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A New Calibration Method of UWB Antenna Delay Based on the ADS-TWR

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Abstract: This paper presents a new Ultra-wideband (UWB) antenna delay calibration method which is based on the Asymmetric Double-sided Two-way Ranging (ADS-TWR) to get the precise information of distance measurement with different UWB devices. We use a similar derivation as ADS-TWR to build the objective function based on the antenna delay model. Then we use Particle Swarm Optimization (PSO) to optimize the objective function and get the independent antenna delay of each device according to combination of different devices antenna delay. Finally we use the least square positioning method to verify the performance of different calibration methods. The result shows that our method is effective to the distance measurement system and positioning system. Compared with rough calibration method and official calibration method, our proposed method greatly improves the accuracy of the systems.

Key Words: Antenna Delay Calibration, UWB, ADS-TWR, DW1000

1 Introduction

Ultra-wideband (UWB) signals have many significant advantages in positioning system [1]. The information of positioning has a wide range of applications in industrial, medical and homecare. For example, personal healthy monitoring, locating person in a hospital, quadrotor position control and others.

The basic of the positioning system is the distance measurement method. There are four methods which can measure the distance between two devices using radio frequency technology, such as TOA, TDOA, AOA and RSSI [2]. For a UWB system, we usual use TOA, it mainly use the time of flight (TOF). If we have a synchronized clock with different devices, we can easily get the distance between two devices by using a message which can record the TOF. We can easily use the two way ranging (TWR) to measure the distance between two devices [3]. But in fact, we can't synchronize the clock in ideal accuracy, so we can't get the accurate TOF to calculate the real distance. To solve the problem, Kim et al proposed a double-sided two-way ranging (DS-TWR) method [4]. It can use three or four messages to estimate the distance between two nodes. DS-TWR method is less affected by the clock drift and frequency drift and it has relatively high accuracy. Although DS-TWR can effectively reduce the effect of clock mismatch between the devices, it has a key drawback that the delay of the transmission cycle and the reception cycle must be symmetrical. So based on the DS-TWR, Jiang et al proposed asymmetrical double-sided two-way ranging (ADS-TWR) [5]. But the ADS-TWR algorithm is hard to scale up to handle multiple tags and/or anchors at a time. Mikhaylov et al proposed the single-sided asymmetric two-way ranging (SSA-TWR) to solve it [6].

In addition to the clock synchronization problem above, antenna delay calibration is another important problem in the high accuracy distance measurement. The TWR model based on the original TWR ranging protocol is used by Ye et al [7]. They introduced the specified antenna delay time into the model. [8] proposed a simple ranging model with transmit antenna delay and receive antenna delay. It's easy to use for antenna delay calibration. Meanwhile, [8] also proposed a new antenna delay calibration method. The method is similar to genetic algorithm (GA). But the calibration method only depends on the simple TWR ranging protocol. It doesn't consider the more complicated distance measurement methods.

For a high accuracy UWB positioning system, we should solve two problems. First is clock synchronization problem, and second is antenna delay calibration problem. As mentioned above, clock synchronization problem can be easily solved by use ADS-TWR method. But there is no antenna delay calibration method to match ADS-TWR method.

In a calibration system, because ADS-TWR have high accuracy and we don't need too many tags and anchors to calibrate at the same time, we can use it as our calibration schema. In this paper, we proposed a new antenna delay calibration method based on the ADS-TWR model. We established the antenna delay model, and introduced it into

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the ADS-TWR model. Then we derived the objective function with the antenna delay. In order to get the optimal antenna delay, we used the particle swarm optimization (PSO) to optimize the objective function. Next we used least squares estimation to get the individual antenna delay of different devices. At last, positioning estimation based on the least squares was used to do the comparison of our proposed and others' antenna delay calibration methods [9].

The outline of this paper is as follows: Section 2 introduces our antenna delay calibration method. It includes the antenna delay model, the objective function, particle swarm optimization, multiple devices antenna delay calibration method and positioning method. Section 3 introduces the performance result and the discussion of our algorithm from distance measurement test and positioning test. And the conclusion is in Section 4.

2 Methods

2.1 Antenna Delay Modelling

DS-TWR is an extension of the basic single-sided two-way ranging in which two round trip time measurements are used and combined to give a time-of-flight result which has a reduced error even for quite long response delays.

The original DS-TWR method needs four messages, but it can be simplified to three messages by using the reply of the first round-trip measurement as the initiator of the second round-trip measurement, shown in Fig.1.

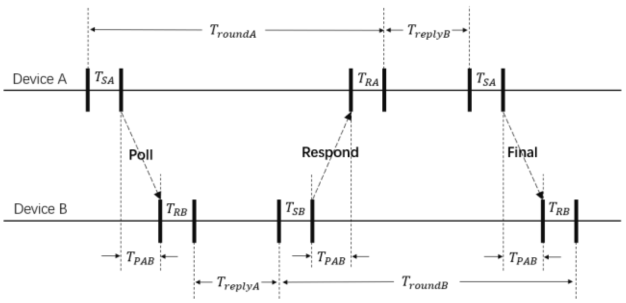

Fig.1: The Time Series of DS-TWR

In the DS-TWR method, device A initiates the first round trip measurement to which device B responds, after which device B initiates the second round trip measurement to which device A responds completing the full DS-TWR exchange. Each device precisely timestamps the transmission and reception times of the messages.

As shown in Fig.1, between two devices, every DS-TWR period can be divided into three parts: poll package, respond package and final package. For each package, time period can be modeled as formulation (1).

$$\begin{cases} T_{roundA} = T_{rA} + T_{sA} + T_{rB} + T_{sB} + T_{replyA} + 2T_{pAB} \\ T_{roundB} = T_{rA} + T_{sA} + T_{rB} + T_{sB} + T_{replyB} + 2T_{pAB} \end{cases} \quad (1)$$

where T_{roundX} means the total time which is from the send moment of device X to receive moment of device X, T_{replyX} means the total time which is from the receive moment of device X to the send moment of device X, T_{pAB} means the flight time in the space from A to B. T_{rX} means the receive antenna delay of device X. T_{sX} means the send antenna delay of device X.

For an individual device, the sum of the send antenna delay and the receive antenna delay can be regarded as a total delay. When we regard T_{rX} and T_{sX} as unknown parameters, formulation (1), which have 4 unknown parameters, is an underdetermined equation set obviously. When we use the total delay in our UWB measurement system, it's the same as the separated delay. So we can make the antenna delay as the formulation (2).

$$\begin{cases} T_{dA} = T_{rA} + T_{sA} \\ T_{dB} = T_{rB} + T_{sB} \end{cases} \quad (2)$$

For two certain devices, the sum of two devices' antenna delays is constant.

$$T_{dAB} = T_{dA} + T_{dB} \quad (3)$$

So we can use formulation (2) and (3) to represent the antenna delay model, and get the formulation (4).

$$\begin{cases} T_{roundA} = T_{dAB} + T_{replyA} + 2T_{pAB} \\ T_{roundB} = T_{dAB} + T_{replyB} + 2T_{pAB} \end{cases} \quad (4)$$

2.2 The Objective Function of Two Devices Antenna Delay Calibration

In DS-TWR method, because the asymmetry of two round-trip measurements' reply time is not concerned, DS-TWR also can be called as symmetric double-sided two-way ranging (SDS-TWR). It means that the reply time must be symmetric when we use the DS-TWR method. But in fact, the reply time is almost impossible to be the same in real devices. So ADS-TWR is selected for this article. We can use the derivation method similar as ADS-TWR from the formulation (4) to introduce our simplified antenna delay model. We easily get the equation as follows:

$$T_{roundA}T_{roundB} = \left(T_{dAB} + T_{replyA} + 2T_{pAB}\right)\cdot\left(T_{dAB} + T_{replyB} + 2T_{pAB}\right) \quad (5)$$

We expand the equation (5):

$$\begin{aligned} T_{roundA}T_{roundB} = {} & T_{replyA}T_{replyB} + 2T_{replyA}T_{pAB} + 2T_{replyB}T_{pAB} \\ & + T_{replyA}T_{dAB} + T_{replyB}T_{dAB} + 4T_{pAB}^2 \\ & + 4T_{pAB}T_{dAB} + T_{dAB}^2 \end{aligned} \quad (6)$$

Then we sum up the equations from (4), and we get (7).

$$T_{replyA} + T_{replyB} = T_{roundA} + T_{roundB} - 2T_{dAB} - 4T_{pAB} \quad (7)$$

We substitute (7) into (6), and easily get the form as (8).

$$\begin{aligned} & T_{roundA}T_{roundB} - T_{replyA}T_{replyB} - \left(T_{replyA}T_{dAB} + T_{replyB}T_{dAB} + 4T_{dAB}^2\right) \\ & = T_{pAB}\left(T_{roundA} + T_{replyA} + T_{roundB} + T_{replyB} + 2T_{dAB}\right) \end{aligned} \quad (8)$$

So the estimation of T_{pAB} can be expressed as (9). In (9), with the exception of T_{dAB}, other parameters can be measured in fact. If we want to get the accurate estimation, we should adjust the T_{dAB} to a suitable value.

$$\hat{T}_{pAB}=\frac{T_{roundA}T_{roundB}-T_{replyA}T_{replyB}-\left(T_{replyA}T_{dAB}+T_{replyB}T_{dAB}+T_{dAB}^2\right)}{T_{roundA}+T_{replyA}+T_{roundB}+T_{replyB}+2T_{dAB}} \quad (9)$$

Because $\hat{T}_{pAB}$ is the estimation of the flight time, we can get the estimation of the distance as (10).

$$\hat{d}_{pAB}=c\hat{T}_{pAB} \quad (10)$$

where $\hat{d}_{pAB}$ means the estimation of the distance from A to B, c means the speed of light. Due to the general air refractive index is 1.00027 [10], we adopt the speed of light in general air is about 299710666.95 m/s.

We assume that a total of n samples have been taken. We hope our estimated distance $\hat{d}_{pAB}$ is as close as possible to the real distance d_{rAB}. So we can get the objective function as (11).

$$\min\frac{1}{n}\sum_{k=1}^{n}\left\|d_{rAB}-\hat{d}_{pAB}\right\|_k \quad (11)$$

Our object is to find the adaptive antenna delay T_{dAB} to minimize the objective function.

In order to solve the objective function (11), we use the PSO. PSO is an algorithm capable of optimizing a linear or non-linear problem and it usually reaches good solutions efficiently [11]. The basic concept of the algorithm is to create a swarm of particles which move in the problem space searching for their solution which best suits the fitness function.

The core of PSO is the need of a fitness function. For our problem, we can make the objective function (11) as our fitness function, so that we can get the best antenna delay T_{dij} for each device pair.

2.3 Multiple Devices' Antenna Delay Calibration Method

In section 2.1, we know how to get the best total antenna delay between two devices. We can use more delay information of different devices to get every antenna delay of a specific device. From the equation (3), we can list the other two equation from B to C and from A to C. We can organize them into the following form (12).

$$T_d'=MT_d \quad (12)$$

where $T_d'=\left[T_{dAB}\quad T_{dAC}\quad T_{dBC}\right]^T$, $T_d=\left[T_{dA}\quad T_{dB}\quad T_{dC}\right]^T$, T_d' is the total antenna delay vector between two different devices, T_d is the individual antenna delay vector of each specific device, M is the transform matrix

$$M=\begin{bmatrix}1&1&0\\1&0&1\\0&1&1\end{bmatrix}.$$

So we can get the T_d like the following form (13).

$$T_d=M^{-1}T_d' \quad (13)$$

The above form is for three devices. If we have more than three devices to do the antenna delay calibration, it means that our equation (12) should be an overdetermined equation. So we should use least squares method to solve it.

$$T_d=\left(M^TM\right)^{-1}M^TT_d' \quad (14)$$

Although the above equation is only for the 3 devices, it's easy to expand to any number of devices.

2.4 Positioning Method

We suppose that there are n anchor nodes (x_1,y_1), (x_2,y_2),…, (x_n,y_n), and their distances from the tag (x,y) are $d_1,d_2,\ldots,d_n$.

According to the distance formula of two-dimensional space, we have the following system of equations.

$$\begin{cases}\left(x_1-x\right)^2+\left(y_1-y\right)^2=d_1^2\\ \qquad\vdots\\ \left(x_n-x\right)^2+\left(y_n-y\right)^2=d_n^2\end{cases} \quad (15)$$

We use equations (15) to derive the least squares form as follows:

$$AX=b \quad (16)$$

where

$$A=\begin{bmatrix}2\left(x_1-x_n\right)&2\left(y_1-y_n\right)\\ \vdots&\vdots\\ 2\left(x_{n-1}-x_n\right)&2\left(y_{n-1}-y_n\right)\end{bmatrix} \quad (17)$$

$$X=\left[x\quad y\right]^T \quad (21)$$

$$b=\begin{bmatrix}x_1^2-x_n^2+y_1^2-y_n^2+d_n^2-d_1^2\\ \vdots\\ x_{n-1}^2-x_n^2+y_{n-1}^2-y_n^2+d_n^2-d_{n-1}^2\end{bmatrix} \quad (18)$$

So the solution of the above least squares problem is (19).

$$\hat{X}=\left(A^TA\right)^{-1}A^Tb \quad (19)$$

3 Experiment Results and Discussion

Fig.2: Our Designed UWB Devices

This section is divided into two parts. The first part is about the antenna delay calibration results of 4 UWB devices which are named as $A0$, $A1$, $A2$ and $T0$. The second part is the positioning test results of T0 which uses three anchors. The UWB devices which we used are designed by ourselves and the key component is the DW1000 which is from the company DecaWave, as shown in Fig.2.

3.1 Antenna Delay Calibration Results for 4 Devices

In the standard distance of 2 meters, we used 4 devices to measure the distance in turn. We sampled different pairs of devices separately and got 900 samples of $A0$, $A1$, $A2$ and $T0$. For the anchor $A0$ and tag $T0$, the samples are $T_{roundA0}$, $T_{roundT0}$, $T_{replyA0}$ and $T_{replyT0}$. Then, based on the distance samples, we used four methods to estimate the antenna delays of different devices. And we got the estimations of the distance by using equation (9) to compare the effects of four methods. Four methods are as follows:

- No calibration. It means that we calculate the distance estimations of the device pairs when the antenna delays are equal to zero.
- Rough calibration method. It means that we use the antenna delays which are from the DW1000 official program. The antenna delays are same and they're not precise enough. In fact, because the devices differ from each other, the true antenna delays can't be exactly same. So we called the calibration method as rough calibration method.
- Official calibration method. It means that we use the calibration method in literature [7]. The method is the official calibration method provided by DecaWave. It is based on the SDS-TWR method. It can establish a linear equation of the distance estimation. It uses a new optimize method like GA to get the antenna delays, but it is equivalent to use least squares estimation because of the linear equation.
- Proposed calibration method. It is the method proposed before. Firstly it use our proposed algorithm in section 2.2 to get the sum of two devices' antenna delays. Then it use our proposed algorithm in section 2.3 to get the individual antenna delays of 4 devices. At last, we use the individual antenna delays to get the estimation of the distance.

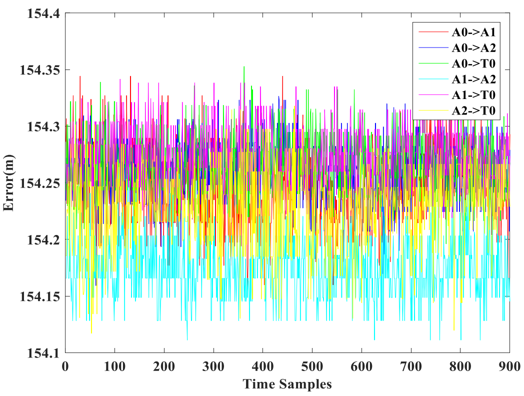

Fig.3: No Calibration

Fig.3 is the result of no calibration. From the Fig.3, the error of different device pairs is relatively large, which are about 154 meters. It shows that the device, which doesn't perform UWB antenna delay calibration, basically doesn't have the correct ranging capability.

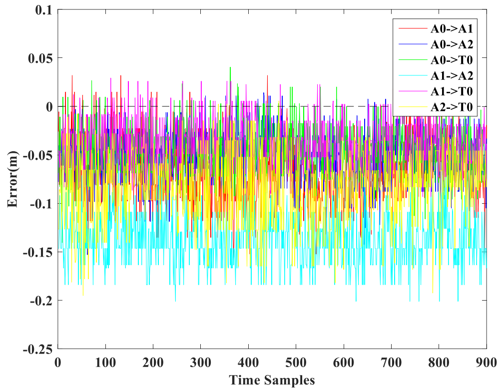

Fig.4: Rough Calibration Method

Fig.4 is the result of the rough calibration method. Compared with Fig.3, the error in Fig.5 is obviously reduced. From the Fig.4, the basic error is about -0.15 meters and the error of different device pairs is relatively scattered. It shows that the same antenna delays can't make up the difference between different devices.

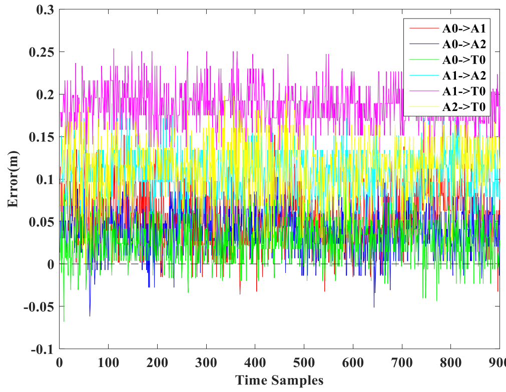

Fig. 5: Official Calibration Method

Fig.5 is the result of the official calibration method. Compared with Fig.4, the error is relatively concentrated, but the error of different device pairs doesn't tend to be uniform enough. It means that the official calibration method can't calibrate the antenna delay error of ADS-TWR method completely.

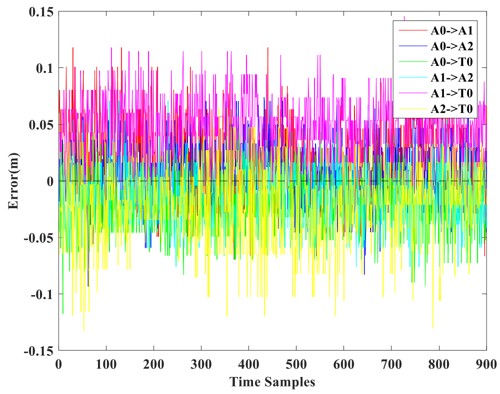

Fig.6: Proposed Calibration Method

Fig.6 is the result of the proposed calibration method. From the Fig.6, we can easily know that the distance estimation error of different device is greatly reduced. They are almost zero. The error is relatively concentrated and the error of different device pairs tends to be uniform. It means that the antenna delay error of all the devices is basically calibrated.

Table 1: The Mean of Error between Different Devices Using Different Calibration Method

Items	No (m)	Rough (m)	Official (m)	Proposed (m)
A0->A1	154.25	-0.06	0.06	0.01
A0->A2	154.26	-0.05	0.04	0.00
A0->T0	154.27	-0.04	0.03	0.00
A1->A2	154.17	-0.13	0.11	0.01
A1->T0	154.27	-0.03	0.18	0.04
A2->T0	154.23	-0.08	0.11	-0.03

Table 1 shows a numerical error result of our different antenna delay calibration methods. From the table above, the error of no calibration is the largest. It means that it's necessary to do the calibration of the different UWB devices. Meanwhile, there is some error of the rough calibration method which implies that antenna delays should be calibrated individually for different devices. Although the rough calibration has better performance in some channels, the DWM1000 module is used as the official recommendation module of Decawave so that the rough calibration value is the average value obtained by Decawave after a large number of tests. For the new UWB module which is designed by DW1000 from the antenna level , the rough calibration value is not available.

The calibration method proposed in this paper has better performance than the official calibration method. Official calibration method is based on the SDS-TWR. The distance estimation equation of SDS-TWR is linear, and the distance estimation equation of ADS-TWR is nonlinear. It essentially determines that the antenna delays, which are from official calibration method, are not suitable for the ADS-TWR. So our proposed calibration method is better.

3.2 Positioning Test Results

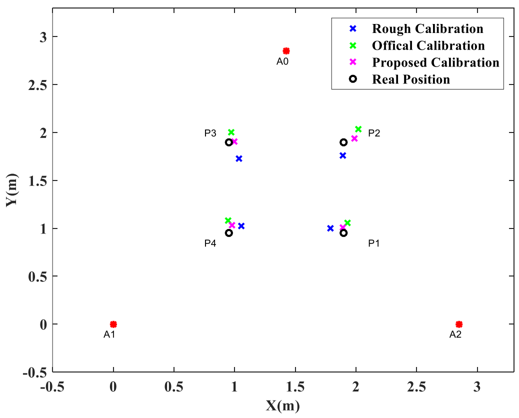

Fig.7: Positioning Result of Different Calibration Method

We used $A0$, $A1$ and $A2$ as anchors, and $T0$ as a tag. Then we set four positions as standard positions, which are named as $P1$, $P2$, $P3$ and $P4$. After that, we placed the tag and got 500 samples of DS-TWR between each anchor and tag in each position. Next we estimated the distance with the rough calibration method, the official calibration method and the proposed calibration method. At last, we averaged over the distance and used the positioning algorithm in section 2.4 to test the performance with different antenna delay calibration method. The positioning results of different antenna delay calibration method are shown in Fig.7.

As shown in Fig.7, the positioning errors of the rough calibration method are obvious. The positioning errors of the official calibration method are smaller. In contrast, the errors of the proposed calibration method are smaller than that of the official calibration method.

In order to evaluate the performance of different calibration method, we calculated the distance between the real position and the position of the different calibration method. We made the distance as the evaluation standard and we got the table 2.

Table 2 shows that our proposed calibration method has the best performance that the distance error is less than 0.1m. Because the antenna delay calibration values are got under the standard distance of 2 meters, it has the best performance of distance estimation in 2 meters. And in this positioning test, different distance estimation will influence the positioning results. So if we get more samples under different standard distances in our proposed calibration method, we will get better positioning performance in the positioning plane.

Table 2: The Error of Positioning Using Different Calibration Method

Items	Rough (m)	Official (m)	Proposed (m)
P1	0.12	0.11	0.06
P2	0.14	0.18	0.10
P3	0.19	0.10	0.05
P4	0.13	0.13	0.09

From the experiment above, we can see that the proposed calibration method has a better performance in a UWB distance measurement and positioning system.

Except above, in our proposed calibration method, we may not use the algorithm in section 2.3 to get the individual antenna delays. So we get the total antenna delays between two devices. This method avoids the problem that the entire calibration equation (12) may be over-determined. But it needs to do the calibration in any two devices when we add a new devices in the positioning system. If we have many anchors, it is complex for a practical application. So we use the individual antenna delays in our article.

In future, for the proposed method, more devices need to be added to carry out comparative tests, so that the method can be proved to be more effective.

4 Conclusion

This paper presents a new calibration method of UWB antenna delay. First of all, we build the objective function through the antenna delay model. We use function optimization method like PSO to solve the objective function. Then we provide the multi-devices antenna delay calibration method, so that we can get the independent antenna delay of each device. At last, we use least square method for positioning system and make it an evaluation indicator of our calibration method. From the experiment, we know the proposed calibration method have better performance than the rough calibration method and the official calibration method. The errors of the proposed calibration method are within 0.1m regardless of distance measurement or positioning.

In summary, we can know that our method has a good performance in UWB antenna delay calibration. It plays a crucial role in the construction of high precision UWB positioning systems.

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