Position localization with impulse Ultra Wide Band

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***Abstract*— In this paper, a low cost UWB-based position localization experiment system is designed and tested in the indoor environment. And a delayed-correlation detector and ultra-high-speed 1bit ADC are proposed to mitigate the estimation error of time difference of arrival (TDOA). And an algorithm using parallel processing and direct path tracking is also proposed to remove the timing-of-arrival (TOA) bias and clock jittering error of TDOA measurement. In our prototype design, we exploit impulse UWB techniques to implement a very low cost localization system that can achieve centimeters localization for indoor applications. The design shows good performance even in heavy multipath indoor environment.**

I. Introduction

Radio ranging and localization system is quit attractive for military and security applications. However, the most obstacles of the localization system are the cost and resolution. Now, the research on ultra wide band (UWB) communication reveals the possibility of implementing the narrow pulse ranging localization system at a very low cost. Compared to the GPS (global position system), which is widely used in both civil and military applications, the UWB localization system provides a more reliable and flexible applications of the indoor and other places where GPS cannot cover. For the past few years, there are also some commercial localization radio systems that have been developed to provide a complement for GPS[2].

UWB system provides a potential very high-resolution ranging technique, which pulse width is far less than 1ns. Though the average power of ultra wideband pulse is very low (refer to the FCC rule) [1], the pulse still promises a very high signal to noise ratio (SNR) locally (within one individual pulse). Therefore, even for the high interference indoor scenarios, the UWB system can provide a great capacity to detect the time of arrival (TOA) for the received signal with a very high accuracy[2], [4]. On the other hand, for the indoor communication, the UWB is completely immune to the dense multipath and fading due to its ultra wide spectrum[4], [5].

Meanwhile the UWB technique provides a very attractive way to implement the radio system with very low cost and low power consumption[4], [6]. In our UWB system, the transceiver is designed with a few simple components, such as the amplifier, filter and comparator in the RF front. Without sacrificing the accuracy of the arrival timing measurement, a simple hardware architecture, which adopts the delay-correlation to detect the narrow received pulses, provides a good performance to estimate the TOA with very low power consumption. After 1GHz sampling, a digital signal processing method is developed to measure the TOA with less 1ns error. Finally, a maximum likelihood algorithm is also deployed to remove errors of the noise and interference which are induced from the co-existed commercial communication systems, for instance the wireless LAN.

In this paper, we will describe a UWB localization prototype system, which adopts a simple architecture to achieve a very high resolution with a low cost.

II. UWB Localization Design

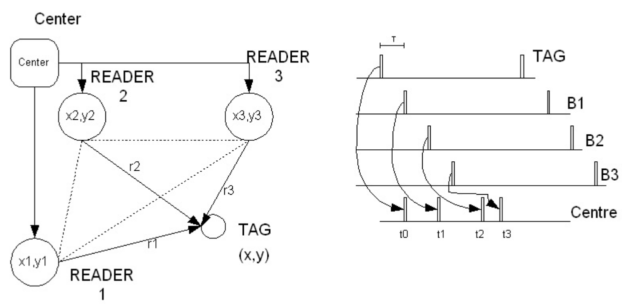

Fig. 1. Localization system with 3 readers and one tag

As shown in Fig.1, the localization system prototype includes several fixed readers (as UWB receiver), a set of moving tags (transmitter) and the processing center. The processing center, which connects the readers with wires, consists a baseband FPGA board and one computer (for graphic display and data processing). During the ranging detection, the tag is sending pulse stream to all the readers. After pulse detection, the readers send the data to the FPGA to measure the time difference of arrival (TDOA). At FPGA, the leading edges of the received pulses B1, B2 and B3 (as Fig.1) are detected and tracked to estimate the TDOA. Meanwhile, the transmitted pulse clock is recovered and the maximum likelihood decision is also implemented to reduce the TDOA errors of the UWB channel and interference. At last, the TDOA data are sent to the computer to calculate the position of the tag.

A. Tag and Readers implementation

Fig.2 shows the prototypes of one reader and one tag that satisfy the FCC UWB specifications [1]. Due to the FCC UWB 3GHz - 10Ghz spectrum restriction, our prototype operates at 3.1GHz - 6GHz bandwidth and the transmitter pulse is about

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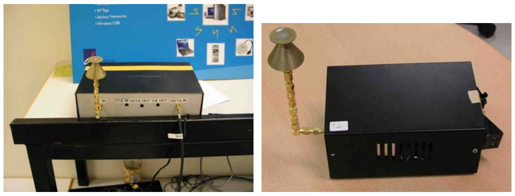

Fig. 2. One reader, one tag and the UWB antenna prototypes

250 picoseconds wide. For simplification, a monopole UWB pulse with 1MHz repetition is generated and filtered by the bandpass filter to fit it into the FCC UWB spectrum mask, and the pulse is transmitted by the omni-direction cone-shaped UWB antenna. The width and the cycle of the UWB pulse guarantee the prototype achieves centimeters resolution and more than 20 meters coverage for indoor localization.

Obviously, with occupying a ultra wideband, the UWB localization prototype is totally immune to the fading and indoor multipath interference[2]. For the typical UWB indoor channel model[8], the maximum delay of the multipath signal is about 10-20 nanosecond for line-of-sight and 100ns for non-line-of-sight, so that the 1MHz repetition pulse (1000ns cycle) and 250 ps width can guarantee that there is no pulse overlapping at the receiver. Therefore, the leading edge is the most important factor to measure the TDOA of the received pulse.

The tag consists of one LNA (low noise amplifier), a pulse generator and a filter that are all operated with an alkaline 9 volts battery. By low power design, when the transmitter is continuously sending the pulse, the tag's battery lifetime can last to more than 3 hours when we use all discrete components to implement the system. And its time can be increased greatly if the tag adopts the burst transmission and sleeping work mode.

In the UWB reader (receiver), the hardware only includes a delayed correlator, an LNA and a low pass filter (LPF). Here the correlator is the critical part of the reader, which provides an easy way to detect the received pulse. As the UWB channel and antenna can be considered as an equivalent band-pass filter, the UWB received pulse looks like a Gaussian pulse envelope combining with a very high frequency carrier ($\geq 4GHz$ - the center frequency of bandwidth). So the received pulse is too narrow to be detected by digital circuit except using the analogue RF detector. Due to the multipath, the pulse waveform can expend to a few tens nanoseconds in the time axis, as shown in Fig.3. Thus, the delayed analogue correlator multiplying the received signal and its one cycle-delayed signal is completely suited to detect the received pulse, and its delayed time can be adjusted with a very high accuracy compared to the digital ways. The good advantages of the analogue delayed correlation are the easy implementation and high time accuracy.

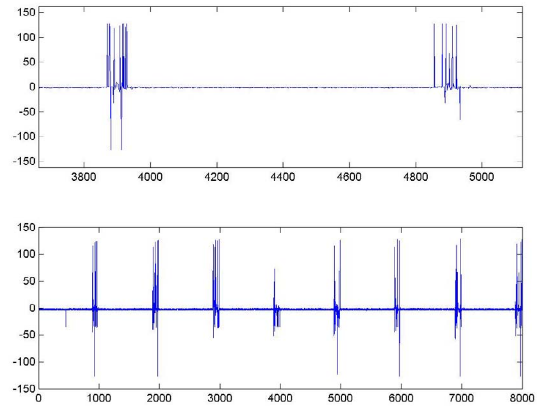

Fig. 3. The output waveform of the correlator is sampled at 1 GHz clock.

B. Delayed correlation detector analysis

The correlation shown in Fig.4 include a multiplier and low pass filter (LPF).Intuitively, the output of correlation detector perfectly preserves the timing of the arrival pulse because the analogue time errors can be eliminated by adjusting the time delay accurately. On the other hand, unlike the BPSK demodulator, the correlator also has less phase noise and amplitude variation for there is no local oscillation.

Assuming the $p(t)$ is the transmitted pulse, then the received signal is given as

$$r(t) = \sum_i \alpha_i p_i(t + \tau_i))cos(\omega t) + n(t) \tag{1}$$

Here, the τ_i is the pulse propagating delay and $cos(\omega t)$ is an approximate carrier waveform with frequency $2\pi\omega$, and α is the amplitude of the received pulse. For UWB channel, the received pulse energy is exponentially decreased with respect the time delay [8]. So that only the multipath of a few tens ns prominently contributes the signal to noise ratio (SNR) to the receiver, i.e., $\tau_i \leq 20ns$. As the pulse cycle T_c is 1 μs, and $T_c \gg \tau_i$, so the multipath delay signal could not overlap the next pulses. The correlator output is

$$s(t) = \int_{-T}^{T} \alpha_0 \parallel p(t) \parallel^2 + N_p + N_0 \tag{2}$$

where N_0 is the noise power and N_p is the power of the delayed pulse (multipath). Obviously, the N_0 and N_p can be summed up to obtain the maximum SNR, and the RAKE receiver is a good way to recover the UWB signal from the noise[4]. However, the RAKE combining output peak will be varying with noise and the multipath changing, and this will lead the ambiguity of the arrival time of the pulse. Therefore, we only rely on estimating the leading edge of the received pulse to obtain the high resolution TDOA measurement. In order to reject the noise and interference, the time of the pulse leading edge is estimated and averaged with maximum likelihood method.

For the ultra wide band signal, the very narrow pulse ($\leq 250ps$) guarantees the direct received signal can be separated from the multipath N_p without any degradation (2). This equation also shows that the pulse received waveform, at certain SNR level, has a very big amplitude above the noise level because the pulse width ($T \approx 250ps$) is far less than the pulse cycle ($T_c = 1\mu s$). Thus the good feathers of the narrowed pulse will make the high-resolution TDOA estimation more feasible and accurate compared to other radio positioning system. The Fig.3 shows the output waveform of the correlator, which is sampled by 1GHz. And the figure also shows that the leading edge of the received pulse is quit steep.

C. Baseband architecture design

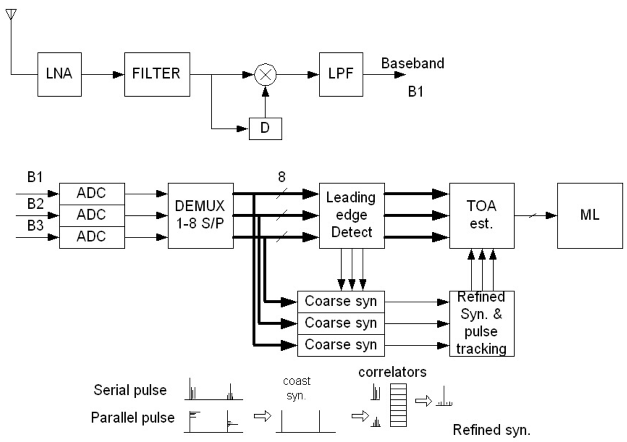

Fig. 4. UWB Receiver diagram

A simplified receiver block diagram is illustrated in Fig.4. After the RF correlator, the one-bit ADC (analogue to digital converter) is used to sample the pulses. In the prototype, 1GHz clock is used to sample the output of the correlator. However, the clock of FPGA circuit cannot be greater than 500MHz, so that a serial-to-parallel (S/P) process is adopted to deal with this problem. Actually, FPGA uses 1 to 8 S/P to re-sample the input data into 8 paths at 125 MHz, and 1 ns timing resolution is also maintained by the parallel processing.

As shown in the Fig.4, the leading edge of the received pulse is detected by two steps. First, after the serial to parallel (S/P) conversion, the 8 parallel signals are combined into one signal to recover and track the pulse clock at 125MHz. This so-called coarse clock is with less edge jittering and allows the pulse arriving time is varying within 8ns. The clock recovery is implemented by the digital phase lock loop (DPLL) techniques. With the DPLL, the false clock recovery can be reduced to minimum. Additionally, to avoid the edge jittering and false clock generated by the interference and noise, a perfect lock indicator is created to represent the good clock tracking, which will reduce the risk of the wrong clock and wrong synchronization. The indicator is a pointer that reports the perfect clock recovery when the repetitive clock locking is achieved. Once the locking is not continuously repetitive or the lock is lost due to the high interference or noise, the indicator will be invalid (set to 0). With the aid of the indicator other than the recovered clock, the refined timing measurement of the TDOA guarantees that fewer errors will be induced by the jittering or false clock.

Secondly, the refined TDOA measurement is conducted with the locking indicator to search and track the first arrival edge of each pulse. This leading edge is detected with the resolution of 1ns from the 8 parallel input data. At this stage, only the data, which is aligned or near to the indicator, are extracted to find and track the leading edge of the received pulse. Furthermore, a most likelihood estimation of TDOA is also implemented to reject the interference and noise affection. If the refined time is estimated as t_refine (≤ 8 ns), then the TDOA T_i between reader A and reader B is

$$T_{AB} = (tA_{coarse} - tB_{coarse}) * 8 + (tA_{refine} - tB_{refine}) \quad (3)$$

where tA_{coarse}/ tA_{refine} are the times measurement of the reader A at 8 ns and 1ns resolution, respectively. And the TDOA can be calculated,

$$TDOA_{AB} = \int_{T_0}^{+T_1} T_{AB} pr(t) dt \quad (4)$$

where T_0 and T_1 are the predefined factors, and they are chosen to make the most measured T_{AB} at the middle of $[T_0, T_1]$. pr is the possibility distribution of the TDOA.

The equation (4) of maximum likelihood method is good for clock jittering resisting and tolerance. For high-speed digital circuits, the asynchronous sampling clock will incur big edge jittering for the data and its clock in the practical system, and they will induce big error to timing estimation and clock recovery. However, the jittering of the clock can be considered as a zero-mean uniform distribution[6], so that the maximum likelihood (ML) will mitigate the jittering if the number of samples is big enough. For higher time resolution, the ML method provide a good tradeoff to the low cost design. Because the system has to increase the sampling clock speed if it uses the hardware to increase a higher time resolution, and this will definitely lead to the high cost and more power consumption.

III. TRIANGULAR ALGORITHM FOR LOCALIZATION

Based on the TDOA, we can use the triangular geometric algorithm to get the tag's position without involving any iterations[3], [7]. For triangular ways, the localization algorithm can be brief as (for 2 dimension $[x, y]$ case):

$$d_{ij} = r_i - rj = ct_{ij} \quad (5)$$

where $r_j = \sqrt{(x - x_j)^2 + (y - y_j)^2}$, r_i and r_j are the distances from tag to i and j reader, $[x_i, y_i]$ is the coordinate of reader i, and $d_{ij} = r_i - r_j$. And t_{ij} is the TDOA of the reader i and j; c is the light free-space speed and $c = 3.0 \times 10^8$ m/s. By solving the above equation, we can easily obtain the position of the tag, as [7] the above equations can be represented,

$$2(x_j - x_i)x + 2(y_j - y_i)y - 2d_{ij}r_j - d_{ij}^2 + V_{ij} = 0; \quad (6)$$

where $V_{ij} = (x_i^2+y_i^2)+(x_j^2+y_j^2)$. For any triangle constructed with 3 readers, the left of the equation (6) can be represented as,

$$2\begin{bmatrix} x_{21} & y_{21} \\ x_{31} & y_{31} \end{bmatrix}\begin{bmatrix} x \\ y \end{bmatrix} + 2\begin{bmatrix} d_{21} \\ d_{31} \end{bmatrix} r_1 + \begin{bmatrix} d_{21}^2 - V_{21} \\ d_{31}^2 - V_{31} \end{bmatrix} \quad (7)$$

From this equation, the $[x, y]$ can be represented with r_1, and

$$\begin{bmatrix} x \\ y \end{bmatrix} = -\begin{bmatrix} x_{21} & y_{21} \\ x_{31} & y_{31} \end{bmatrix}^{-1} \left(\begin{bmatrix} d_{21} \\ d_{31} \end{bmatrix} r_1 + \frac{1}{2}\begin{bmatrix} d_{21}^2 - V_{21} \\ d_{31}^2 - V_{31} \end{bmatrix}\right) \quad (8)$$

After using the equation (8) replace the $[x, y]$ of the equation (6), then a second order equation of r_1 is obtained. And the $[x, y]$ can be calculated after the new equation of r_1 is solved. Consequently, there are two resolutions of r_1 and the positive one is selected to estimate the TDOA while the negative one is get rid of. However, the two answers of r_1 will be both positive or negative sometimes. In this case, only way to select the correct answer is using more readers and the redundancy can eliminate the incorrect one.

The above triangulation algorithm is easy to implement with low complex computation. However, this algorithm will induce more distance error in some location, for instance, the place where the tag is very closing to one of the readers or the place where the tag is far away from the readers' triangle, as shown in Fig6. In this figure, the dots are the real positions of the tag, and the circles are the estimated position with the TDOA plus a random errors which is uniformly distributed within $[-0.5, 0.5]$ ns. And the contour figure shows the error distribution and the reader triangle coverage area. Obviously, within the triangle of the readers, the estimated error is less than 30 centimeters, but outside the triangle and at the location very closed to the readers the error is enormous bigger.

In order to reduce the location error, the readers' triangle shape should be configured to give a better coverage for the certain area (room), for example, the lower part of Fig6, which uses three corners of the room to put the readers, shows a good coverage improvement with less errors than the upper one. Additionally, except using more readers and better triangle shape coverage, the differential localization algorithm, which calculates the relative position between the known previous position and the current one, can also provide a good way to reduce the estimated error. The differential way is very good for tracking the moving tag and reducing the estimation bias error.

Now, let us only consider the bias error and the random error of the TDOA, here the estimated TDOA can be represented as $t_{ij} = (t_i - t_j) + t_{bias} + \epsilon$, where ϵ is the random error generated by noise and interference and t_{bias} is the estimation bias. Usually, the estimation bias error is generated by the follows: the geometry error, the near far effect and the circuit delays. Using the differential TDOA the above (8) becomes

$$\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = -P^{-1}\left(\begin{bmatrix} \Delta t_{21} \\ \Delta t_{31} \end{bmatrix} cr_1 + \frac{1}{2}\begin{bmatrix} d_{21} \\ d_{31} \end{bmatrix} \Delta r_1 + K\right) \quad (9)$$

Where the Δt_{ij}, Δr_1 are the differential time and distance between the previous point and current point. K is a constant matrix only containing Δt_{ij} and P is also a constant matrix of the coordinates of the readers as (8).

From the equation (9), the $[\Delta x, \Delta y]$ and Δr_1 can be obtained from the previous position and the differential TDOA values, so that most of the bias error can be removed by this equation. In order to avoid the error accumulation and wrong localization when the tag dwells in the same place, the motion detection of the tag should be deployed to help us improving the position estimation by the ML and the differential methods alternatively. For example, if the tag is motionless then the TDOA will be accumulated and averaged to remove the errors generated by the noise and interference. On the contrast, if the tag is move to new position, then we will use equation (9) to calculate the position of the tag with more accuracy.

IV. Experiment results and analysis

TDOA(ns)	**Estimation & its percentage**		
0	1 (33%)	4 (27%)	-1 (1.7%)
2	5 (34%)	8 (27%)	1 (4.3%)
3	2 (47%)	8 (39%)	-5 (7%)
5	5 (35%)	8 (23%)	-5 (6%)
8	9 (25%)	12 (23%)	7 (16%)
11	13 (29%)	16 (17%)	9 (14%)
15	17 (40%)	13 (18%)	14 (13%)
18	17 (42%)	18 (16%)	14 (11%)
22	21 (36%)	23 (22%)	26 (2.9%)
24	25 (34%)	23 (21%)	20 (12%)
136	137(41%)	140(31%)	127(14%)

TABLE I
The real time delay is measured by Oscilloscopes, and rounded to 1 ns.

The table I shows the TDOA estimation results that are obtained by the digital parallel processing. When the time difference value of the pulse arrival is varying from 1ns to 137ns, the FPAG uses the pulse detection and tracking circuitry to calculate the TDOA. There are only the three most likely integers (1ns unit) are listed in the table I for each TDOA measurement, and the percentages of the estimated TDOA is obtained from 5000 samples. The table shows that the most estimations are very closing to the real values and the big errors are rare. So, the ML method is quit suited to get a very good TDOA with a very high accuracy ($\leq 1ns$).

The table II shows the TDOA estimations by the maximum likelihood algorithm within a 6×5 square meters room. Like the above analysis, the TDOA estimation error is quit small while the tag is located in the readers' triangle (B1, B2, B3). And the errors will become bigger when the tag is far away from the readers' triangle. All these data show that the above error analysis is the same as the experimental results.

Real: (t12, t13, t32)	Estimated	ERROR
(-9, -4, -4.9)	(-9.3, -4.4, -4.5)	(0.3, 0.4, -0.4)
(14.3, 10.5, 3.8)	(14.2, 11.2, 4.2)	(0.1, -0.7, -0.4)
(-4.3, -8.5, 4.1)	(-4.1, -7.5, 4.3)	(-0.2, -1.0, -0.2)
(1.2, -5.8, 6.9)	(0.9, -4.8, 6.3)	(0.3, -1.0, 0.6)
(-4.9, -8.7, 3.8)	(-4.3, -8.6, 5.3)	(-0.6, -0.1, -1.5)
(-0.4, -5.8, -5.6)	(-0.5, -5.7, -7.1)	(0.1, -0.1, 1.5)
(12.1, 7.1, 5.1)	(11.8, 9.3, 3.5)	(0.3, -2.1, 1.6)
(-11, -5.8, -5.3)	(-9.1, -5.4, -2.8)	(-1.9, -0.4, -1.5)

TABLE II
TIME ESTIMATION AND ERRORS

Fig.5 shows the real positioning tracking for our prototype. The green arrow is the tag moving direction, and the small circles are the estimated position that is quit closed to the real one. The upper figure shows that within or near the readers' triangle, the positioning error is less than 30 centimeters. Only a very few estimation is outside this range, but this can be mitigated by the motion detection and averaging algorithm. In the lower figure, the tag is moving from one edge of the triangle to the distant far away place. Within the triangle, the estimation is obeying the move direction with small errors, but error is bigger when the tag is far away from the triangle. Especially, in the places near the door, the estimation error is quit big due to it is outside the coverage area. Overall, the estimated results satisfy the expectation of the design.

V. CONCLUSION

The prototype of an low power, ultra-wideband transceiver intended for low cost, high resolution, indoor positioning localization was presented. The implementation issues of this system, including the TDOA estimation algorithm, timing error reduction and the positioning algorithm were discussed in relation to their impact on both performance and simple circuit design constrains. In addition, the issues of interference and estimation bias were discussed, and the implications for higher accuracy UWB localization system were explored.

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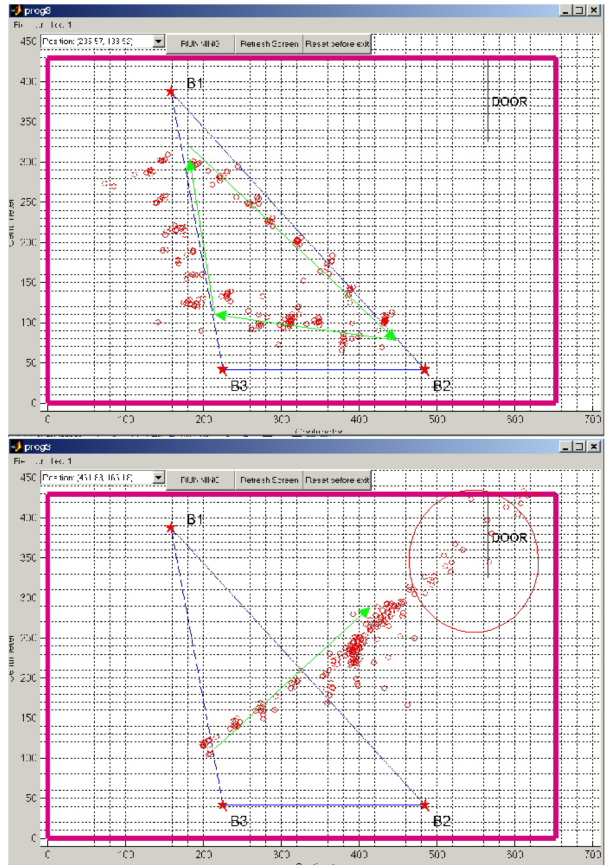

Fig. 5. The real tag positioning tracking. The arrows are the real moving direction of the tag, and the circles are the estimated localization by the TDOA.

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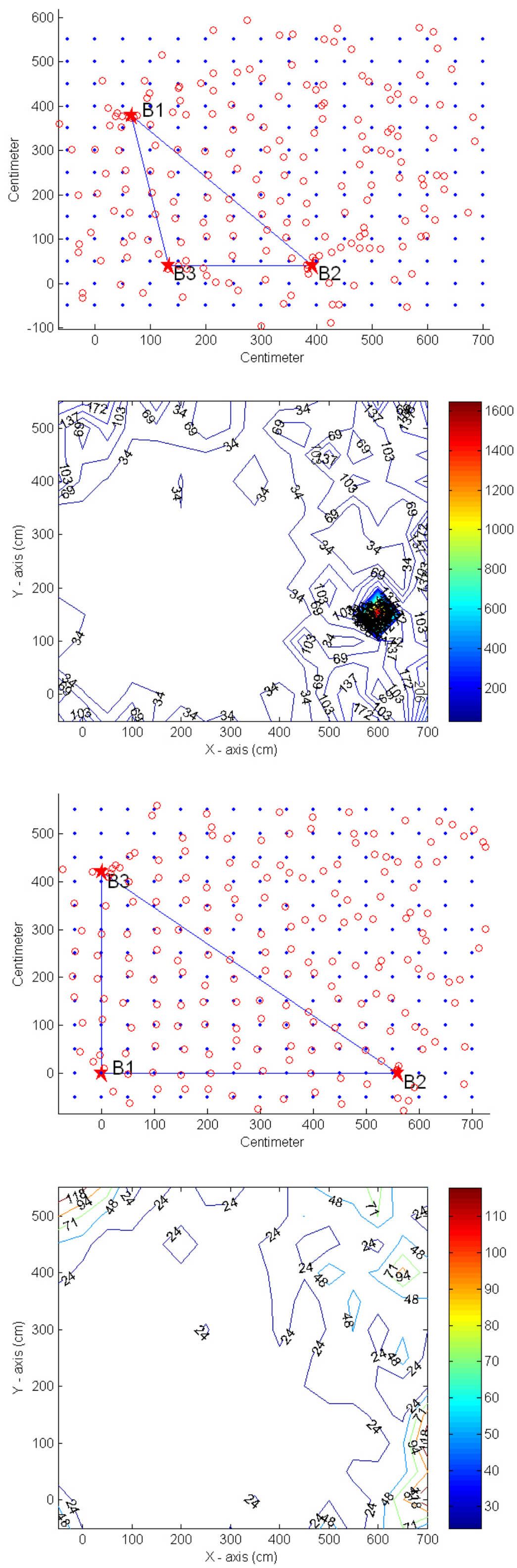

Fig. 6. Triangular localization errors with respect to different positions of the reader and tag. The dots are the real tag's positions, and the circles are the estimated position. The contours show the error distributions of triangulation algorithm.