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Enhancing Accuracy of UWB-based Indoor Positioning System using Kalman Filtering

Abstract. *The purpose of this research was to evaluate the effect of Kalman filtering on the indoor positioning system based on short-range radio technology. The contribution consists of an open-source implementation of a positioning system that achieves remarkable results in the real world scenario. Compared to capabilities of the original device and software, the presented approach reduces errors and shortens positioning times. While the study is focused on a stationary situation, its practical application is not limited to this scenario.*

Streszczenie. *Celem przedstawionych badań była ocena wpływu filtrowania Kalmana na system pozycjonowania wewnątrz pomieszczeń, oparty na technologii radiowej krótkiego zasięgu. Wkład autorów to otwartoźródłowa implementacja systemu pozycjonowania, która osiąga znaczące wyniki w rzeczywistym zastosowaniu. W porównaniu z oryginalnym urządzeniem i oprogramowaniem, przedstawione podejście zmniejsza błędy i skraca czas pozycjonowania. Chociaż badanie koncentruje się na sytuacji stacjonarnej, jego praktyczne zastosowanie nie ogranicza się do tego scenariusza.* ***(Zwiększenie dokładności opartego na UWB systemu pozycjonowania w pomieszczeniach przy użyciu filtrowania Kalmana)***

Keywords: UWB, indoor positioning, Kalman filtering
Słowa kluczowe: UWB, pozycjonowanie w pomieszczeniach, filtrowanie Kalmana

Introduction

There is an increasing demand for precise and dependable solutions for indoor positioning in a variety of fields, including navigation, asset tracking, and location-based services [1]. The following examples will illustrate importance and vast potential of this technology.

By tracking power tools, mobile machinery, and other equipment, positioning technology enhances asset management and reduces losses in industries. Additionally, it improves workplace safety by ensuring the proper use of safety equipment and detecting slips and falls. Worker tracking facilitates healthy and ergonomic working practices, leading to increased productivity and employee well-being [2].

Modern healthcare, like industry sector, is a complex endeavor that requires efficient management of specialized personnel and expensive equipment. Positioning technology offers asset tracking and theft prevention capabilities. In aging societies with labor shortages, it becomes indispensable for providing adequate care to seniors, minors, newborns, individuals with cognitive disabilities and patients with mental health conditions by the means of Active and Ambient Assisted Living [3]. Furthermore, indoor positioning may significantly improve emergency response times, saving lives [4].

Positioning technology extends beyond industry and healthcare, finding applications also in smaller niches. Indoor positioning opens up personalized marketing and advertising possibilities [5]. Location estimation and proximity detection can enhance visitor immersion in interactive art exhibitions, creating unique and engaging experiences [6].

Currently, positioning systems developed for indoor applications are usually based on locally generated RF signals from sources such as readily available Wi-Fi routers, active Radio Frequency Identification (RFID) readers, inexpensive Bluetooth beacons and specialized ultra-wideband (UWB) beacons [7, 8]. As shown in table 1, the resolution and other parameters of the aforementioned radio standards exhibit significant differences [2]. Alternatively other types of signals such as ultrasound, infrared and visible light may be utilized [9].

In such a positioning system, a set of stationary reference stations known as bases or beacons is necessary for establishing the position of a mobile station. Research presented in this article uses UWB beacons for reference points in multilateration process [10].

Multilateration techniques

Multilateration as shown in figure 1 is a technique that determines the position of an object by leveraging distance measurements to a set of other known points. Unlike trilateration, which uses exactly three reference nodes, multilateration expands on this concept by utilizing more nodes. This increase in the number of reference nodes allows for enhanced accuracy in pinpointing the object's position [11].

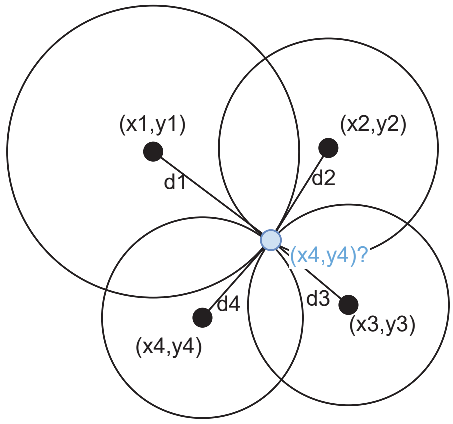

Fig. 1. An example of multilateration

Position estimation through ranging relies on the transmitted radio signal. Therefore, connectivity between base stations and the mobile device has to be available. Essentially, position can be determined based on two signal characteristics:

- Length of the signal path,
- Angle of the signal arrival.

Above approaches have more variants such as Received Signal Strength Indicator (RSSI), Time of Arrival (ToA), Time Difference of Arrival (TDoA), Angle of arrival (AoA) and more [12, 13].

Unlike triangulation, the trilateration and multilateration algorithms do not rely on angular measurements [14]. The distances are calculated by timing the UWB signals transmitted between the target node and the reference nodes [15].

Signal strength measurement

Assume that an omnidirectional antenna is mounted on a plane surface upon which the location of the moving station is to be determined. As the distance between the transmitter and receiver increases, the energy per unit area of the

Table 1. Comparative Analysis of Common RF-Based Standards for Indoor Positioning

Method	Deployment	Cost	Ease of use	Resolution	Operational range
Wi-Fi	Easy	Low	Easy	Medium, 1 m	Long, 50 m
Active RFID	Difficult	High	Challenging	High, 10 cm	Short, 15 m
Bluetooth LE	Challenging	Medium	Easy	Medium, 1 m	Moderate, 30 m
UWB	Challenging	High	Easy	High, 10 cm	Short, 20 m

wavefront decreases, following the inverse-square law. Consequently, there exists a direct relationship between the signal path length and the RSSI. Since modern receivers routinely measure and report this parameter, implementing the RSSI method becomes the simplest option which can be also easily employed in more advanced computations [16].

Spatial settings such as households, hospital rooms, warehouse buildings, libraries, and restaurants are occupied by a myriad of common objects and appliances. These elements introduce substantial attenuation, greatly impairing indoor positioning systems that rely on signal strength for accurate localization [15]. For example, at 5 GHz frequency that is commonly used by Wi-Fi, a wood board may introduce about 1 dB of attenuation while human body introduces as much as 5 dB of attenuation. Furthermore, phenomena such as reflections, refractions, and diffractions also occur leading to multipath interference that reduces signal-to-noise ratio (SNR) on the receiver side, hence degrading position estimation. Therefore positioning methods based on signal strength have the lowest quality among all and require significant algorithmic effort to achieve desired quality [17].

Time of flight measurement

Another popular ranging technique, referred to as Time of Arrival (ToA), is also commonly known as Time of Flight (ToF). In this approach the distance can be estimated by measuring time of signal propagation which is precisely timestamped at transmission and reception instants. Then, the distance between the transmitter and the receiver is simply calculated using the speed of electromagnetic wave in free space and the timestamp difference. This ranging technique is relatively straightforward to implement and offers high accuracy [18].

Considering short indoor distances and large speed of light, time measurement would require precise clock synchronization between signal source and destination. Therefore a round-trip-time method is used in which signal is transmitted to and back from the receiver. Time of the signal processing on the responding device may be measured by that device, then incorporated into response and considered in calculations performed by the transmitter.

Measurement of signals phase

Time Difference of Arrival (TDoA) is another prevalent ranging technique used in UWB positioning systems. While ToF uses the absolute time of flight, TDoA employs multiple receiving nodes and measures the relative signal arrival times. The target-receiver distance estimation is based on the difference in arrival times. If devices are stationary or their physical speed is so low that it can be neglected then phase shift between consecutive signals depends only on distance.

The biggest challenge when implementing this ranging technique is ensuring time synchronization between the receiving nodes. One of the advantages of TDoA over simple Two-Way Ranging (TWR) is the higher positioning frequency [19, 20].

Proposed positioning algorithm using Kalman filtering

A Kalman Filter, also known as a Linear Quadratic Estimator (LQE), is used for filtering, smoothing and predicting the modeled object's state using a mathematical model and available observations. In UWB positioning, as discussed in this article, it is used to minimize the signal noise thus reduce measurement error [15, 21, 22].

The following equation describes a system with linear dynamics and noise:

$$x_k = Fx_{k-1} + Bu_{k-1} + w_{k-1} \tag{1}$$

and an observation equation as follows:

$$z_k = Hx_k + v_{k-1} \tag{2}$$

where x_k is a state vector, v_k is the input vector and z_k is an output vector at the discrete-time step k. w_k and v_k symbolize the process and measurement noise, which both have a normal probability distribution.

The Kalman filtering process consists of two steps. The first one is a *prediction* step, which outputs the next discrete-time step values of the state vector. It can be described by the following equation:

$$\hat{x}_k^- = F\hat{x}_{k-1} + Bu_{k-1} \tag{3}$$

$$P_k^- = FP_{k-1}F^T + Q \tag{4}$$

where P is the covariance of the state estimation error.

The second part is the *update* step. The result of the previous step is updated using the Kalman gain K_k and new measurements.

$$K_k = P_k^- H^T (HP_k^- H^T + R)^{-1} \tag{5}$$

$$\hat{x}_k = \hat{x}_k + K_k(z_k - H\hat{x}_k^-) \tag{6}$$

$$P_k = (I - K_k H)P_k^- \tag{7}$$

Q and R are known covariance matrices. The algorithm is recursive, and both the state estimation $\hat{x}_k$ and covariance P_k are used as input data for the next iteration [22].

In practical applications, especially indoors, there are various sources of interference, leading to non-line of sight (NLoS) measurements and multipath errors. In this scenario, a different sensor can be used to supply adequate data for positioning purposes, such as an Inertial Measurement Unit (IMU), consisting of an accelerometer, a magnetometer and a gyroscope. The Kalman Filter can be used both for data filtering and sensor fusion, with necessary modifications to the mathematical model of the system to include the newly available measurements [23].

To improve positioning accuracy based on UWB, a hybrid algorithm combining multilateration and Kalman filtering has been developed and implemented. By employing multilateration, reference nodes can be utilized beyond the traditional three-point configuration, resulting in improved positioning accuracy.

The multilateration algorithm used utilizes the least squares method, with the circle formula as a residual. This method estimates the unknown position of a target node by minimizing the sum of squared residuals calculated using the following equation:

$$R_i = (x - x_i)^2 + (y - y_i)^2 - r_i^2 \tag{8}$$

The equation 8 describes the formula used for the construction of a cost function utilized in the multilateration algorithm. The actual cost function is a vector $(R_1 R_2 \ldots R_n)$ containing a residual for every anchor used in the positioning process.

Based on equations 1 and 2, a simplified model for the system has been used, accounting for the fact that this system has no input:

$$\hat{x}_k^- = F\hat{x}_{k-1} \tag{9}$$

$$z_k = Hx_k \tag{10}$$

where the state matrix x is:

$$x = \begin{bmatrix} x & y & a_x & a_y \end{bmatrix}^T \tag{11}$$

the transition matrix F equals:

$$F = \begin{bmatrix} 1 & 0 & \frac{\Delta t^2}{2} & 0 \\ 0 & 1 & 0 & \frac{\Delta t^2}{2} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{12}$$

and the observation matrix H is a 4x4 identity matrix.

By combining multilateration output with real-time accelerometer readings derived from an onboard MEMS accelerometer using a Kalman filter, the algorithm enhances mobile device positioning accuracy even further. In contrast to external but complete IMUs with gyroscopes, the use of the internal accelerometer assures a better balance between accuracy and complexity of the mobile device.

In preliminary findings, indoor positioning applications show promising results, particularly in environments where a rapid response is essential. A Kalman filter's capacity to optimally combine sensor data while accounting for uncertainties and noise is instrumental to the accurate and robust estimation of moving platform positions.

Assessment of Practical Implementation

The multilateration algorithm and Kalman Filter presented in this study were evaluated using a positioning system implemented on a DWM1001-DEV development board manufactured by Quorvo. The development board incorporates a module comprising a DW1000 UWB transceiver, an ST LIS2DH12TR MEMS accelerometer, and a Nordic Semiconductor nRF52832 microcontroller equipped with Bluetooth capabilities. The selection of this board as our test platform was motivated by its cost-effectiveness, widespread availability, and established usage within the research community [13, 10, 19, 22, 24].

Software used for evaluation consists of three components: firmware for development modules, a script for data

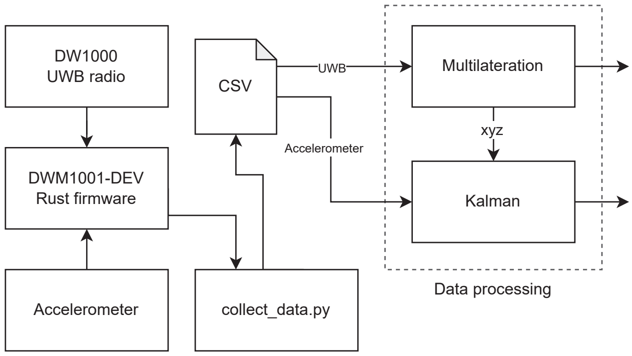

Fig. 2. System block diagram

collection, and a program implementing the algorithm for filtering and processing data. Relations between these parts and data flow are presented in the figure 2.

The firmware for both the receiving and transmitting modules of the system is built on an open-source library *dw1000-rs* written in Rust. Rapidly emerging Rust is gaining popularity where C language dominated solely, due to its exceptional performance, type-safety, and built-in support for concurrency. Rust's capabilities and the firmware's design contribute to a robust and efficient system, meeting the core requirements for reliable indoor positioning and location-based applications.

Device firmware facilitates control over the low-level hardware of both mobile and stationary nodes, enabling real-time data capture. It leverages the Two-Way Ranging (TWR) technique for precise distance measurement between modules, providing essential pre-multilateration raw data for further processing and analysis.

Using Python, a simple data acquisition program was developed. This script is run on a PC that is connected to a module via a USB cable. By using its UART serial connection, it acquires data from the device and saves it as a CSV file.

A data filtering program is the final component of the evaluation system that utilizes the data collected by the above discussed software and hardware. Various offline calculations are carried out, including multilateration, fusion of sensors, and filtering.

To assess the performance and robustness of UWB positioning in a realistic setting, it was decided to take measurements within a regular living room rather than in an artificial empty room or a clean laboratory setting. Through this ap-

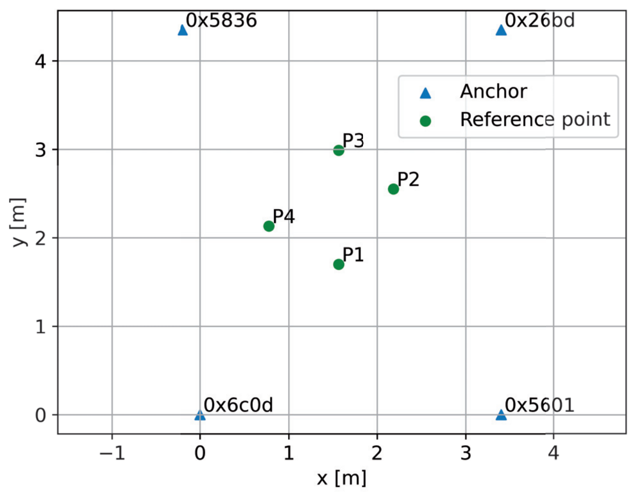

Fig. 3. Anchor and reference point placement

proach, we can address the challenges and noise that arise in real-world scenarios, providing a more accurate representation of the system's behavior in real-life circumstances. Living room setting introduces potential sources of interference, including furniture, plants, appliances, and other objects that can obstruct UWB signals. This can lead to signal attenuation and NLOS measurements. Additionally, measurements taken in these conditions are prone to higher noise levels than a laboratory or empty room setting.

The anchors have been installed approximately 20 cm from the ceiling in the corners of the room in order to ensure the best possible line of sight. Due to the lack of a precise reference positioning system (e.g., laser-based), the positions of anchors and predefined reference points were manually determined with a measuring tape. The figure 3 illustrates how anchors and reference points are arranged within the experimental test environment. The mobile "tag" device was repeatedly placed at reference locations as part of the evaluation process. The previously described positioning system was used to acquire UWB distance measurements.

This experiment aimed to determine the position of a stationary device. An individual test involved the conduct of 30 measurement series, with each series lasting 60 seconds. A fixed position of the device was maintained during each measurement, and the distances between the device and each anchor were recorded. A total of 11,719 distance measurements have been collected. A comparison of position measurements with and without the Kalman filter was conducted in order to assess the accuracy and stability of the measurements. The evaluation of the Kalman Filter for a UWB positioning system revealed several findings.

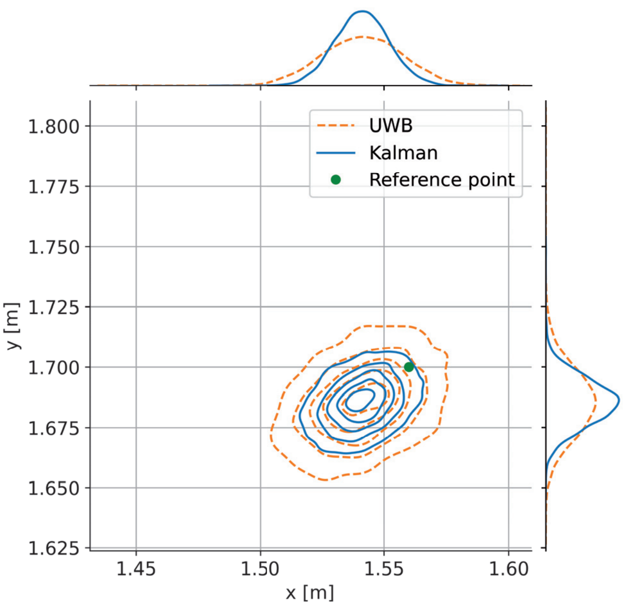

Fig. 4. Bivariate distribution of positioning results for P1

Table 2. Average RMSE of plain and Kalman-filtered data for different locations

	P1 [cm]	P2 [cm]	P3 [cm]	P4 [cm]
UWB	3.2	13.4	21.1	8.8
Kalman	2.8	13.3	21.1	8.6

Table 2 illustrates the reduction in average absolute error caused by the Kalman Filter across some of the reference points. A particular result was the reduction of positioning noise, as shown in figure 4, and error noise, as shown in figure 5 and table 3. A contour plot based on kernel density

Table 3. Standard deviation of error of plain and Kalman-filtered data for different locations

	P1 [cm]	P2 [cm]	P3 [cm]	P4 [cm]
UWB	2.2	1.4	3.1	1.2
Kalman	1.5	1.0	2.9	0.9

estimations is shown in Figure 4. Each curve represents a level of probability density p of the position estimation. The p levels chosen are 0.1, 0.3, 0.5, 0.7, and 0.9. In the plot, the green dot indicates the actual location of the reference point. Table 2 and figure 5 demonstrate that the Kalman Filter was effective in reducing the standard deviation of errors.

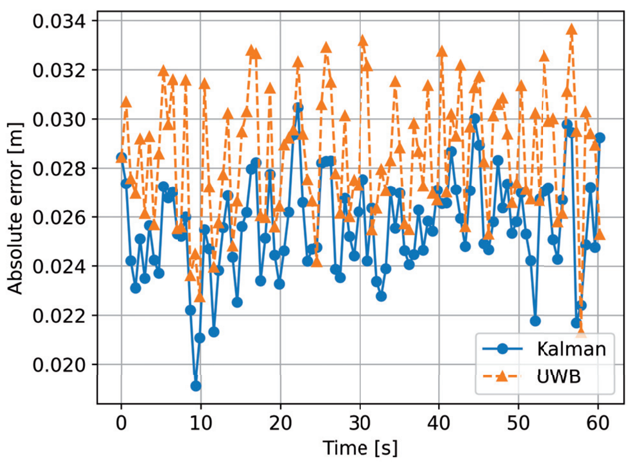

Fig. 5. Absolute error over samples for P1.

Furthermore, as shown in figure 5, the implemented Kalman filter is effective after just 4-5 samples or 3-4 seconds. Therefore, it is suitable for positioning stationary objects in a short period of time.

Conclusion

Using Kalman filters to combine sensor data, the UWB positioning system demonstrated remarkable improvements in accuracy and stability. A significant reduction in noise has been achieved through the implementation of the filter, resulting in a reduction in the standard deviation of errors. The accuracy achieved allows for the precise location of stationary objects in a remarkably short period of time, making UWB systems highly valuable for applications requiring real-time positioning information.

In general, the study indicates that UWB positioning technology augmented with Kalman filtering can make significant advancements. It is therefore a promising solution for a wide range of industries, including asset tracking, indoor navigation for people in need of assistance, and industrial automation.

Further testing is planned to complement the stationary experiments in this study by assessing movement patterns, as well as investigating different environmental scenarios.

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