# Ultra-wideband Indoor Positioning Based on Triangle Midpoint Algorithm

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***Abstract*—In this paper, we present an experimental indoor positioning system consisting of three anchor nodes and a tag, which uses a microprocessor with an ultra-wideband wireless transceiver device. The scheme based on the time-of-arrival technique and triangle midpoint algorithm provides accurate localization in a limited indoor area. The average localization error of the proposed positioning system placed in the indoor space of 732cm×488cm×220cm is 12.87cm. The experimental results demonstrated that the proposed system has the characteristics of high precision localization and less computation time.**

***Keywords-indoor positioning; ultra-wideband (UWB); time-of-arrival (TOA); triangle midpoint algorithm(TMA).***

## I. INTRODUCTION

Many different positioning technologies are applied to the indoor environment for research, including Radio Frequency Identification Devices (RFID) [1][2], infrared sensors [3], Zigbee [4], Wireless Networks (Wi-Fi) [5], low Power Bluetooth [6] and so on. These different technologies are usually selected from the Received Signal Strength Indicator (RSSI) to achieve indoor positioning. Signals are relatively easy to be blocked by objects and cause poor penetration. They are easily affected by multiple path interferences, and the accuracy is mostly low. Therefore, it is necessary to set multiple reference points in the indoor environment or build the database in advance to improve the indoor positioning accuracy.

Ultra-wideband (UWB) wireless transmission technology has excellent transmission quality in complex indoor environments and has the advantages of high transmission speed, excellent resistance to multi-path interference, low power, high penetration, and high time accuracy [7]-[9]. UWB transceiver utilizes a very short Radio Frequency (RF) pulse to achieve high bandwidth connections. It can execute an accurate measurement of time delay and distance difference [9][10]. Many algorithms for UWB indoor positioning have been proposed such as calculating the Time-Of-Arrival (TOA) or Time-Difference-Of-Arrival (TDOA) schemes [12]. From the above, it is known that UWB is quite suitable for indoor positioning, and the positioning accuracy is high, even reaching a minimum error of 10 cm.

This research mainly uses a microprocessor to control UWB device, and then uses TOA triangulation method, combined with a fast positioning Triangle Midpoint Algorithm (TMA) to implement an accuracy indoor positioning system. First, a single tag based on a single base station measures its positioning accuracy and Environmental Parameter Calibration (EPC). After that, three base stations are placed in the three corners of the laboratory space, and the distances of the tags are respectively captured to test the arrival time method. Finally, the test results input into computer to evaluate and explore the positioning accuracy and computation time.

This paper is organized as follows; the indoor wireless positioning system is presented in Section II. Then, the UWB positioning scheme is briefly explained in Section III. After that, the implementation of the positioning algorithm is described in Section IV. Then, experimental setup and results are discussed in Section V. Finally, Section VI concludes the paper.

## II. INDOOR WIRELESS POSITIONING SYSTEM

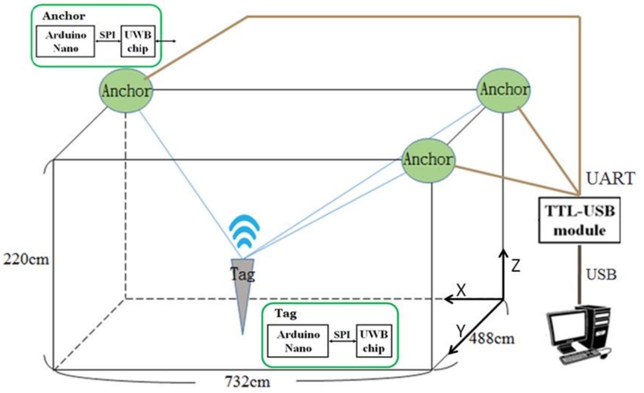


Figure. 1. Block diagram of UWB Indoor wireless location system

Figure 1 is a block diagram of UWB indoor wireless positioning system. The green ellipse is the base station that is an anchor. In the middle of the figure, the gray inverted triangle is a tag to be located. The base station is placed in three corners of the experimental space and connected to the computer using Universal Asynchronous Receiver and Transmitter (UART) through a Transistor-Transistor Logic-Universal Serial Bus (TTL-USB) module. Then the measured data are written in JAVA programming language of TOA triangulation positioning scheme, and finally by the coordinate system to calculate a positioning point and its error for real-time operation. The tag and anchors are integrated by the Arduino microprocessor with a UWB device (DW1000) as shown in the inset of Figure 1. The control program is programming in the microprocessor and communicates with the UWB device via the Serial Peripheral Interface Bus (SPIB). The base station and the tag are a wireless signal transmission using ultra-wideband pulses.

The DW1000 [13] is a single chip radio transceiver Integrated Circuit (IC) compliant with the IEEE 802.15.4-2011 UWB standard. It facilitates real time location of assets into an accuracy of +/- 10 cm using either two-way ranging TOA measurements or one-way TDOA schemes. Moreover, DW1000 spans 6 radio frequency bands from 3.5 GHz to 6.5 GHz and also supports data rates of 110 kbps, 850 kbps and 6.8 Mbps. The transmitting or receiving signal for the DW1000 is used as a semi-directive antenna. The signal will be transmitted in an arc towards the antenna's facing side. This means that the back of the antenna has poor signal. It is a factor that affects the accuracy of the distance measurement on the anchor and needs to be taken into account.

## III. UWB POSITIONING SCHEME

This section describes various methods of implementing UWB two-way ranging scheme between two nodes. In all of the schemes that follow one node acts as initiator, initiating a range measurement, while the other node acts as a responder listening and responding to the initiator, and calculating the range.

### A. *Single-sided TWO-way Ranging*

Single-Sided Two-Way Ranging (SS-TWR) involves a simple measurement of the round trip delay of a single message from one node to another and a response sent back to the original node. The operation of SS-TWR is as shown in Figure 2, where Tag initiates the exchange and Anchor A responds to complete the exchange and each device precisely timestamps the transmission and reception times of the message frames, and so can calculate time $T_{\text{round A}}$, and $T_{\text{reply A}}$ , by simple subtraction. The resultant TOA, $T_{\text{prorA}}$, may be estimated by the equation:

$$T_{propA} = \frac{1}{2}\left(T_{roundA} - T_{replyA}\right) \tag{1}$$

and then multiplied by the speed of light c can be obtained the distance $D_A$ between the two devices:

$$D_A = T_{propA} \times C \tag{2}$$

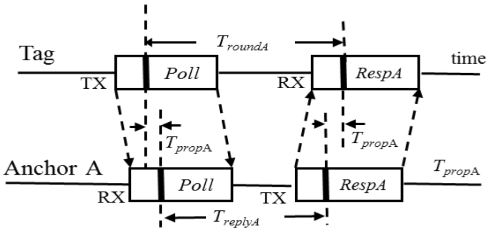


Figure. 2. Single station SS-TWR scheme

### B. *Double-sided Two-way Ranging*

Double-Sided Two-Way Ranging (DS-TWR), is an extension of the basic SS-TWR in which two round trip time measurements are used and combined to give a TOA result which has a reduced error even for quite long response delays. Figure 3 shows the DS-TWR of multiple stations for single tag [13]. It can be seen in the graph that the tag sends a poll message which is received by three anchors in the infrastructure who reply in successive responses with packets RespA, RespB and RespC after which the tag sends the Final message received by all three anchors. This allows the tag to be located after sending only 2 messages and receiving 3. Anchor A and the tag can calculate the corresponding time $T_{\text{propA}}$, and then multiplied by the speed of light c can be obtained the distance $D_A$ between the two devices:

$$T_{propA} = \frac{\left(T_{round1A} \times T_{round2A} - T_{reply1A} \times T_{reply2A}\right)}{\left(T_{round1A} + T_{round2A} + T_{reply1A} + T_{reply2A}\right)} \tag{3}$$

$$D_A = T_{propA} \times C \tag{4}$$

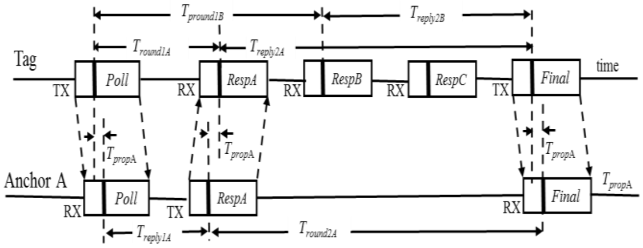


Figure. 3. Multiple station DS-TWR scheme

Similarly, between anchor B, anchor C and the tag can calculate the corresponding time $T_{\text{prorB}}$ and $T_{\text{prorC}}$, and then multiplied by the speed of light c can be obtained the distance of $D_B$ and $D_C$ between the two devices.

## IV. POSITIONING ALGORITHM

The concept of the Triangle Centroid Algorithm (TCA) was first proposed by Prof. Nirupama Bulusu of the University of Southern California [14]. The main reason is that if unknown nodes can receive signals from N anchor nodes, unknown nodes can consider as anchor nodes and the triangle centroid of the polygons formed by overlapping places [15]. However, the actual space has a high degree of complexity. In the real environment, the distance from the tag to the base station is slightly larger than the actual value. The circle drawn according to the TOA method not only intersects at one point but overlaps with the triangle area in the figure. Figure 4 shows the principle diagram of TCA where A, B, C are base stations, and T is the target tag.

The three-circle intersections obtained from the TOA method in all cases can locate in the same triangle as the previous section, and the target can estimate by triangle centroid algorithm. When F anchor leaves far away, the area of the three-circle interaction will not approximate as a triangle-shaped DEF. When TCA is used to estimate the target coordinates, the accuracy will decrease because of too narrow triangles. Therefore, we propose a TOA Triangle Midpoint Algorithm (TMA) to improve positioning accuracy.

From Figure 4, we can speculate that the tag position will be very close to the arc DF and arc EF so that the tag will fall in the upper right corner of the yellow area near the arc DE. Here, we propose to use the point M of the intersection DE as the method of positioning coordinates to improve the error of the TCA.

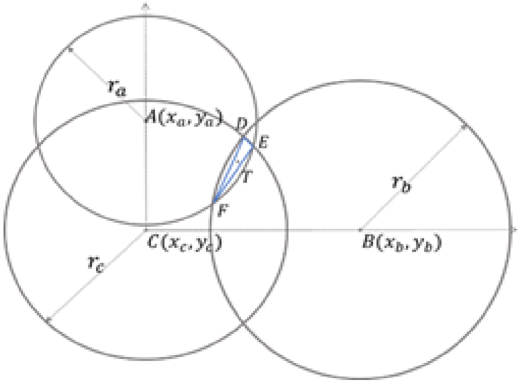


Figure. 4. The Principle diagram of the TCA

The coordinates of D($x_d$, $y_d$) shown in the Figure 3 can be inferred from the triangle formula

$$\begin{aligned}&\sqrt{(x_d - x_a)^2 + (y_d - y_a)^2} \le r_a\\&\sqrt{(x_d - x_b)^2 + (y_d - y_b)^2} = r_b\\&\sqrt{(x_d - x_c)^2 + (y_d - y_c)^2} = r_c\end{aligned} \tag{5}$$

Similarly, the coordinates of E($x_e$, $y_e$) are derived. Finally, we find the coordinates of the midpoint M($x_m$, $y_m$) of arc DE as coordinates of the target after positioning:

$$x_m = \frac{x_d + x_e}{2}, \; y_m = \frac{y_d + y_e}{2} \tag{6}$$

The TMA software processing flow is shown in Figure 5. When the base station starts up, it will enter the standby state and determine whether there is a message in the tag. If no signal is received, it will continue to standby. Otherwise, the base station will synchronize with the tag. After bi-directional ranging performs after synchronization, the distance data is obtained. The TOA positioning calculation is performed using the JAVA programming language. The next step is to establish a coordinate system and place the three groups of base station positions as the center of the circle at the origin (0, 0), the X-axis point (X, 0) and the Y-axis point (0, Y). The distances measured by the three groups of base stations and tags plot as a radius, and then the TMA is used to locate and calculate the intersection points D and E between the origin circle and the other two circles. Second, calculate the midpoint M between the two points D and E, and finally, use M as the positioning coordinate. After ending the algorithm, determine if the tag is offline. If the tag is disconnected, the base station returns to the standby state. If the tag continues to transmit, the bidirectional ranging is continued.

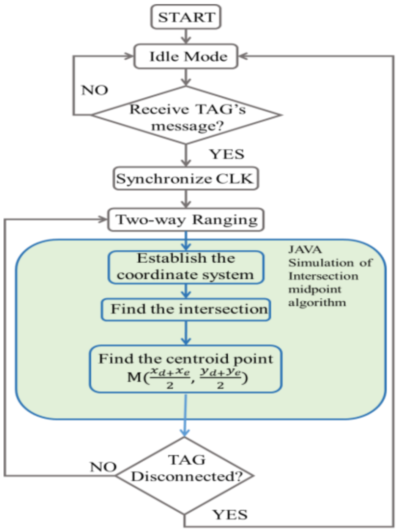


Figure. 5. Flow chart of TMA scheme

## V. EXPERIMENTAL SETUP AND RESULTS

In this experiment, a 12×8 coordinate system was established on a lab room space of 732cm×488cm×220cm by a 61cm×61cm square grid on the ceiling. The base station placed in the three corners of the lab and connected it to the computer, and then measure the distance of the tag unilaterally as shown in Figure 1. The measured distance is estimated by the of the computer positioning algorithm. Finally, the positioning error is calculated by the coordinate system.

### *A. One-to-One Ranging Test*

One-to-one obstacle-free distance test between devices was first performed. The measured actual distance starts from 50 cm, and then an experiment is conducted every 50 cm. The test results were recorded, and 30 test values were averaged as test values until the actual distance was up to 10 m. A total of 20 one-to-one accessibility measurements are performed. Figure 6 is the error calculated from the one-to-one accessibility test value versus actual value. It can be found that the error is less than 6% at a distance which is less than 6 m. The converted error is approximately 20 to 30 cm. When the distance is more than 6 meters, the error starts to increase gradually.

Since the one-to-one ranging distance between devices directly affects the positioning accuracy, we correct the measured values from 0.5m to 10m interval for every 0.5m. The value is corrected as the demarcation point between the minimum value of the subsequent segment and the maximum value of the previous segment; for example, the average value of 30-data measured at distance of 6.5m is 6.889m, and the minimum value is 6.68m. The measured error is 0.389m. Next, the maximum value of 30-data measured at distance of 6m is 6.39m. Therefore, we can calculate that the demarcation point will be (6.68+6.39)/2 =6.54m. When the measured distance is greater than 6.54 m, the measured value must be deducted 0.389m. The error of the one-to-one distance test after correction is about 0.1m, and the accuracy is much improved.

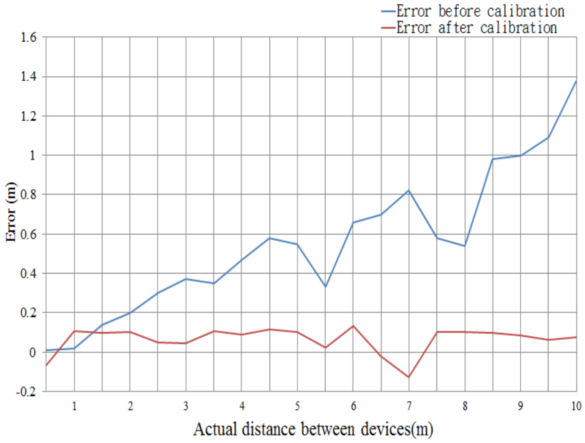


Figure. 6. Calibration of localization error

The height of the tag on the Z axis will affect the accuracy of the distance measurement. When the distance between two nodes on the XY plane is 6m, the error is 0.082m under the height of 1m on the Z axis. And when the distance between two nodes is 1m, the error is 0.414m under the height of 1m on the Z axis. Therefore, in order to improve the accuracy of the three-dimension measurement, tag position should be as far as possible with three anchors in the same plane.

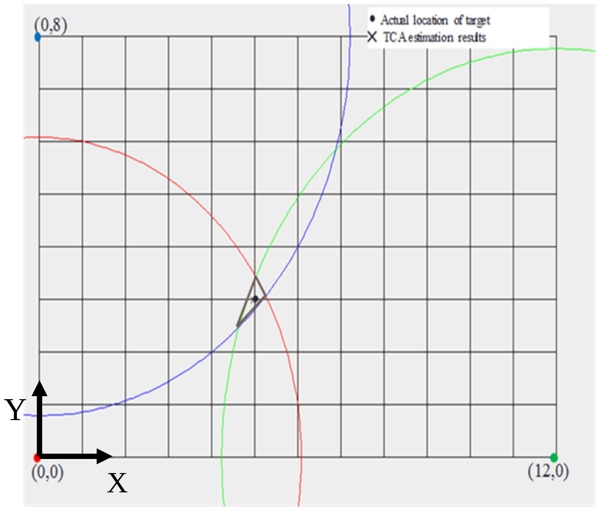


Figure. 7. TCA localization of tag at (5, 3)

## B. *TCA Localization Test*

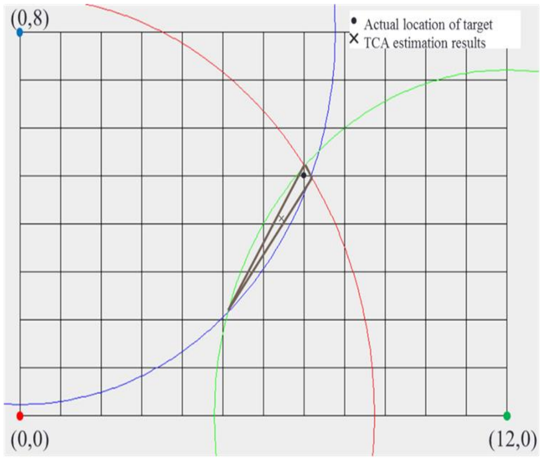


Figure. 8. TCA localization of tag at (7, 5)

TABLE I. LOCALIZATION ERROR FOR VARIOUS ALGORITHMS

| Coordinates | Error (cm) of triangle centroid algorithm | Error(cm) of triangle midpoint algorithm | Error (cm) of inner triangle centroid algorithm |
|---|---|---|---|
| (1,2) | 23 | 26.19 | 20.22 |
| (3,1) | 3.31 | 10.85 | 10.84 |
| (3,6) | 24.3 | 8.048 | 7.88 |
| (5,3) | 1.92 | 16.99 | 14.58 |
| (7,3) | 19.95 | 13.59 | 12.11 |
| (7,5) | 63.68 | 8.57 | 8.54 |
| (10,7) | 188.45 | 14.48 | 14.48 |
| (11,3) | 80.49 | 10.03 | 9.98 |
| (11,5) | 145.55 | 6.93 | 6.93 |
| (12,6) | 202.96 | 13 | 12.92 |
| Average error (cm) | 75.36 | 12.87 | 11.85 |
| Standard deviation | 72.91 | 5.36 | 3.76 |

We placed three base stations on the origin (0, 0), Y-axis (0, 8), and X-axis (12, 0); the tag is placed at different points in the coordinates. When a positioning coordinate of the tag is located at (5, 3) shown in Figure 7, the calculated positioning coordinate after TCA execution is (4.97, 2.99). The error is converted to approximately 1.92 cm; however, when the positioning coordinate of the tag is located at (7, 5) shown in Figure 8, the calculated positioning coordinate after TCA execution is (6.43, 4.12). The actual error is converted to approximately 63.68 cm. Finally, when the positioning coordinate of the tag is located at (11, 5), the calculated coordinate after TCA is (9.73, 2.98). The actual error is converted to about 145.55 cm. From test results when the tag is located far away from the XY coordinates, the positioning using the TCA scheme will be invalid. The main reason is that the triangle completed by the TCA is too narrow, resulting in the measurement error is greater when the tag is far away from the XY coordinates. The detailed experimental results of 10 coordinate points by TCA scheme are shown in Table 1.

### C. *TMA Localization Test*

To solve the problem when the tag is placed on the X and Y coordinates with larger values, the triangle is too narrow and long to decrease accuracy shown in Figure 8. Therefore, we propose a solution for the midpoint of the triangle. The intersection of the red circle and the blue circle and the intersection of the red circle and the green circle are selected, and the middle point is taken as the rear coordinate after positioning shown in Figure 9. This can avoid the large change of the blue circle and the green circle.

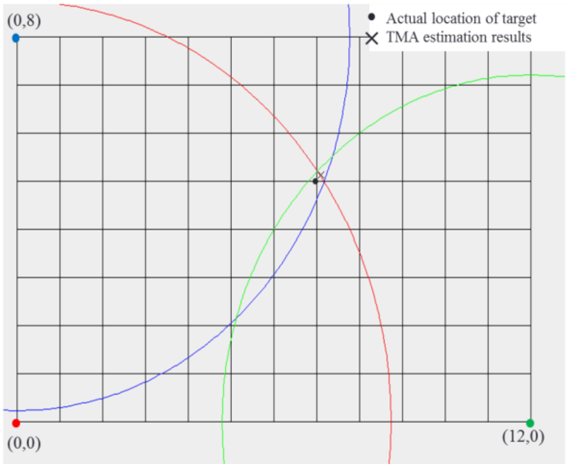


Figure. 9. TMA localization of tag at (7, 5)

When a positioning coordinate of the tag is located at (7, 5) shown in Figure 9, the calculated positioning coordinate is (7.09, 5.1). The error is converted to about 8.57 cm. When the positioning coordinate of the tag is located at (11, 5) shown in Figure 10, the calculated positioning coordinate is (11.1, 5.04), and the error is converted to about 6.93 cm. The detailed experimental results of 10 coordinate points by TMA scheme are shown in Table 1.

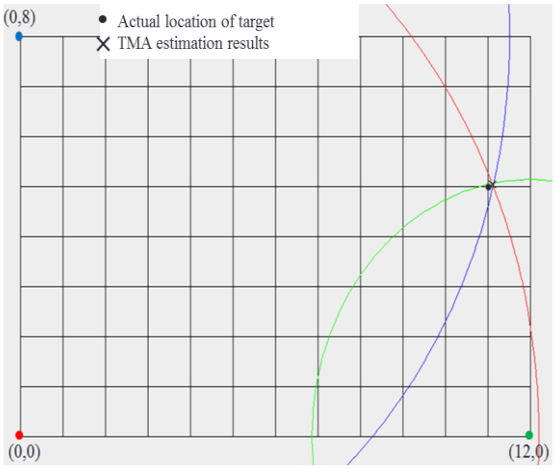
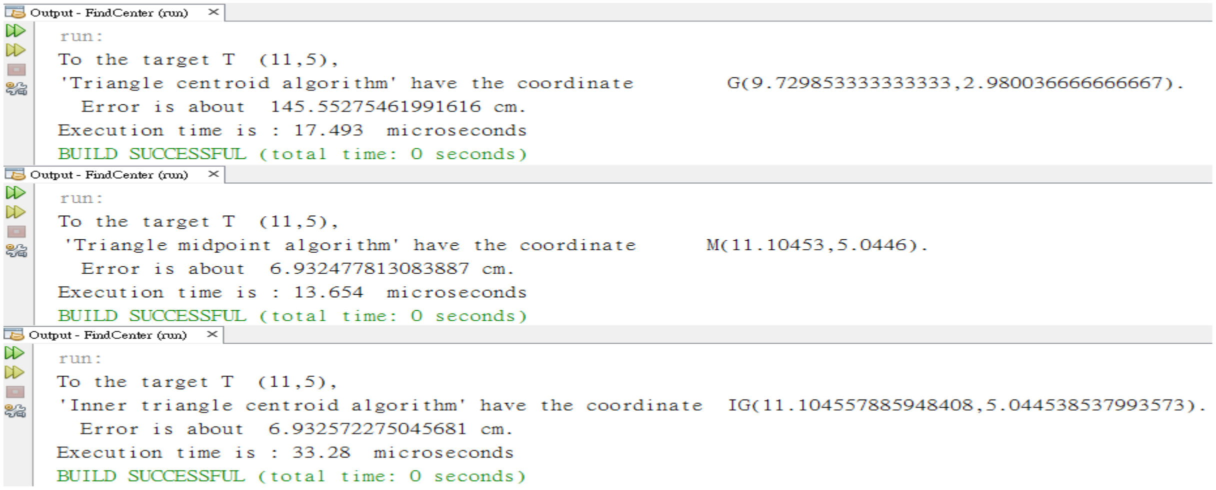


Figure. 10. TMA localization of tag at (11, 5)

### D. *Comparison of Algorithm*

To understand the performance of proposed TMA, we write a computer program to compare localization error for various algorithms. The Inner Triangle Centroid Algorithm (ITCA) [16] published by Nantong University of China. The comparison error is the distance between the coordinates of the tag calculated by each algorithm and the actual position of the target. A total of ten points in the ordinates take for ranging experiments. Finally, the average error and standard deviation figure out. It can be seen from Table 1 that the accuracy of the ITCA is the highest with an average error of approximately 11.848 cm. The accuracy of



```
run:
To the target T  (11,5),
'Triangle centroid algorithm' have the coordinate      G(9.729853333333333,2.980036666666667).
  Error is about  145.55275461991616 cm.
Execution time is : 17.493  microseconds
BUILD SUCCESSFUL (total time: 0 seconds)
```

```
run:
To the target T  (11,5),
 'Triangle midpoint algorithm' have the coordinate     M(11.10453,5.0446).
  Error is about  6.932477813083887 cm.
Execution time is : 13.654  microseconds
BUILD SUCCESSFUL (total time: 0 seconds)
```

```
run:
To the target T  (11,5),
'Inner triangle centroid algorithm' have the coordinate  IG(11.104557885948408,5.044538537993573).
  Error is about  6.932572275045681 cm.
Execution time is : 33.28  microseconds
BUILD SUCCESSFUL (total time: 0 seconds)
```

Figure. 11. Computation time for different algorithms

ISBN: 978-1-61208-653-8

TMA is slightly lower than that of the ITCA. The average error is about 12.869 cm. Moreover, the TCA performs well in some coordinates at the positioning (3, 1) and positioning (5, 3). However, when the target is farther away from the origin, the TCA cannot accurately locate the target. The average error is 75.36 cm.

The computation time of the algorithm at the positioning (11, 5) shown in Fig. 11 that the algorithm of the proposed TMA is simple and requires only 13.654 μs for positioning; and the algorithm of ITCA is comparatively complexity, therefore, takes 33.28 μs to execute it once. It can be seen that the accuracy of proposed algorithm is very high. At the same time, the simple calculation process can be reduced the computation time.

## VI. CONCLUSION

This study experimented and demonstrated a high-precision indoor positioning system based on time-of-arrival technique and triangle midpoint localization algorithm in a limited indoor space. We characterized existing ultra-wideband localization algorithm schemes and explored a high-accuracy algorithm method. According to experimental results that the accuracy of the one-to-one ranging between the anchor and a tag is almost within 10 cm. Moreover, the average error of the ultra-wideband positioning systems is about 12.87 cm to use the triangle midpoint localization algorithm in a laboratory space of 732cm×488cm×220cm. Finally, we also compare the execution time of various positioning algorithms. The experimented results show that the proposed algorithm has a simple calculation process which can reduce the computation time and reach a real-time process.

The security aspects in the positioning can be treated at the positioning algorithm. Cryptographic techniques could be used for improving the security and privacy of location information in the actual applications. This issue still largely lacks sufficient solutions and can be expected as a future work item.

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