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A Real Time Ultra-Wideband Location System for Smart Healthcare

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***Abstract*—**Driven by the demand of intelligent monitoring in rehabilitation centers or hospitals, a high accuracy real-time location system based on UWB (ultra-wideband) technology was proposed. The system measures precise location of a specific person, traces his movement and visualizes his trajectory on the screen for doctors or administrators. Therefore, doctors could view the position of the patient at any time and find them immediately and exactly when something emergent happens. In our design process, different algorithms were discussed, and their errors were analyzed. In addition, we discussed about a , simple but effective way of correcting the antenna delay error, which turned out to be effective. By choosing the best algorithm and correcting errors with corresponding methods, the system attained a good accuracy. Experiments indicated that the ranging error of the system is lower than 7 cm, the locating error is lower than 20 cm, and the refresh rate exceeds 5 times per second. In future works, by embedding the system in wearable IoT (Internet of Things) devices, it could provide not only physical parameters, but also the activity status of the patient, which would help doctors a lot in performing healthcare.

***Keywords*—**Intelligent monitoring, IoT devices, real-time location, smart healthcare, ultra-wideband technology.

I. Introduction

IN hospitals or rehabilitation centers, to prevent accidents and let supervisors handle emergencies in time, monitoring of patients all the time is necessary. For example, when a serious disease occurs, doctors need to locate the patient and give first aid immediately. In the past, they need to walk around to check the state of patients regularly. Thus, they cannot pay attention to all patients at the same time. It is not uncommon to miss some patients. Therefore, a real-time monitoring system is urgently needed. Many excellent systems have been proposed [1]-[3], intended for wireless physical parameter monitoring. However, little research has been done about indoor real-time location. And location precision is an urgent problem to be solved [4].

At present, location methods mainly include infrared, RFID (radio frequency identity), Bluetooth, WIFI, ZigBee, GPS and UWB. Infrared is based on distance measurement of light. Precise as it is, infrared system is often disturbed by ambient light and other obstacles. Want et al. designed an Active Badge system, but this system maintained only 5 m-10 m accuracy [5]. RFID systems like LANDMARC achieved 5 cm-5 m accuracy with the help of "nearest neighbor" algorithm [6]. Bluetooth systems, based on signal channel attention or fingerprint methods, have the advantage of small size and low power, but only attained 2.5 m accuracy [7]-[8]. Principle of WIFI localization is similar [9]. Since wireless access points are everywhere, WIFI location systems are quite easy to deploy, whose accuracy ranges 2-5 m. Compared with those methods, ZigBee technology has a relative lower accuracy of merely 1 m-8 m [10], [11], but consumes very low power.

As discussed above, ordinary location methods only maintain 1 m-10 m accuracy. When used for location in rooms and hallways, they are likely to give out a wrong place. To further improve location accuracy and overcome these problems, we proposed a UWB real-time location system, which achieves an accuracy of lower than 20 cm and a refresh rate of 5Hz for positioning.

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II. Algorithms

A. Measure Distance

The proposed location system is based on ranging, so accurate ranging algorithms will guarantee a precise location estimation. Distance is obtained by measuring signal propagation time in the air, which is called TOF (time of flight). TOF was first put forward in 2000 by Mccrady et al. [12], and first used for ranging by Andre et al. [13]. Distance can be described as:

$$Dist = c \times TOF \tag{1}$$

Set c equal to $299792458\ \mathrm{m/s}$, then distance can be calculated by multiplying the *TOF* by *c*. There are two algorithms to measure the time of signal flying in air: SS-TWR (Single-sided Two Way Ranging) and DS-TWR (Double-sided Two Way Ranging).

B. SS-TWR

Fig. 1 shows the process of message passing between a tag and an anchor. A message is sent from tag A at time t_1, and received by anchor B at t_2. After a short delay T_{reply}, anchor B sends a response message at t_3, finally the message arrives at tag A at t_4. In Fig. 1, T_{prop} denotes the time of message flying between tag A and anchor B.

Define clock error in tag A as e_A, clock error in anchor B as e_B , then the ranging error is:

$$error \approx \frac{1}{2}(e_A - e_B)T_{reply} \tag{2}$$

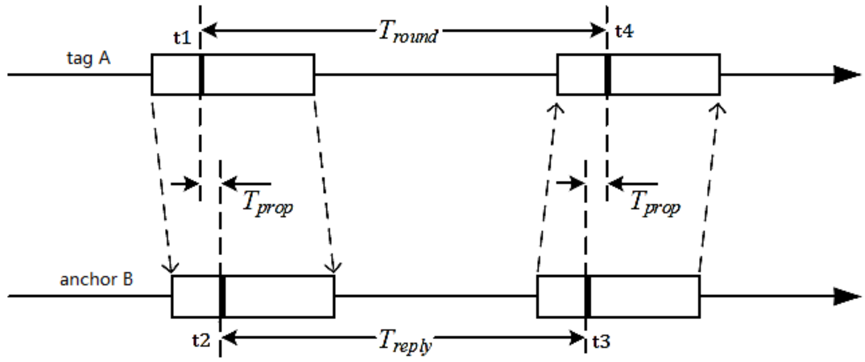


Fig. 1 Process of message passing in SS-TWR

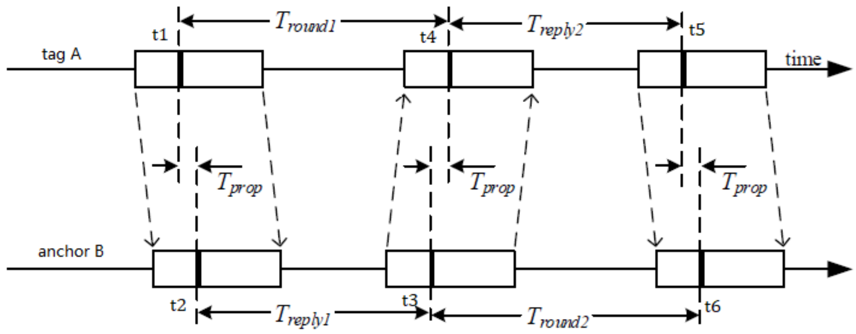


Fig. 2 Process of message passing in DS-TWR

C. DS-TWR

Fig. 2 shows the message passing process of DS-TWR algorithm. Different from SS-TWR, it includes a third message called "final message". The final message is sent from tag A and received by anchor B.

As shown in Fig. 2, the error of the system is

$$error = \frac{1}{4}(e_A - e_B)\Delta T_{reply} \tag{3}$$

where

$$\Delta T_{reply} = T_{reply1} - T_{reply2} \tag{4}$$

It is obvious that error is proportional to ΔT_{reply}, when ΔT_{reply} is decreased to a very small value, ranging error is also decrease. By comparing (3) with (2), we found that error of DS-TWR algorithm is much smaller than SS-TWR.

D. Asymmetric DS-TWR

For most applications, it is hard to decrease ΔT_{reply} to a very small value, since devices need time to transmit and receive messages. An improved algorithm was adopted—ADS-TWR (Asymmetric Double-sided Two Way Ranging). The process of message passing is same as DS-TWR; the only difference is that the former does not require T_{reply} to be the same. ADS-TWR method calculates T_{prop} with

$$T_{prop} = \frac{T_{round1} \times T_{round2} - T_{reply1} \times T_{reply2}}{T_{round1} + T_{round2} + T_{reply1} + T_{reply2}} \tag{5}$$

Use k_a to denote the ratio of clock in tag A to standard clock, and k_b to denote ratio of anchor B to standard clock. Ideally, the following relation exists

$$\frac{k_a + k_b}{2} = 1 \tag{6}$$

Therefore, error of ADS-TWR system is

$$error = T_{prop} \times (1 - \frac{k_a + k_b}{2}) \tag{7}$$

Compared to DS-TWR, error of ADS-TWR is similar but the latter does not require ΔT_{reply} to be zero. So, ADS-TWR system supports more tags work together and maintains same accuracy for every tag.

E. Location Algorithm

Trilateral centroid locating algorithm and maximum likelihood estimation algorithm are used to calculate the position of an object. There are 3 anchors placed at points B_1-B_3 (three points should not be on a same line, shown in Fig. 4). Point A is the target to be located. Since coordinates of 3 anchors are pre-determined, when distances between A and each anchor are measured, coordinates of A (assume (x, y)) can be calculated by the following formula ((x_i, y_i) is the coordinate of the i-th anchor):

$$\begin{cases} (x - x_1)^2 + (y - y_1)^2 = r_1^2 \\ (x - x_2)^2 + (y - y_2)^2 = r_2^2 \\ (x - x_3)^2 + (y - y_3)^2 = r_3^2 \end{cases} \tag{8}$$

These statically indeterminate equations should be estimated by means of nonlinear least square method, combined with Taylor series. A best position estimation will be calculated.

Error in trilateral centroid location algorithm is determined by two factors, one is geometric distribution of anchors, and the other is the precision of each measured distance value. According to Liu's research [14], to minimize location error, anchors need to be distributed in a cellular manner, as shown in Fig. 3. For our trilateral centroid system, to achieve better accuracy, we should distribute 3 anchors at three vertices of an equilateral triangle manner. Fig. 4 shows anchors' distribution in a trilateral centroid system.

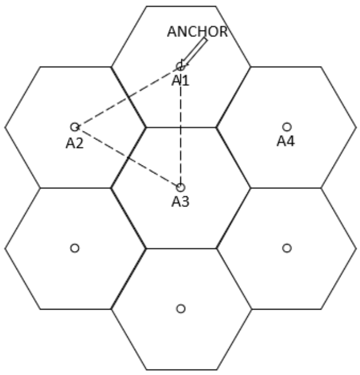


Fig. 3 Cellular distribution of anchors

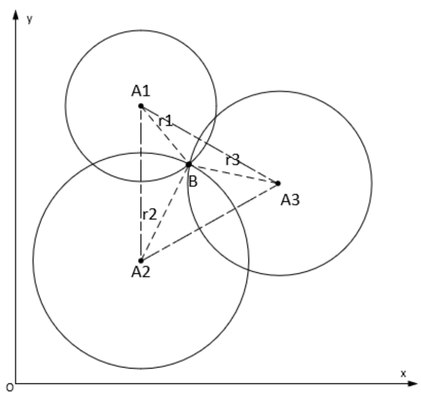


Fig. 4 Trilateral centroid location model

III. System Design

A. Module Design

We select DW1000 as the communicate chip for location system. Produced by DACAWAVE company, DW1000 is a fully integrated single chip UWB low-power and low-cost transceiver IC compliant to IEEE802.15.4-2011. It can be used for 2-way ranging or location systems with a precision of 10 cm. The chip also has a good immunity to multipath fading. Low power consumption and high reliability make it a great choice for smart healthcare systems.

DW1000 needs a host controller, so we choose STM32 as host controller. It is an ARM Cortex-M3 kernel chip, with several timers, ADC, DMA, SPI, IIC, and other powerful peripherals on it. The controller runs at a maximum frequency of 72 MHz. Furthermore, we add an OLED screen on it to display the measured result. Fig. 5 shows the architecture of the system.

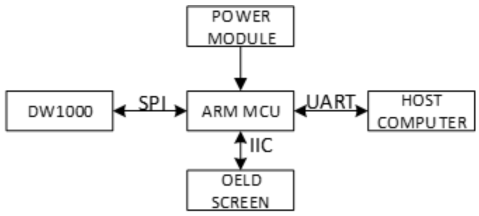


Fig. 5 Architecture of the system

B. System Calibration

When the signal passes through the amplifier and PCB circuits, transmission delay is not negligible. Thus, we introduced a delay variable τ to compensate the transmit delay. Since a very short delay will cause huge error, precise calibration is mandatory. For example, 1 ns time error will lead to 30 cm distance error in the result.

Fig. 6 shows our proposed algorithm to calibrate τ. The variable τ should be calibrated with the procedure described in it iteratively. After calibration, the final τ will be saved into DW1000 registers. So, we only need to calibrate our system the first time we use it.

To perform calibration, we place two modules separated by L_a meters. L_a is a predefined distance by users. According to DW1000 datasheet, it is usually around 5 meters for channel mode 2. An error function is defined as:

$$F = \|L - L_a\|_2 \quad (9)$$

It stands for the difference between measured distance and actual distance. When F is small enough, measured distance is approximately equal to the actual value.

IV. Experiments

A. System Calibration Test

We apply the proposed calibration algorithm described above to the system. Fig. 7 shows the process of searching optimal delay value. In Fig. 7, red 'X' stands for a set of best delay parameters, and blue dots mean bad parameters. As the number of iterations increases, red 'X' points become more and more concentrated. After iteration, delay converges to a specific value.

B. Two Way Ranging Test

We will perform SS-TWR, DS-TWR, ADS-TWR algorithms separately to test the performance of ranging system statically. First, we set one module as anchor mode, and the other tag mode. Then, we place two modules separately by a pre-set distance. The system will be tested at 6 pre-set distances (unit: cm): 100, 200, 500, 800, 1200 and 2000. For each distance, we observe and record 200 results. Ranging errors and Mean Square Errors (MSE) are shown in Table I and Fig. 8.

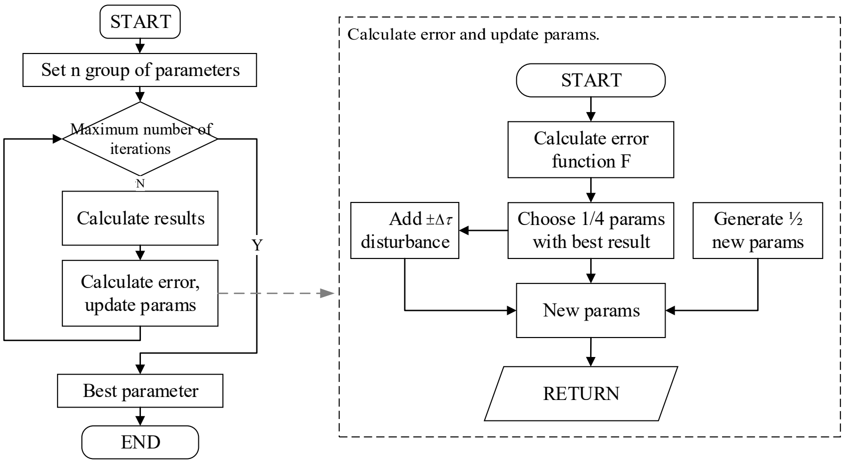
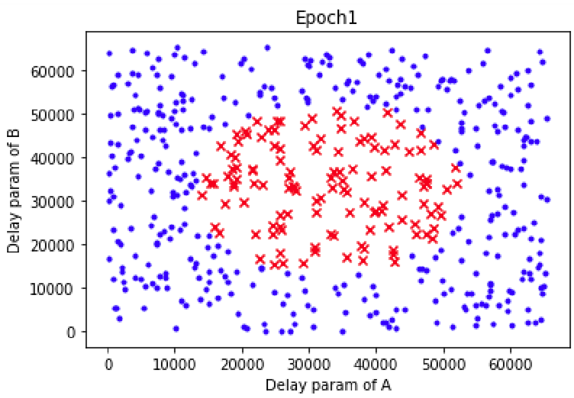
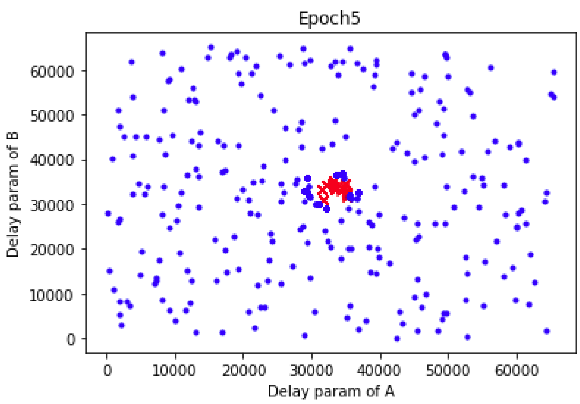


Fig. 6 Calibration algorithm of system

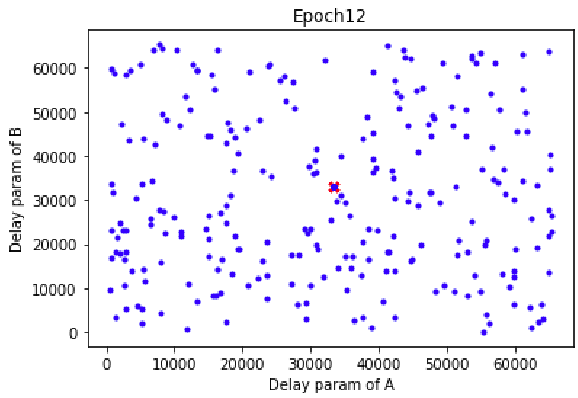
It can be concluded from Table I and Fig. 8 that SS-TWR has the largest ranging error (> 15 cm). Error of DS-TWR and ADS-TWR are similar (< 10 cm). Errors of 3 algorithms are consistent with theoretical error analysis in Section II. The improved ADS-TWR method achieves the best error stability, even at 20 m away. By analyzing time consumption of ranging messages, we calculated that the system has a ranging rate at more than 10 Hz.



(a) epoch 1



(b) epoch 5



(c) epoch 12

Fig. 7 Process of searching best parameters

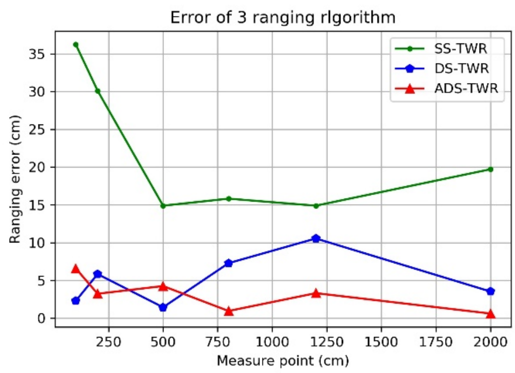


Fig. 8 Errors of 3 ranging algorithms

Since ADS-TWR has the best performance especially when dealing with several tags' messages simultaneously, we will adopt ADS-TWR algorithm in the location system.

C. Location System Test

Based on trilateration centroid location algorithm, a real-time location system can be established. The system consists of 3 anchors, 1 listener station and some tags. What needs to be added is that the listener station receives every message sent by modules, analyzes it and sends it to the computer. The listener tag is used only for the convenience of recording and visualizing results in this experiment.

A triangular open area with side length of at least 5 m was selected for location test. We place 3 anchors separately at 3 vertices of the triangle area. Anchors' coordinates are $(0,0)$, (5,0) and $(2.5, 2.5\sqrt{3})$. They are denoted as *ANCHOR1*, *ANCHOR2* and *ANCHOR3*. In Fig. 9, they are represented by green squares.

We have chosen four points A, B, C, D in the area for static location test. The actual and measured coordinates of four points are shown in Table II. As shown in Fig. 9, an object starts from point D, stays for a while, then moves to B along the red dashed line. Next, it stays at B, moves to A, stays, finally arrives C. Fig. 9 plots the object's real-time position in the location test. Blue dots are measured results, and red dashed line is the actual trace of the object. Fig. 10 also plots the object's real-time trace, to be displayed on the screen for doctors and supervisors.

TABLE I
MEASURED RESULT OF 3 RANGING ALGORITHMS

Point (cm)	SS-TWR		DS-TWR		ADS-TWR	
	Error (cm)	MSE (cm)	Error (cm)	MSE (cm)	Error (cm)	MSE (cm)
100.00	36.23	1337.22	2.29	12.21	6.58	49.71
200.00	30.11	913.20	5.83	36.44	3.23	91.66
500.00	14.89	242.59	1.44	6.56	4.25	27.66
800.00	15.82	267.68	7.28	62.88	0.95	5.19
1200.00	14.89	225.89	10.55	123.38	3.31	13.97
2000.00	19.71	434.76	3.53	16.46	0.61	2.89

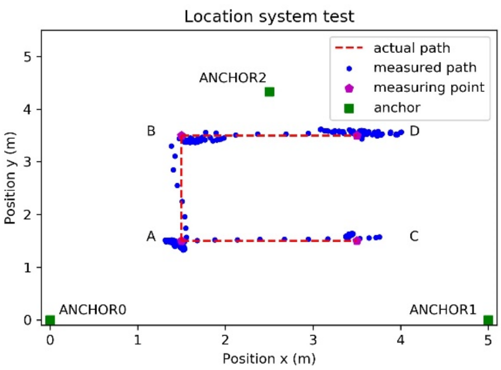


Fig. 9 Location system test

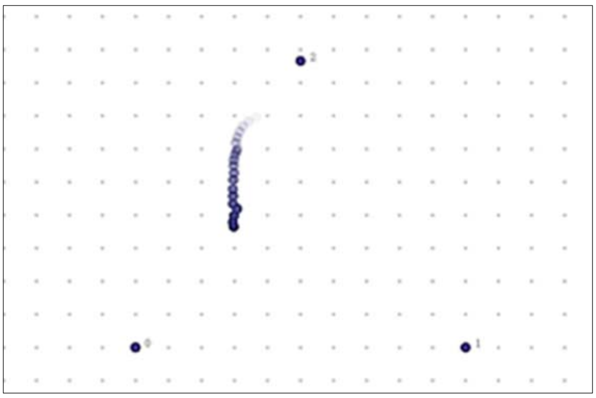


Fig. 10 Location trace software

It can be concluded from Table II that static location error remains below 18 cm. The minimum error is 7 cm, the average error is about 12 cm.

For dynamic test, let the object move along the path D-B-A-C as shown in Fig. 9. The measured path is plotted with blue dots in Fig. 9. The measured path fits actual path (red dashed path) quite well.

In the dynamic location test, each location process costs 0.196 seconds. So, location rate is about 5 Hz, which is enough for tracking an object. E.g., if an object moves at a speed of 1 m/s, the location will maintain a resolution of 20 cm. Considering power consumption, we program the system to adjust location rate automatically. When the object moves fast, location rate increases to 5 Hz, and when the object keeps still, location rate decreases.

TABLE II
STATIC LOCATION TEST

Measure point	Actual position (m)	Measured position (m)	Error (m)
A	(1.50, 1.50)	(1.43, 1.47)	0.076
B	(1.50, 3.50)	(1.59, 3.41)	0.127
C	(3.50, 1.50)	(3.68, 1.51)	0.180
D	(3.50, 3.50)	(3.57, 3.55)	0.086

V. CONCLUSIONS

In recent years, IoT technology has enabled wireless and smart healthcare in rehabilitation center, hospitals and other healthcare institutions. In this paper, a high accuracy real-time location system is proposed, which will equip previous wireless healthcare systems with high accuracy and real-time location functions. The proposed UWB system is easy to deploy. It requires only several anchors, and outperforms traditional IR, WIFI and ZigBee location systems. Combining this system with wireless physical parameter measurement system, supervisors could view the physical states of every patient clearly and conveniently, just on a screen. This may change healthcare into a smart style. However, currently the system only supports limited tags. As number of tags increases, system performance decreases. In future works, we will consider further improving the system tag capacity, and optimize location algorithms.

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