Fig.1 shows), and d_1, d_2, …, d_n represent the distances between the listener and beacons, respectively.

$$\begin{cases} (x-x_1)^2 + (y-y_1)^2 + h^2 = d_1^2 \\ (x-x_2)^2 + (y-y_2)^2 + h^2 = d_2^2 \\ \vdots \\ (x-x_n)^2 + (y-y_n)^2 + h^2 = d_n^2 \end{cases} \tag{3}$$

Then, the formula above can be re-arranged to arrive at the form of $\mathbf{AX} = \mathbf{b}$ .Where,

$$\mathbf{A} = \begin{bmatrix} 2(x_1 - x_n) & 2(y_1 - y_n) \\ 2(x_2 - x_n) & 2(y_2 - y_n) \\ \vdots & \vdots \\ 2(x_{n-1} - x_n) & 2(y_{n-1} - y_n) \end{bmatrix} \tag{4}$$

$$\mathbf{b} = \begin{bmatrix} x_1^2 - x_n^2 + y_1^2 - y_n^2 - d_1^2 + d_n^2 \\ x_2^2 - x_n^2 + y_2^2 - y_n^2 - d_2^2 + d_n^2 \\ \vdots \\ x_{n-1}^2 - x_n^2 + y_{n-1}^2 - y_n^2 - d_{n-1}^2 + d_n^2 \end{bmatrix}, \quad \mathbf{X} = \begin{bmatrix} x \\ y \end{bmatrix} \tag{5}$$

Then, the result vector can be calculated by the method of *Least Squares*: $\hat{\mathbf{X}} = \left(\mathbf{A}^{\mathrm{T}}\mathbf{A}\right)^{-1} \mathbf{A}^{\mathrm{T}}\mathbf{b}$.

As Fig.1 shows in our experimental scenario, four beacons are placed on the ceiling and the distance samples are collected by placing the listener at 64 points on the plane of the floor, which is parallel with the plane containing the beacons. Similar to the method in [2], we calculate each listener's position by using the distances to the closest three beacons. According to the formulas above, the listener's coordinate on the floor can be achieved by (6).

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} 2(x_1 - x_3) & 2(y_1 - y_3) \\ 2(x_2 - x_3) & 2(y_2 - y_3) \end{bmatrix}^{-1} \times \begin{bmatrix} x_1^2 - x_3^2 + y_1^2 - y_3^2 - d_1^2 + d_3^2 \\ x_2^2 - x_3^2 + y_2^2 - y_3^2 - d_2^2 + d_3^2 \end{bmatrix} \tag{6}$$

C. Sources of error when measuring distance

Under common room conditions (temperature, pressure and humidity), the velocity of the ultrasound v_1 is about 344 m/s, and the velocity of the RF signal v_2 is 3×10^8 m/s. As the velocity assures that $v_1 \ll v_2$, equation (2) can be simplified as reflected in (7).

$$d \approx \Delta t \times v_1 \tag{7}$$

From (7), we can see that the distance is determined by two parameters, Δt and v_1 . Thus, any factors, which disturb the listener's ability to obtain the real Δt or the velocity of the ultrasound, would result in measurement errors. In [2], there are six error sources described (table I). As table I shows, the first five sources are related to the parameter Δt , and the last one, which includes temperature, humidity and atmospheric pressure, affects the velocity of ultrasound. According to [2] and the lessons described in [9], the original Cricket system design has discovered the solutions for source 3 and 6 in table I. The original Cricket has a very good ability to compensate for temperature variations. Problem 1, 4 and 5 are inherent characteristics of Cricket, which means that users should try to avoid them by suitably deploying the beacons and using effective coding style. Traditionally, the errors in detecting ultrasound were regarded as a hardware implementation problem and had not been sufficiently considered in the original Cricket system design. However, in our experiments, we found that the detection time of ultrasound signal can vary significantly with respect to the relative orientation angle of antennas and the distance between them. This is true even when there is a direct line of sight path between the beacon and the receiver. This is due to the effect of ultrasonic fading in the environment. In the next section, we discuss the impact of the influences from ultrasonic fading by a series of experiments, and then propose a compensation method as a solution.

III. Further Verification of the Error Causes

Based on the analysis above, we further analyze the error caused by the attenuation of ultrasonic waves. The geometric relationship of the localization scenario is also shown in Fig.1, where d represents the distance between the beacon and

TABLE I. LIST OF ERROR CAUSES

	ERROR CAUSES	RELATED TO THE PARAMETER
1	Lack of line-of-sight	Δt
2	Errors in detecting ultrasound	Δt
3	Timing quantization	Δt
4	Variable interrupt service routine delay	Δt
5	Arithmetic quantization	Δt
6	Environmental factors	$v_{Ultrasound}$

listener, h represents the distance between the floor and the ceiling, and another important parameter θ is defined as the orientation angle between the beacon and the listener. Intuitively, the ultrasonic signal strength is reduced as d and θ become larger [10]. The following subsections verify the assumption and determine the relationships of distance measurement error with respect to given d and θ.

A. Verifying the effects of the ultrasonic fading

The Cricket is equipped with 255-400SR12 and 255-400ST12 [11] as the ultrasonic transceiver, which works at the frequency of 40KHz. According to [2], the MCU detects the coming ultrasound just as the signal strength exceeds the pre-set threshold (65mV) in the comparator. In accordance with the principles of ultrasonic sensing, the transducer in the ultrasonic receiver needs more time to be activated to generate output with lower excitation voltage. Moreover, the weaker signal after the amplifier needs more time to reach the threshold. Therefore, we think that fading of ultrasonic signals in the different conditions will introduce arrival detection errors, and then affect the precision of measuring distance.

Two test-points (in Fig.2) are added to the hardware of the original Cricket system and an oscillograph (TDS2024B-Tektronix) is used to observe and verify the analysis above. In Fig.3(a), the triangular wave from the Test Point I represents the signal envelope of the ultrasonic pulses, which reflects the process of the energy accumulating by the receiver. The wave from Test Point II illustrates the generation of the rising edge, as detected by the comparator with a threshold of $65mV$. The right subfigure Fig.3(b) describes how the attenuation of the ultrasound delays the detecting of the rising edge and then affects the TDOA. As the threshold is only $65mV$ and it is easy to be reached after amplification (peak value can be $1.5V$), the main reason for the delay associated with the fading is that the receiver needs more time to accumulate the energy and then generate the output when the input ultrasonic pulses are weaker.

In the next subsection, two series of experiments are designed to obtain the relationship between signal fading and distance measuring errors.

B. Determining the relationship between measuring error and ultrasonic fading

The ultrasonic signals will fade as the distance increases

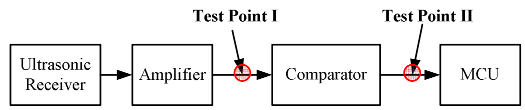

Figure 2. The hardware for detecting ultrasound.

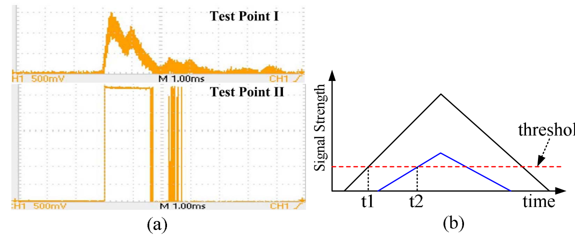

Figure 3. The fading affects the detection of the ultrasound's arrival. In (a), test-point I shows the ultrasonic signal after the amplifier and test-point II shows the result after comparing the signal with the threshold. The first rising edge is captured by MCU and recognized as the arrival of the ultrasound. (b) illustrates how the attenuation affects the TDOA.

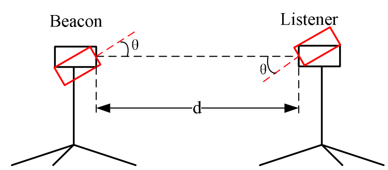

Figure 4. The experiment scenario for determining the potential relationships between measuring errors and the causes of fading, namely, d and θ.

and the orientation angle gets larger. That is, the measuring errors are affected by the rotation angle and the distance between the beacon and the listener. The experiment configuration is shown in Fig.4. The Beacon periodically transmits RF and ultrasonic signals, and the listener detects the two signals, obtains the TDOA and calculates the distance.

1) The relationship between measuring error and distance. As Fig.4 shows, θ is fixed at 0 and the distance d is changed to find the relationship between the measuring error and d. To obtain detailed information about how error changes as distances become larger, we used $5cm$ as the experiment's incremental distance, and tested distances from $30cm$ to $600cm$. The experiment results show that the error fluctuates between $-2cm$ to $0cm$ randomly and lacks a regular relationship between the measuring error and distance.

2) The relationship between measuring error and orientation angle. Again we use the configuration in Fig.4, but this time distance d is fixed. We carried out this experiment by changing the orientation angle from 0° to 60° (an angle larger than 60° is not recommended according to the Cricket system manual[12]) with incremental angle changes of 10°. Table II shows the measurement error results of changing the θ at various distances between the beacon and the listener. Each data point is the average of 30 measurements and the variance of the measurements are small (<1%). The table establishes a clear trend that the error becomes larger as the orientation angle increases.

IV. Our Method for Error Compensation

Based on the experiments of last section, we know that the relationship between the measuring error and the distance is not regular. However, the orientation angle affects the measuring error in a regular way. Based on these regular effects, a method is proposed to compensate for the measuring error, which is relative to the orientation angle, as much as possible.

We use the total least squares (TLS) technique to obtain a linear equation with respect to the relationship between θ and error. Then the error can be compensated by subtracting a value according to the fitting equation for each distance measuring. We use linear regression to fit the data on the samples in table II, as it is the simplest way, yet it can provide almost equally well results as non-linear data fitting. The non-linear way will be discussed as an independent issue in Section V.

For convenience, we use x to represent the abscissa θ, and y for the ordinate absolute measuring error. Suppose there are n samples (as Fig.5 shows), and their coordinates are (x_1, y_1), (x_2, y_2), $\cdots$, (x_n, y_n). First, the mean of these points, $(\bar{x}, \bar{y})$, can be achieved using formula(8).

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad \bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i \tag{8}$$

Then, the linear equation is supposed to be(9).

$$a(x - \bar{x}) + b(y - \bar{y}) = 0 \tag{9}$$

By the principle of TLS[13] and the assumptions above, we obtain the objective equation(10), which represents the sum of squares of the Euclidean distances between the sample points and the line determined by(9). Then, what remains is to find

TABLE II. The Results of the Experiment for Determining the Relationship between the Error and the Orientation Angle (the unit of the errors is cm)

Distance \ Angle	0°	10°	20°	30°	40°	50°	60°
90cm	0	0.9	1.0	2.0	3.0	5.0	6.0
120cm	-1.0	-0.7	0	0	1.4	3.0	4.2
150cm	0	0	1.0	2.0	3.0	5.0	6.0
180cm	-1.0	-1.4	-1.0	0	1.4	3.0	4.8
210cm	0	0	1.0	2.0	3.5	4.3	6.0
240cm	-1.4	-1.0	-1.0	0	2.0	3.0	6.0
270cm	0	0	1.0	2.0	3.2	5.0	6.7
300cm	1.4	2.0	2.6	3.2	5.0	7.0	8.0
330cm	-0.5	-0.4	0	3.3	2.0	4.0	5.8
360cm	1.0	1.0	1.8	3.0	4.0	5.5	7.1
390cm	-1.1	-1.0	0	1.0	3.0	3.5	5.7
420cm	0.2	0	1.0	2.3	3.2	5.0	7.3
450cm	-1.6	-1.3	-1.0	0.6	1.4	3.4	5.5
480cm	-0.1	0	0	1.8	2.7	4.8	6.6
510cm	-2.0	-2.2	-1.8	-0.2	1.2	3.4	9.0
540cm	-0.9	-1.0	0	1.4	2.6	5.3	8.1
570cm	-2.8	-2.7	-1.9	3.2	4.0	7.1	9.1
600cm	-1.4	-1.0	-0.8	1.0	1.5	3.6	6.0

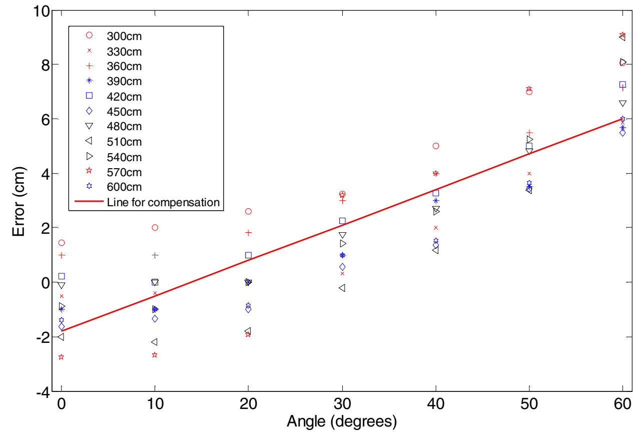

Figure 5. Data-fitting for compensation.

suitable a ψand b toψminimize $D(a, b, \bar{x}, \bar{y})$.

$$\begin{aligned} D(a,b,\bar{x},\bar{y}) &= \sum_{i=1}^{n} \frac{\left[a(x_i - \bar{x}) + b(y_i - \bar{y})\right]^2}{a^2 + b^2} \\ &= \mathbf{Mt} \\ &= \begin{bmatrix} x_1 - \bar{x} & y_1 - \bar{y} \\ x_2 - \bar{x} & y_2 - \bar{y} \\ \vdots & \vdots \\ x_n - \bar{x} & y_n - \bar{y} \end{bmatrix} \frac{1}{\sqrt{a^2 + b^2}} \begin{bmatrix} a \\ b \end{bmatrix} \end{aligned} \tag{10}$$

Thus, the problem becomes how to find the vector $\begin{bmatrix} a & b \end{bmatrix}^T$ to let $D(a, b, \bar{x}, \bar{y})$ be minimal. According to [13], the solution can be achieved by algorithm 1.

Algorithm 1 Calculate the parameters for the objective line

1: $\bar{x}, \bar{y} \leftarrow (x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$

2: $\mathbf{M} \leftarrow \bar{x}, \bar{y}, (x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)$

3: $EIG(\mathbf{M}^{\mathbf{T}}\mathbf{M})$ /*EIG means eigenvalue decomposition*/

4: Find the minimal eigenvalue

5: $\begin{bmatrix} a & b \end{bmatrix}^T \leftarrow$ the eigenvector related to the minimal eigenvalue

6: $y = -\frac{a}{b}x + \frac{a\bar{x} + b\bar{y}}{b}$ /*the result line*/

In our experiment scenario, as Fig.1 shows, the largest θ is no more than 60° (the angle from Beacon 1 to the coordinate $(420, 420)$ on the floor is the largest one, with a value of 59.43°), and the distances are between $300cm$ and $590cm$. Hence, the data measured under the distance range of $300cm$ to $600cm$ in table II were used to do data-fitting in accordance with the method described above. By the steps described in algorithm 1, we determined the line equation as (11) shows, in which, x represents the orientation angle θ and y is the distance compensation value related to the θ. The original samples and the result line of the data-fitting are shown in Fig.5.

$$y = 0.13x - 1.80 \quad (11)$$

According to (11), θ should firstly be known for the error compensation. As Fig.1 shows, the value of θ is unknown as the listener's position is undetermined before the positioning process is done. Thus, we can only use the currently measured distance to estimate it. Based on the configuration in Fig.1, the orientation angle is computed via the geometric relationship:

$$\theta = \arccos\frac{h}{d} \quad (12)$$

V. Performance Verification and Analysis

The experiment discussed in Section III verified the d-error and θ-error relationships. Then a compensation method was proposed based on the discovered relationship between θ and error to reduce the error of distance measurement. In this section, we design the experiments for the comparisons to verify the effectiveness of the error compensation method.

A. Experimental setup

Compared with the experiment scenario in Fig.4, the effectiveness of the compensation is verified in a localization scenario. As Fig.1 shows, four beacons are deployed on the ceiling on the same plane parallel with the floor. One listener is placed at an intersection point on the floor during a location test. The scenario covers a scope of $420cm \times 420cm$ and 64 intersection positions are tested in total. The listener receives the RF and ultrasonic signals from the beacons and calculates the distances according to TDOA. Then, the listener uploads the distance values to a personal computer (PC) via a serial port (for the experiment data analysis only as this is not necessary for the Cricket localizing applications) and the distance data are analyzed on the PC. Like the method in [2], we also choose the distances to the closest three beacons to calculate the coordinate of each intersection.

To see whether the compensation method would improve the localization precision, we process the measured distances in two ways. First, like the original Cricket, the three distance values are directly used to calculate the coordinate of an intersection by (6) without compensation. Second, supposing the measured distances for an intersected point to the closest three beacons are d_1, d_2 and d_3, and the compensation value is y_c, we pre-treat the distances in accordance with algorithm 2, and then we calculate the coordinate by (6) based on the pretreated distances. Finally, the two groups of coordinate results of all intersections, with and without the compensation, are compared to verify the effectiveness of our method.

B. Performance of the compensation method

The positioning results of the first two rows of the intersections are shown in Fig.6, in which the diameter of a circle represents the error between the real position of an intersection and the position localized by Cricket. The errors are decreased after the compensation. The cumulative distribution function (CDF) in Fig.7 shows that after using compensation, the percentage with an error of less than 10cm increases to 94% from 66%. This illustrates that the localization performance is improved remarkably with the compensation method. Moreover, some of the key parameters in table III further prove the effectiveness of our method. The maximal error is drastically reduced, and the average error is reduced from 9.66cm to 5.60cm, which means that the accuracy of localization is enhanced by38%. Also, the standard deviation of the error is reduced from 7.80cm to 3.99cm, which means that the stability of the localization is improved by 49%.

Algorithm 2 The steps for error compensation

1: **for** each d_i **do**
2: calculate the θ by (12)
3: calculate the compensation value y_c by (11)
4: $d_i \leftarrow (d_i - y_c)$
5: **end for**

C. Issuses about non-linear data-fitting and θ calculation

1) About non-linear data-fitting. We have also tried the non-linear polynomial fitting by extending algorithm 1. For example, the equation of quadratic fit is described as (13). Using the new fitting equation to replace (11) in algorithm 2, the localization error and volatility based on non-linear fitting and those based on linear fitting are compared in table IV. The improvement on the positioning error is no more than 0.06cm, which shows that the improvement we get from increasing the fitting order is tiny.

$$y = 0.0021x^2 + 0.0078x - 0.7865 \quad (13)$$

2) About calculatingθ. As there is an error between the values of the measured distance and the actual distance, θ is estimated by (12) with an error. Based on(12), the first derivative of θ is drawn in Fig.8. As d approaches 300cm, $\partial\theta/\partial d$ will tend to be infinite. So we drew the line at a starting point of (301, 2.33) to make it clearer. From this starting point, the curve of $\partial\theta/\partial d$ continues to sharply decrease as d increases. Combining the trend of the curve in Fig.8 and the distance errors in table II, we discuss the errors caused by calculating θ using (12) in three ranges and the results are described in table V. In table V, the relationship between θ and d is determined geometrically by the scenario in Fig.1. $Max\_\Delta d$ represents the maximal error of distance, and it can be looked up in table II according to the range of θ and d. $Max\_\partial\theta/\partial d$, which represents the maximal $\partial\theta/\partial d$, corresponds to the minimal d in the related range as it decreases monotonically with d. The maximal error of θ ($Max\_\Delta\theta$) in first two ranges is calculated by approximately $Max\_\Delta d \times Max\_\partial\theta/\partial d$ as $\partial\theta/\partial d$ is small. As $\partial\theta/\partial d$ becomes lager in the third range, $Max\_\Delta\theta$ is calculated by (12) directly by using $Max\_\Delta d$ and the minimal d in this range. The maximal error of compensation value ($Max\_\Delta C$) is

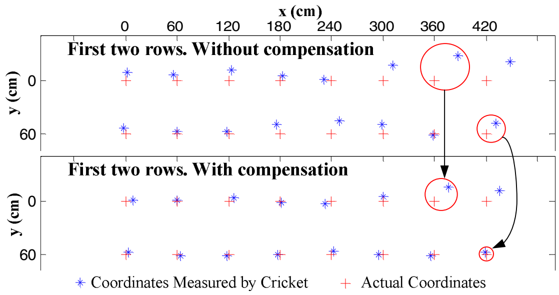

Figure 6. The effectiveness of the proposed compensation method.

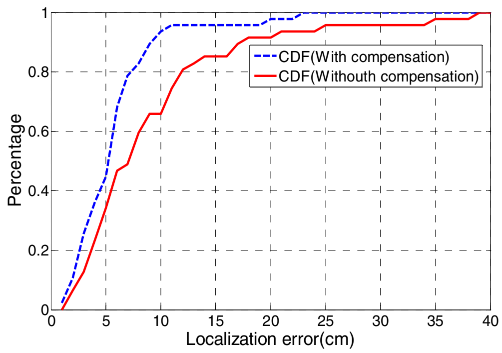

Figure 7. The CDF of the localization errors.

calculated by $0.13\times Max\_\varDelta\theta$ according to (11). Table V shows that the maximal error of θ and the maximal error of compensation value are small in all of the three ranges of distance even when the error of the measured distance is large. Generally, this explains why the compensation method can work well even when there is an error from calculating θ by (12) with a measured distance.

TABLE III. KEY PARAMETERS REFLECTING THE EFFECTIVENESS OF THE PROPOSED COMPENSATION METHOD (ε REPRESENTS ERROR)

Key Parameters	Not Compensated	Compensated
Minimal ε	1.56cm	0.25cm
Maximal ε	38.48cm	22.12cm
Average value of ε	9.06cm	5.60cm
Standard deviation of ε	7.80cm	3.99cm
The percentage that ε < 10cm	66%	94%

TABLE IV. THE RESULTS BASED ON DIFFERENT COMPENSATION WAYS

Key Parameters	Linear Fit	Quadratic Fit	Cubic Fit	Quartic Fit
Average value of ε	5.60cm	5.55cm	5.54cm	5.60cm
Standard deviation of ε	3.99cm	3.56cm	3.54cm	3.79cm

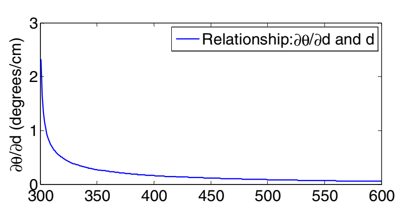

Figure 8. $\partial\theta/\partial d$ vs d (related to Fig.1, h = 300cm).

TABLE V. ERRORS CAUSED WHEN CALCULATING θ BY (12)

θ	d	$Max\_\varDelta d$	$Max\_\partial\theta/\partial d$	$Max\_\varDelta\theta$	$Max\_\varDelta C$
30°~60°	346cm~600cm	9.1cm	0.29°/cm	2.64°	0.34cm
10°~30°	305cm~346cm	3.3cm	1.02°/cm	3.37°	0.44cm
0°~10°	300cm~305cm	2.0cm	+∞	6.60°	0.86cm

VI. SUMMARY AND CONCLUSION

In this paper, we analyzed the causes of the error in the Cricket system in high precision localization scenarios and verified the analysis through a series of experiments. Results show that the measurement error increased in an approximately linear manner with the increase in the orientation angle between the beacon and the listener.

Based on analysis and experimental results, we designed an error compensation method to improve the performance of the Cricket system. The results from the verification experiments show that after using the compensation, the average positioning error is reduced from 9.06cm to 5.60cm, which means the performance is enhanced by 38%. Meanwhile, the standard deviation of the error is reduced from 7.80cm to 3.99cm, a 49% improvement.

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REFERENCES

[1] "The Cricket indoor location system," http://cricket.csail.mit.edu/.

[2] N. B. Priyantha, "The Cricket indoor location system," in *Computer Science and Engineering at the MIT*, 2005.

[3] N. J. Thomas, D. G. M. Cruickshank, and D. I. Laurenson, "Performance of a TDOA-AOA hybrid mobile location system," in *International Conference on 3G Mobile Communication Technologies*, 2002.

[4] J. Hightower and G. Borriello, "A survey and taxonomy of location systems for ubiquitous computing," *IEEE Computer Magazine,* vol. 34, pp. 57-66, 2001.

[5] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The Cricket location-support system," in *Proc. 6th ACM MOBICOM*, 2000.

[6] N. B. Priyantha, A. Miu, and H. Balakrishnan, "The Cricket compass for context-aware mobile applications," in *Proc. 7th ACM MOBICOM*, 2001.

[7] N. B. Priyantha, H. Balakrishnan, E. Demaine, and S. Teller, "Mobile-assisted localization in wireless sensor networks," in *Proc. IEEE INFOCOM Conference*, 2005.

[8] D. Moore, J. Leonard, D. Rus, and S. Teller, "Robust Distributed Network Localization with Noisy Range Measurements," in *Sensys*, 2004.

[9] H. Balakrishnan, R. Baliga, and et.al, "Lessons from developing and deploying the cricket indoor location system," in *Computer Science and Engineering at MIT*, 2003.

[10] R. Kazys, L. Mazeika, and R. Dicpetris, "Modelling of spatial and frequency responses of the ultrasonic interferometer used for displacement measurements," *ULTRAGARSAS* vol. 45, pp. 29-33, 2002.

[11] "Ultrasonic transducers:255-400ST12 and 255-400SR12," Kobitone Company, http://www.mouser.com/catalog/specsheets/KT-400242.pdf.

[12] "Cricket v2 user manual," http://cricket.csail.mit.edu/v2man.html.

[13] X. D. Zhang, *Matrix analysis and applications*: Publishing house of Tsinghua University and Springer, 2005.