An Experimental Correction Model for UWB Through-the-Wall Distance Measurements

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***Abstract*—this paper presents error analysis and error correction for UWB signal based ranging using P410 RCMs (PulsON 410 Ranging and Communication Modules). We propose a theoretical model for precise ranging in complex indoor environments. The model intends to correct the range error incurred by rich multipath propagation and signal penetration through walls. The experimental results show that through the model based error correction, the distance measurement accuracy can be improved significantly.**

***Index Terms*-UWB, P410 RCMs, range error correction model**

I. INTRODUCATION

UWB (Ultra-Wideband) is a promising technology especially widely investigated for short-range communications and indoor location [1]. With the large bandwidth, UWB signal has a high resolution in time that contributes to resolve multipath components and improve the ranging accuracy [1]. This is because impulse-based UWB signal is single-cycle pulse signal with an extremely low duty cycle. UWB also owns a high signal-to-noise ratio (SNR) such that the ranging error can be much smaller compared with narrowband systems. Besides, UWB signal possesses the capability of penetrating through obstacles [2]. Due to these prominent properties of UWB signals, Federal Communications Commission (FCC) in the USA granted UWB for the unlicensed use in 2002 [3]. Since then, UWB technology has drawn great attention from both academia and industry especially in indoor location. UWB has been studied for applications in various scenarios, including assisted living [4], smart home [5], and location and tracking [6].

Since time of arrival (TOA) measurement accuracy is directly affected by signal bandwidth and usually a higher bandwidth will produce more accurate TOA measurement, we can use UWB for precise ranging and positioning by TOA or TDOA (Time Difference of Arrival). However, for the common indoor environments, such as office building, teaching building, and hospital building, UWB signal is interfered by obstacles and walls, resulting in significant degradation in positioning accuracy. Reference [7] proposes an experimental model for UWB distance measurements in corridors. This model describes the relationship between ranging error and distance. However, comparing with the ranging error caused by corridors, the ranging error caused by penetrating through walls is much greater. As a fact, the capability of penetrating obstacles is a major advantage of UWB signal. With the advantage, the number of sensor nodes can be reduced significantly for an indoor location based application.

In this paper, we propose a new model for UWB through-the-wall distance measurement. The model not only takes account of the ranging error caused by corridors, but also takes ranging error caused by a wall into account.

The remainder of this paper is organized as follows. Section II briefly describes the hardware equipment used in our experiment, namely the P410 RCM manufactured by Time Domain [8]. In section III, we introduce the proposed model. Finally, in section IV, we give a conclusion for this paper.

II. PULSON 410 RCM PLATFORM

The P410 RCM as shown in Fig. 1 is a multi-purpose platform based on UWB technology that can be used for peer-to-peer distance measurement, data communication, and as part of a ranging network [8]. Besides, it can also measure channel impulse response and serve as a monostatic, bistatic, or multistatic radar. The P410 RCM owns a RF band spans from 3.1GHz to 5.3GHz, with a center frequency of 4.3GHz. Each module is composed of a single small board and a UWB antenna. Before starting work, we need to connect P410 RCMs to energy sources. We also can program P410 RCM using C or Matlab libraries provided by the producer.

The P410 RCM uses TW-TOF (Two-Way Time-of-Flight) to accurately measure the

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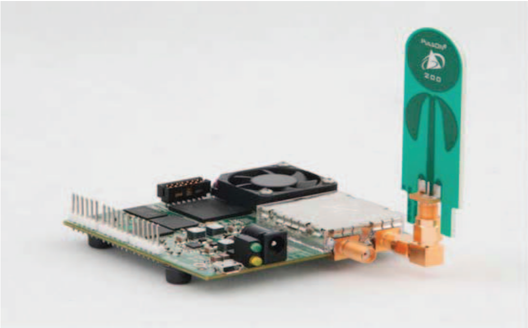

Figure 1. P410 RCM hardware with an antenna.

distance between two units with update rate up to 125Hz [8].

Fig. 2 shows the diagram of distance measurement procedure by TW-TOF, producing the PRMs (Precision Range Measurements). In addition, P410 RMCs also provide other two kinds of distance values —CRE (Coarse Range Estimate) and FRE (Filtered Range Estimate). During one measurement, one module (referred to as requester) sends a ranging message packet to another module (referred to as responder), and the responder returns a message packet to the requester after receiving the message. The range measurement is finished in a host (e.g. a laptop or a microprocessor) that the requester has to be connected to. All the data are recorded in the log files.

III. AN EXPERIMENTAL MODEL

In this section, we analyze the characteristics of distance measurement error when ranging in corridors, and the ranging error caused by signal propagation through a wall or multiple walls. A model is then proposed based on the analysis to describe the relationship between ranging error and distance. Two P410 RCMs, one as requester and the other as responder, are used in the experiment. Both the two modules are fixed on the same plane about 1.5 meters above the ground. Every distance is measured one thousand times continuously.

A. *Experiments on the Relationship between Error and Distance*

The experiment was first conducted in corridors on the 3rd floor and 4th floor of a teaching building in Wuhan University. The distances between the requester and responder are selected to be between 1 meter and 19 meters.The experiment was then conducted in the basement garage of a Library in Wuhan University, using the same range of distances to compare the difference of ranging error in different scenarios. For each distance and fixed positions of the requester and responder, 1000 consecutive distance measurements are produced and the measurement errors are calculated. Fig. 3 and Fig. 4 show the mean and standard deviation of the distance measurement errors, respectively.

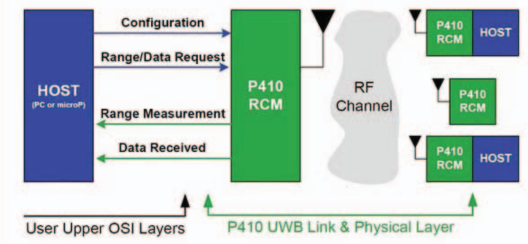

Figure 2. Illustration of P410 RCM system interface.

As shown in Fig. 3, ranging error means are generally stable for the library garage scenario, mostly ranging between 30mm and 40mm when distance is greater than 3 meters. However, for the teaching building scenario, ranging error means tend to increase with the increase of range. The difference could be due to the fact that the garage is much wider than the corridors, so that the multipath interference in the corridors is more severe than that in the garage.

Since ranging error mean can reflect the central tendency of ranging errors, we can roughly model ranging error based on ranging error means. Meanwhile, it can be seen that the ranging errors are large in all three scenarios when the distance is one meter. That is because if the transmitter and receiver are very close to each other, the strength of the transmitted signal is so strong that the received signal strength will saturate or the receiver will compress the received signal strength. In compression, the bias of the range readings will change and will become slightly non-linear. However, the ranging measurement algorithm in the device assumes that the radio link is being operated in

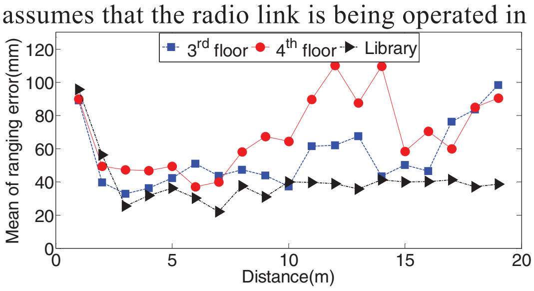

Figure 3. Mean of ranging error versus distance in three different scenarios.

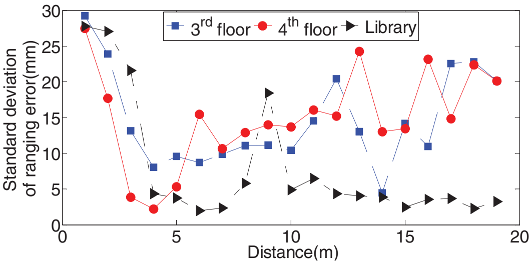

Figure 4. Standard deviation of ranging error versus distance in three different scenarios.

its linear range [8]. As a result, the accuracy of range under compression will be compromised.

B. Experiments on the Through-the-Wall Range measurement

In the experiment, we chose 10 walls from 4 different scenarios (library garage, teaching building, office building, and student dormitory). For each measurement, the sum of the distance from requester to the wall and that from the wall to responder is one meter [1]. Thus, the true distance between requester and responder is one meter plus the thickness of the wall. Table 1 shows the mean and standard deviation of ranging errors from the four different scenarios.

We can observe that the ranging error means are nearly equal for the same scenario. Strength or power attenuation of radio signals including UWB signal through a wall is associated with the properties of the wall, including the thickness, material, and moisture content [9][10]. The consistency in error means for the same scenario indicates the very similar thickness, material and moisture content of the wall over the tested locations. The relatively large variations in the office building as well as in the student dormitory may result from the wall's property variation as well as the environmental variation around the wall.

Next, we analyze the relationship between ranging error and the angle between the wall and signal propagation path. The same wall in the teaching building is used and three different angles are tested as shown in Fig. 5. The mean and standard deviation of ranging errors are shown in Table 2.

As displayed in Table 2, for the same wall, the difference of ranging errors under different angles is within 5 cm. Thus, for low precision positioning, we can regard the through-the-wall ranging error as a constant roughly.

TABLE I
THE MEAN AND STANDARD DEVIATION OF RANGING ERRORS FROM DIFFERENT SCENARIOS

Scenario	The thickness of Walls (cm)		Mean (mm)	Standard deviation (mm)
Library	L_A	30	574.3	24.9
	L_B	30	569.2	28.7
Teaching building	T_A	25	247.5	20.1
	T_B	25	249.4	20.8
	T_C	25	232.1	26.7
Office building	O_A	30	279.4	33.1
	O_B	30	203.9	28.5
	O_C	30	235.5	26.9
Student dormitory	S_A	30	254.1	5.5
	S_B	30	299.6	27.8

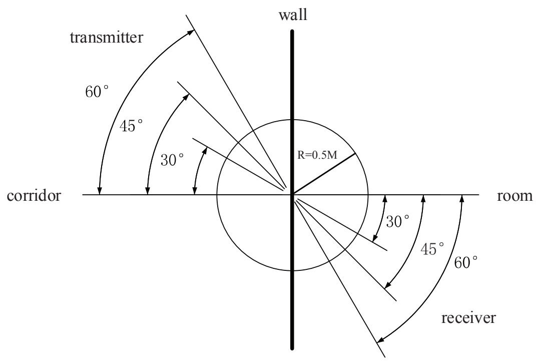

Figure 5. The angel between signal propagation path and the wall.

TABLE II
THE MEAN AND STANDARD DEVIATION OF RANGING ERRORS OF DIFFERENT ANGLES

Angle(degree)	0	30	45	60
Mean(mm)	232.0	213.9	191.6	204.4
Standard deviation(mm)	26.7	26.1	21.6	5.7

Naturally, with the increase of walls, UWB signal strength will decay more quickly until the signal cannot be detected. In our experiments, we found that the responder cannot receive signal sometimes after the signal travels through two thick walls （approximately 30cm each）. Although the signal can penetrate more walls occasionally, the received signal quality or SNR is usually rather low. Therefore, we think UWB signal only can penetrate through one thick wall in the scenarios tested [2].

C. The Proposed Error Model

According to the above analysis, on one hand, we know the ranging error is related to distance. On the other hand, if UWB signal penetrates through a wall, range measurement will produce another nearly constant error. Furthermore, all ranging errors in our experiments are positive and hence the distance measurement is longer than the true distance. Thus, we propose a distance measurement model as in (1).

$$\begin{cases} \hat{r} = r - \left(a\tilde{r} + b\right) - w; & with\ a\ wall; \\ \hat{r} = r - \left(a\tilde{r} + b\right); & without\ walls. \end{cases} \tag{1}$$

where $\tilde{r}$ denotes the true distance, r denotes the distance measurement of $\tilde{r}$, $a\tilde{r}+b$ denotes the ranging error that is associated with the true distance $\tilde{r}$, $\hat{r}$ denotes the corrected distance measurement, and w denotes the ranging error caused by a wall. In fact, $\tilde{r}$ is unknown, so $\tilde{r}$ is replaced with $\hat{r}$ for

[1] Comparing with the effect of wall, we can ignore the effect of saturate. However, to obtain more accurate modeling, the distance between requester and responder should be larger than 4 meters.

[2] In the following proposed model, if we get signal that has penetrated through more than one wall, we will exclude the range measurement from position determination.

simplicity.

$$\begin{cases} \hat{r} = (r - b - w)/(1 + a); \ \text{with a wall}; \\ \hat{r} = (r - b)/(1 + a); \quad \text{without walls}. \end{cases} \quad (2)$$

30 range measurements between 5 and 19 meter were collected in the corridors on the 3rd floor and the 4th floor of the teaching building altogether. Using the least squares (LS) technique, we then obtain the estimate of coefficients a and b as:

$$[a,\ b] = [0.0028,\ 0.0306]^T. \quad (3)$$

After obtaining the coefficient a and b, we compare the mean of ranging errors with the values fitted by LS as shown in Fig. 6. It is easy to observe that the linear approximation is appropriate. Relatively large difference occurs for part of distances between 10 and 16 meters. That is because the responder happens to be located between two gates and the multipath interference could be more serious.

Based on the average of the three means (see Table I), w is simply given as:

$$w = \frac{1}{3}(0.2475 + 0.2494 + 0.2321) = 0.243. \quad (4)$$

By substituting (3) and (4) into (2), the final model is produced as in (5).

$$\begin{cases} \hat{r} = (r - 0.2736)/1.0028 \quad \text{with a wall}; \\ \hat{r} = (r - 0.0306)/1.0028 \ \text{without walls}. \end{cases} \quad (5)$$

In order to verify the performance of the proposed model, two through-the-wall range measurements are conducted. Table 3 shows the RMSE of the original measurement range r and the model based corrected range $\hat{r}$.

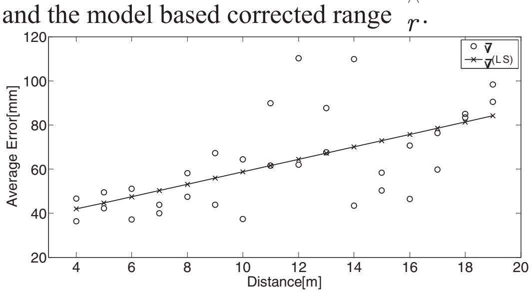

Figure 6. The values of error mean $\bar{v}$ and its linear approximation $\bar{v}^{(LS)}$.

TABLE III
THE RMSE OF r AND $\hat{r}$

True distance [mm]	3535	6015
$RMSE_{origin}$ [mm]	292.7	378.8
$RMSE_{model}$ [mm]	11.7	54.8

V. CONCLUTION

The capacity of penetrating one or more obstacles is a major advantage of UWB signal, comparing with other narrowband signals, which can be favorable for indoor ranging, localization and tracking. In this paper, we have proposed a range correction model for UWB through-the-wall localization in the teaching building scenario. Through the model based range measurement correction, ranging accuracy and hence positioning accuracy can be improved significantly. Ongoing work will focus on the evaluation of the model through conducting more experiments with different pairs of the UWB RCMs.

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