A high-accuracy indoor positioning system based on UWB

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Abstract. In this paper, a high-accuracy indoor positioning system based on the ultra-wideband (UWB) technique is proposed. The proposed system uses a simple ranging process to obtain the distance between the mobile node and the fixed base stations. Besides, an improved time of arrival (ToA) algorithm with Kalman filtering is proposed to improve the positioning accuracy. Measurements have been performed in the real indoor 13m*7.6m environment with many obstacles and the root-mean-square error (RMSE) is less than 0.3m. The proposed system offers a wide range of application in robotics, industrial automation, post-sorting system and so on.

1 Introduction

Localization systems with high accuracy is urgently needed for both commercial and governmental interests, with the popular of location-based services [2]. According to geolocation information, localization techniques can be classified into two categories: outdoor localization and indoor localization. Outdoor technologies like Global Positioning System (GPS), has been applied into many applications. But they cannot provide accurate indoor geolocation, which has its own independent market and unique technical challenges [12].

Many solutions have been proposed based on various kinds of information, e.g. ToA [1, 6, 11], time difference of arrival (TDoA) [5], phase of arrival (PoA) [3], phase difference of arrival (PDoA) [13], received signal strength indicator (RSSI) [7], etc. Localization algorithms can be simply classified into two categories: triangulation-based methods and pattern matching based methods.

The major challenge in the indoor positioning is that there are many obstacles. RSSI algorithm [10] is difficult to distinguish the small angle change of the mobile nodes because of the multipath disturbance. [9] uses a frequency modulated continuous wave (FMCW) based signal as the carrier but can only work well under the ideal fading model. [8] positioning is achieved by combining vector network analyser with the angle of analysis signal wave, which requires special signal angle antenna. [4] obtains a positioning accuracy less than 1.68m, but the bandwidth of 2GHz is required.

Due to the ability to penetrate obstacles and fine ranging resolution, UWB offers great advantage for achieving high positioning accuracy in indoor environments [2]. In this paper, an indoor positioning system with improved ToA based on UWB is proposed. The paper is organized as follows. To begin with, the system including the UWB signal and the ranging method is described in section 2. Then we describe the

improved positioning algorithm with Kalman filtering in section 3. In section 4, both the motion trajectory and the positioning accuracy are measured to verify the performance of proposed positioning system. Finally, the conclusion is drawn in section 5.

2 System Design

2.1 The UWB signal

American Communications Commission officially decided in 2002 to open up the 3.1GHz-10.6GHz spaces for UWB to be used for the indoor communication. Federal Communication Commission (FCC) defines the UWB signal as:

$$\frac{(f_H - f_L)}{f_c} \geq 20\% \quad \text{or} \quad f_H - f_L \geq 500\text{MHz} \quad (1)$$

Where f_H and f_L are the upper frequency and lower frequency, when the peak power decreases to 10dB, respectively. And $f_c = \frac{f_H + f_L}{2}$ is the center frequency. According to Shannon's theorem, the large channel bandwidth can improve the capacity of the channel. The signal bandwidth of UWB system can be as high as 500MHz to 7.5GHz, thus UWB system can achieve high-speed transmission, as high as several hundred Mb/s to 1Gb/s in the short distance, even with high signal-to-noise ratio (SNR). Fig. 1 shows the comparison between the UWB and narrowband signals.

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Fig.1. The comparison between the UWB and narrowband signals.

UWB system directly uses ultra-narrow pulse to excitation antenna without carrier. It is easy for the pulse generator to generate the bell-shaped pulse, which is similar to the shape of the Gauss function wave. Thus, the most commonly pulse waveform for the UWB system is the Gauss pulse, and expression of the Gauss pulse in the time domain is:

$$f(t) = \pm \frac{\sqrt{2}}{a} \exp\left(-\frac{2\pi t^2}{a^2}\right) \quad (2)$$

where $\alpha^2 = 4\pi\sigma^2$ is the pulse factor, and σ^2 is the variance. The pulse factor determines the width of the pulse. The smaller the pulse factor, the narrower the pulse width will be, and vice versa. The pulse is usually designed to be as a non-current component, which can increase the pulse radiation. The second derivative of Gaussian pulse is mostly used as UWB signal waveform.

The UWB signal transmitting module in this paper is implemented based on the DW1000 chip, which supports the IEEE 802.15.4-2011 UWB standard. The system uses the binary phase modulation (BPSK) and the expression of BPSK is given by:

$$s(t) = \sum_{k=-\infty}^{\infty} b_k p(t - kT_f) \quad (3)$$

where $b_k \in \{-1, 1\}$ is the modulation signal, $p(t)$ is the pulse signal and T_f is the pulse period.

Table 1. Poll message

21	22	23	24 and up
1	1 octet	1 octet	0 to 88 octets
function	temp	vbat	optional user payload
0x21	0xTT	0xVV	-

Table 2. Response message

21	22	23	24	25 and up
1 octet	1 octet	1 octet	1 octet	0 to 88 octets
function	activity	send ToF report	activity parameter	optional user payload
code				
0x10	0x02	0x01	0x00	-

Table 3. Final message

21	22 to 26	27 to 31	32 to 36	37 and up

1 octet 1 octet	5 octet 5 octet	5 octet 5 octet	5 octet 5 octet	0 to 88 octets
function code	poll message TX time -stamp	response message RX time -stamp	embedded predicted TX time -stamp final	optional user payload
0x29	-	-	-	-

2.2 Ranging method

The signal frame is used in this paper for the communication transmission between the mobile node and the fixed base stations. Since the positioning system needs at least three fixed base stations to carry out the distance for the mobile node, four different frame structures, poll message, response message, final message and report message, are used for the handshake communications between base stations and mobile node. The first is the poll message, as shown in the table 1. Poll message can only be sent by the mobile node for the first communication, which is used to initialize the ranging method. Response message is sent by the fixed base stations. Once receive Poll message, the stations will send Response message, which includes the function code of 0x21 and a string of 8 bits ToF information, as shown in table 2. The final message includes three sets of 8-bit timestamps and optional user payload. Report message is similar to the information structure of the Poll message, but it contains four calculated timestamps. The ranging process can be regarded as the three handshakes protocol between the mobile node and the base stations. The well ranging requires precise TX and RX information. When the base station communicates with the mobile node, it needs to maintain a good synchronization. The ranging process is as shown in the fig.2.

Fig.2. The ranging process.

Each handshake process contains an event stamp. When the handshake process finishes, the time of flight (TOF) is obtained by calculating all the timestamps.

$$\text{TOF} = \frac{1}{4}(2T_{\text{RR}} - T_{\text{SP}} - 2T_{\text{SR}} + T_{\text{RP}} + T_{\text{RF}} - T_{\text{SF}}) \quad (4)$$

The distance between the mobile node and the fixed base station can be obtained by multiplying TOF with the speed of light.

3 The improved positioning algorithm

3.1. ToA

The positioning algorithm used in this paper is based on ToA, which is a time delay positioning method. All arrival delay is the propagation time between signals. The positioning can be achieved by calculating the distance between the mobile node and the base station. Making multiple circles by using the fixed base stations as the centers and the measured distances as the radius, the multiple circles has an intersection and the intersection point is the theory position of the mobile node. To achieve this position, at least three rounds are needed, that is why three fixed base stations are needed, as shown in Fig.3. According to Fig.3, the position equations can be obtained as:

$$d_i = \sqrt{(x_i - x)^2 + (y_i - y)^2} \quad (5)$$

where (x, y) , (x_i, y_i) ($i = 1, 2, 3$) and d_i are the position of the mobile node and the fixed base stations and the measured distances, respectively. The equation is not a set of nonlinear equations, but they can be reduced to a linear equation group and obtain the solution (x, y) .

Fig.3. The diagram of ToA

It is necessary to establish an index to correctly evaluate the positioning accuracy. The index used in this paper is the root-mean-square error (RMSE), which is a frequently used measure of the differences between predicted values and the measured values. In the actual measurement, since the number of observations is always limited, the measured value can only be replaced by the most accessible value and the square root error is very sensitive to the large or small error in a set of

measurements. because RMSE is the square root of the mean square error, RMSE can well reflect the accuracy of the measurement. RMSE of the positioning accuracy is given by:

$$\text{RMSE} = E\sqrt{(x - \hat{x})^2 + (y - \hat{y})^2} \quad (6)$$

3.2 Kalman filtering

As the excellent predictability, Kalman filtering is used to improve the positioning accuracy in this paper. Kalman filtering is an algorithm that optimally estimates the state of the system by using a series of measurements observed based on linear system state equation. Because the measurements observed contain statistical noise and other inaccuracies, the optimal estimation can also be considered as a filtering process. The state and measurement functions of the Kalman filtering are as follows:

$$s(k+1) = As(k) + \Gamma w(k) \quad (7)$$

$$z(k) = G(k)s(k) + v(k) \quad (8)$$

From Eq. 7 and Eq. 8, the states at k time and $k+1$ time

are linked by the state function. Therefore, with the given

initial values of the state vector and the estimation error, the real-time of state vector can be estimated by the iteration. There are two steps in the iteration of Kalman filter. The first is the prediction of the state as follows:

$$\hat{s}\left(\frac{k}{k-1}\right) = A s(k-1) \quad (9)$$

$$P\left(\frac{k}{k-1}\right) = A P(k-1) A^T + \Gamma Q(k) \Gamma^T \quad (10)$$

$$K(k) = P\left(\frac{k}{k-1}\right) G(k)^T \left[G(k) P\left(\frac{k}{k-1}\right) G(k)^T + R(k) \right]^{-1} \quad (11)$$

The second is the correction of the measured values.

$$\hat{s}(k) = \hat{s}\left(\frac{k}{k-1}\right) + K(k) \left[z(k) - G(k) \hat{s}\left(\frac{k}{k-1}\right) \right] \quad (12)$$

$$P(k) = [I - K(k)G(k)] P\left(\frac{k}{k-1}\right) \quad (13)$$

where $\hat{s}(k/k)$ and $\hat{s}((k+1)/k)$ are the state estimation and state prediction vectors, respectively, $P(k/k)$ and $P((k+1)/k)$ are the covariance matrix of estimation error and forecast error, respectively, and $K(k)$ represents the Kalman gain. As shown in the Fig. 4, compared with the traditional ToA, the simulated RMSE becomes much better for the improved ToA with Kalman filtering. RMSE is close to 0 when the sample increases to 100. The simulation results in Fig. 5 also shows that the improved ToA with Kalman filtering has a better performance in the field of mobile node tracking compared to the traditional ToA, which means that the accuracy is improved. Besides, the measured values tend to be stable when the sample increases.

Fig.4. RMSE simulation.

4 Result and Discussion

To verify the performance of proposed indoor positioning system, UWB system contained a mobile node and three base stations is considered. The experiment is done in a 13 m*7.6 m environment. The mobile node is marked as T0.

Fig.5. Tracking simulation.

Fig.6. The motion trajectory.

The three fixed base stations are marked as A1, A3 and A4. As shown in the Fig. 6, the purple line is the trajectory of the mobile node and the experiments are conducted in a complex indoor environment with many obstacles. From the measurement results, a small turn of the mobile node can be displayed in the motion trajectory, thus proposed indoor positioning system

based on UWB has excellent properties. Besides, when the communication is blocked by the obstacles, the not line of sight (NLOS) error is generated, resulting in the small fluctuations in the motion trajectory.

In the experiment, the true position of the mobile node is measured and compared with the estimated position by the system to calculate the RMSE. As shown in Fig. 7, the positioning error of proposed indoor positioning

Fig.7. Measured RMSE.

system based on UWB is less than 0.3 m when the sample is larger than 40, which can meet the needs of the indoor position very well.

5 Conclusion

A high-accuracy indoor positioning system is presented and measured in this paper. UWB technique is used as the ability to penetrate obstacles and fine ranging and the ranging process is simplified to reduce the complexity. Particular attention has been taken to improving the ToA algorithm by utilizing the Kalman filtering, and an outstanding measured RMSE of 0.3m is achieved. Owing good performance, proposed system shows its superiority in the indoor location-based service.

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