Experimental Investigation of an IR-UWB Positioning System with Comparators

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SUMMARY  Impulse Radio (IR)-Ultra Wideband (UWB) enables accurate ranging due to very short duration pulses. Therefore, UWB may provide accurate positioning capability. In order to relax the complexity in circuit implementation, UWB system with low resolution analog digital converters (ADCs) has been investigated. In this paper, the accuracy of UWB positioning with comparators is investigated through experiment. The accuracy of positioning with comparators is compared to that with 8 [bit] ADCs, and effectiveness of the system with the comparators is confirmed within the area of 1.8 × 1.8 [m].

key words: IR-UWB, positioning, comparator

1. Introduction

IR-UWB systems utilise very short pulse with the duration of less than 1 [ns]. The short duration of the UWB waveform enables the system to provide high data rate communications as well as accurate positioning. While the accuracy of conventional indoor positioning techniques such as the one with wireless LAN terminals is several meters, the accuracy of the UWB positioning is in the order of centimeters [1].

However, due to the limitation of the transmission power, the UWB positioning system may be only for indoor applications. The existing narrowband radio systems (television broadcasting, wireless LAN, satellite, global positioning system, etc.) use the frequency band which overlaps with the band assigned for UWB. Therefore, the transmission power of the UWB radio systems is strictly regulated as less than −41.3 [dBm/MHz] for the protection of the existing narrowband radio systems. Thus, the transmission distance of UWB is limited and IR-UWB is expected to be employed in indoor positioning systems.

Researches on UWB positioning have been conducted and published. In [2] or [3], the fundamental theory of UWB localization has been presented. From a practical point-of-view, IR-UWB has been a candidate for RF tag applications with locating capability in IEEE802.15.4a [4]. IEEE 802.15.4a is the standardization group working on a new physical layer for low data rate communications for location-aware networking.

One of the problems regarding UWB positioning is implementation of its circuits. IR-UWB systems require synchronization circuits with the accuracy of tens of picosecond [5]. It is very difficult to design and control the characteristics of analog circuits with such accuracy. On the other hand, if the UWB signal is processed in digital domain, an ADC with very high sampling rate and high resolution is required, and the cost and power consumption of the ADC may be significantly high.

IR-UWB positioning systems with high speed and low resolution ADCs have been proposed in the previous researches to relax the requirement in complexity. Relative distance measurement with 1.5 [bit] ADC has been investigated in [6] and [7]. Accuracy of the system has been investigated through computer simulation in [6], and the combinations of transmission and reception antennas have been evaluated with the measured signal waveforms in [7]. In [9] and [10], ranging with a high speed comparator has been investigated. [9] has concluded that precise ranging is possible with rectangular template signal and a comparator for signal detection if the transmitter and the receiver are synchronized. [10] has shown that the accuracies of ranging with a 8 [bit] ADC and a comparator are equivalent. In [11], a UWB positioning system with high speed comparators has been presented.

In this paper, UWB positioning with comparators is evaluated through the experiment. To extend from [9] and [10], the accuracy of positioning with 8 [bit] ADCs or comparators are compared. In addition, since the sampling speed of the ADC limits the resolution of position estimation, the possible estimated positions of the transmitter can be obtained. Thus, the modal value of the estimated positions is then calculated. The proposed system solves the equation with Newton-Raphson method and estimates the position of the transmitter with One Way Ranging-Time Difference of Arrival (OWR-TDOA) [4]. OWR-TDOA is employed as it is one of the typical algorithm for positioning and has been discussed in IEEE TG4a. The accuracy of positioning with comparators is compared to that with 8 [bit] ADCs. It is confirmed that the accuracy with the low resolution comparators is slightly lower than that with 8 [bit] ADCs.

2. Experiment System

2.1 System Overview

Figure 1 shows the block diagram of the positioning system in this research. Pulse signal is generated and output from the I/O port of a field programmable gate array (FPGA)
board, and is directly transmitted through a monopole Tx antenna. The pulse signal is received by the Rx antenna and amplified by the low noise amplifier (LNA) on each receiver branch. Finally, the pulse signal is converted to 1 [bit] digital data by the comparator. Based on TDOA, the position of the transmitter is estimated by the processing unit.

The transmitter consists of the FPGA board as shown in Fig. 1. The FPGA board generates a rectangular pulse signal through the digital I/O port. The pulse duration is 4 [ns], and the pulse interval is 200 [ns]. The generated signal is transmitted through the monopole antenna.

Figure 2 shows the block diagram of the receiver. The received signal is amplified by the LNA and converted into 1 [bit] digital samples. The digitized samples are averaged in terms of the corresponding phase of the pulse frame in order to reduce the noise power. Next, the averaged pulse samples are correlated with template signal and the correlator output is compared with a threshold. The receiver estimates the timing of the pulse signal by detecting the correlator output that exceeds the threshold. The position of the transmitter is then estimated by the TDOA.

2.2 Digitization with Comparator

The comparator converts the received signal waveform, \( r(t) \), into digital samples \( \{0, 1\} \). Here, the converted digital sample, \( r_d(x) \), is defined as

\[
r_d(x) = \begin{cases} 
1, & r(xT_s) > 0 \\
0, & \text{otherwise.}
\end{cases}
\]  

(1)

where \( T_s \) is the sampling interval.

The digitized samples is averaged over the multiple frames to reduce the noise power. The averaged sample is expressed as

\[
r_{\text{ave}}(x) = \left\lfloor \frac{\sum_{n=0}^{N-1} r_d(x + N_f \times n)}{N} \right\rfloor,
\]  

(2)

where \( r_{\text{ave}}(x) \) is the averaged sample, \( r_d(x) \) is the \( x \)-th digitized sample, \( N \) is the number of pulse frames for averaging, \( N_f \) is the number of samples per one frame. Figure 3 shows the averaging process. \( N \) pulse frames are collected and the samples with the corresponding phase of the frame are averaged.

2.3 Detection of Received Pulse Timing

Figure 4 shows the pulse detection algorithm. The correlation value is given as follows

\[
r_{\text{cor}}(x) = \sum_{m=0}^{N_f-1} (r_{\text{ave}}(x + m) \times 2 - 1) \times r_{\text{tem}}(m),
\]  

(3)

where \( r_{\text{cor}}(x) \) is the correlation of the averaged received signal, and \( r_{\text{tem}}(m) \) is the template signal whose waveform is rectangular. First, the averaged pulse signal is converted from \( \{0, 1\} \) to \( \{-1, 1\} \). Next, the converted signal is correlated with the rectangular template signal. The received timing is then determined with correlation values. The first delay at which the correlation value exceeds the threshold is recognized as the received timing as shown Fig. 5.

2.4 Position Estimation with TDOA

The position of the transmitter is estimated with the timings
of the received pulse signals at three reference receivers. From the received timings, the difference of the relative distances between the transmitter and the receiver 1 or the receiver 2 is calculated as
\[ d_{12} = (T_1 - T_2) \times c, \]  
(4)
and the difference between the transmitter and the receiver 1 or the receiver 3 is given as
\[ d_{13} = (T_1 - T_3) \times c \]  
(5)
where \( T_k \) is the received timing at the receiver \( k \), and \( c \) is the propagation speed of radio wave (\( 3 \times 10^8 \) m/s). Using \( d_{12} \) and \( d_{13} \), the position of the transmitter, \( (x, y) \) is calculated as
\[ \begin{align*}
    d_{12} &= \sqrt{(X_2 - x)^2 + (Y_2 - y)^2} \\
    &\quad - \sqrt{(X_1 - x)^2 + (Y_1 - y)^2}, \\
    d_{13} &= \sqrt{(X_3 - x)^2 + (Y_3 - y)^2} \\
    &\quad - \sqrt{(X_1 - x)^2 + (Y_1 - y)^2}
\end{align*} \]
(6)\( -7 \)
where \((X_i, Y_i)\) is the position of the \( i \)-th antenna. Equations (6) and (7) mean that two hyperboloid lines can be drawn to determine the position using TDOA. Newton-Raphson method is used to decide the Tx position from the following equations [12].
\[ \begin{align*}
    f_1(P) &= d_{12} - \sqrt{(X_2 - x)^2 + (Y_2 - y)^2} \\
    &\quad + \sqrt{(X_1 - x)^2 + (Y_1 - y)^2}, \\
    f_2(P) &= d_{13} - \sqrt{(X_3 - x)^2 + (Y_3 - y)^2} \\
    &\quad + \sqrt{(X_1 - x)^2 + (Y_1 - y)^2}
\end{align*} \]
(8)\( -9 \)
where \( P = [x \ y]^T \) is the position vector of the transmitter, and \( T \) denotes transpose. From Eqs. (8) and (9)
\[ f(P) = 0 \]
(10)
where
\[ f(P) = \begin{bmatrix} f_1(P) \\ f_2(P) \end{bmatrix}. \]
(11)
The position is decided recurrently. Suppose that the \( k \)-th estimated position is given as
\[ P_k = \begin{bmatrix} x_k \\ y_k \end{bmatrix}. \]
(12)
f\((P_k)\) is then determined with a recurrence equation
\[ P_{k+1} = P_k - J(P_k)^{-1}f(P_k) \]
(13)
where the Jacobian matrix of Eq. (13) is
\[ J = \begin{bmatrix} \nabla f_1 \\ \nabla f_2 \end{bmatrix}. \]
(14)
Initializing \( P_0 \), calculation of \( P_k \) is repeated until \( J(P_k)^{-1} \) is sufficiently small.

2.5 Detection Errors

To maximize positioning accuracy, the threshold for pulse timing detection should be optimized. If the threshold is too low, the probability of false alarm increases as shown in Fig. 6. To avoid false alarm, the threshold should be high enough or the number of averaging samples should be large enough to reduce the noise. The correlation value has several peaks because of the impulse response of a channel or the group delay of an antenna [8]. Therefore, the second or the later peaks may be detected as the first arrival path if the threshold is relatively high as shown in Fig. 7. When the threshold is too high, miss detection occurs as shown in Fig. 8. If miss detection occurs, the timing search may exceed the one frame length. In this case, the system recognizes detection error with the status of “no pulse detection.” When false alarm or miss detection occurs, detected TDOA, \( d_{12} \) or \( d_{13} \), can be larger than the distance between the receivers as shown in Fig. 9. In this case, the position of the transmitter cannot be calculated because Eqs. (8) and (9) cannot be solved. The hyperboloid can be drawn from Eqs. (8) and (9) when the following conditions are satisfied.
\[ -d_{1212} \leq d_{12} \leq d_{122}, \]
(15)
\[ -d_{1313} \leq d_{13} \leq d_{133}, \]
(16)
where \( d_{12} \) is the distance between the receiver 1 and the receiver 2, \( d_{13} \) is the distance between the receiver 1 and the receiver 3. If the conditions (15) and (16) are not satisfied,
no solution in Eqs. (8) and (9) can be obtained. In this case, the system recognizes detection error with the status of “no solution.”

3. Measurement Results

3.1 Hardware Devices for Measurement

The hardware devices used in the experiment are shown in Table 1. An FPGA board with a Xilinx Virtex-II Pro chip is used in the transmitter. The maximum timing jitter of the FPGA’s I/O port is 0.26 unit interval that is about 0.5 [ns] with 500 [MHz] clock. This is the largest noise source of this experiment setup [13]. At the receiver side, the sampling frequency and the resolution of the ADC is 1 [GHz] and 8 [bit]. The frequency range of the LNA is 1 to 2700 [MHz] and the gain is fixed to 20 [dB]. The receivers are synchronized to calculate TDOA.

3.2 Measurement Conditions

The measurement conditions are shown in Table 2. The ADCs are assumed as comparators by converting 8 [bit] data into 1 [bit] data. A monopole antenna is used as the transmission antenna because the transmitter should be simple for active RF tag applications. The size of the receiver is not significant for those applications in general, and a circular monopole antenna with wide-band characteristics is used as the reception antenna [10]. The transmitter and the receivers are put into an anechoic chamber. The size of the chamber is L3.0 × W2.0 × H3.0 [m] and the antennas are put on the platform with the height of 0.3 [m]. The middle of the chamber is assumed as the position of (90,90) [cm].

The transmitted pulse signal generated with the FPGA board is shown in Fig. 10. The pulse duration is 4 [ns] and the interval between the pulses is 200 [ns]. As only one transmitter is used, no multiple access schemes are required. Thus, the pulse signal is not modulated and it is assumed that each frame consists of one pulse signal and the interval (200 [ns]).
The digitized samples with the comparators and the averaged samples are shown in Fig. 11. Since the frame length is 200 [ns], the average over 200 samples corresponds to 40 [ms]. The power of the noise is reduced as the number of the samples used for averaging increases.

A rectangular pulse with the duration of 2 [ns] as shown in Fig. 2 is used as the template signal at the receiver side. The rectangular waveform is easy to generate with digital circuits and works as a search window for pulse search to reduce the noise.

For accurate positioning, the number of the samples for averaging and the threshold for timing detection should be optimized. Here, the transmitter is placed at (150, 150) [cm]. The accuracy is evaluated with root mean square (RMS) error of the estimated position.

### 3.2.1 Optimization for the System with Comparators

Figure 12 shows the probability of no solution in Eqs. (8) or (9) versus the threshold. The threshold is normalized by the possible maximum value of correlation. With the normalized amplitude shown in Fig. 11 and the rectangular template signal shown in Fig. 13, the maximum correlation value is 2. If the threshold is too low, the probability of no solution increases because the received timing is detected in the noise period. If the threshold is too high, the probability of no solution also increases since the receiver may miss the detection of the first correlation peak. The threshold can be set lower as the number of averaged samples increases and the power of the noise reduces.

Figure 14 shows the probability of no pulse detection. When the threshold is 0.7 or higher, the probability of no pulse detection increases rapidly.

Figure 15 shows the RMS error of the estimated position vs. the threshold. When the threshold is 0.3, the RMS error is minimum.

To minimize the probability of no solution and the RMS error, the number of averaging is set to 200, and the threshold is set to 0.3.
3.2.2 Optimization for the System with 8 [bit] ADCs

The accuracy of positioning with 8 [bit] ADCs is also estimated. The same optimization process as the proposed system is used. Figure 16 shows the probability of no solution and Fig. 17 shows the RMS error. As the result of optimization, the threshold is set to 2.5, and the number of averaged samples is set to 200.

3.3 Measurement Results

3.3.1 RMS Error of the Estimated Position

The estimated positions of the transmitter is measured with 9 different positions as shown in Table 3. The RMS errors of the estimated position are 20–70 [cm]. Generally speaking, if the distance between the transmitter and the receiver increases, the accuracy of the estimated positioning is deteriorated due to the reduction of the received signal energy. This is applicable for the case as with the transmitter at (150,150). However, if the transmitter is close to one of three antennas, it is away from the other antennas. Thus, the accuracy is not linear to the position of the transmitter. Measurement results of the system with 8 [bit] ADCs are shown in Table 4. From the figures, it is clear that the accuracy of positioning with comparators is slightly lower than that with 8 [bit] ADCs.

Table 3  RMS error of the system with comparators.

<table>
<thead>
<tr>
<th>x axis(cm)</th>
<th>y axis(cm)</th>
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<th>90</th>
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<tr>
<td>30</td>
<td>28.13</td>
<td>22.91</td>
<td>31.53</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>22.51</td>
<td>15.20</td>
<td>45.28</td>
<td></td>
</tr>
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<td>39.04</td>
<td>44.19</td>
<td>73.72</td>
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Table 4  RMS error of the system with 8 [bit] ADCs.

<table>
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<th>90</th>
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<td>30</td>
<td>21.93</td>
<td>16.21</td>
<td>12.36</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>14.76</td>
<td>16.01</td>
<td>21.27</td>
<td></td>
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<tr>
<td>150</td>
<td>31.75</td>
<td>22.34</td>
<td>32.19</td>
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Table 5  RMS error with modal value with comparators.

<table>
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<th>y axis(cm)</th>
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<th>90</th>
<th>150</th>
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<td>150</td>
<td>13.89</td>
<td>11.52</td>
<td>38.91</td>
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</tbody>
</table>

Table 6  RMS error with modal value with 8 [bit] ADCs.

<table>
<thead>
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<th>y axis(cm)</th>
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<td>5.74</td>
<td>12.01</td>
<td>4.91</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>11.49</td>
<td>2.32</td>
<td>10.11</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>13.98</td>
<td>12.58</td>
<td>12.86</td>
<td></td>
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</table>

3.3.2 Positioning with Modal Value

Since the resolution of the ADCs is finite, the possible estimated positions of the transmitter is limited as shown in Fig. 18. The modal value of the estimated positions is calculated [14]. By calculating the modal value, it is possible to exclude the influence of estimated positions with large measurement error. The results with the proposed system is shown in Table 5. Compared with Table 3, the measurement error is reduced for entire positions. The RMS error with the modal value for the system with 8 [bit] ADCs are shown in Table 6.

In both systems, the accuracy is in the order of tens of centimeters. The accuracy of the proposed system is comparable with that of the system with 8 [bit] ADCs.

4. Conclusions

The experimental UWB positioning system has been built and the accuracy of the system has been measured. The proposed system detects the UWB pulse signal with the comparators and estimates the position of the transmitter through the OWR-TDOA technique. The accuracy of the estimated positions is at the order of tens of centimeter within the area of 1.8 x 1.8 [m]. In this measurement conditions, the system with comparators has achieved comparable accuracy with the system with ADCs of 8 [bit] resolutions.

References


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