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3D Accuracy Assessment of an Indoor UWB Positioning System for UAV Emergency Applications Using VICON Ground Truth

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Abstract: In recent years, amid the growing frequency of natural disasters and large-scale emergency scenarios, unmanned aerial vehicles (UAVs) have become essential tools for executing risky missions, without jeopardizing the lives of search and rescue personnel. While GNSS represents the most mature and robust positioning method, it becomes unreliable in indoor scenarios, as it is affected by multipath and non-line-of-sight (NLOS) conditions. This paper evaluates the 3D positioning accuracy of an ultra-wideband (UWB) indoor positioning system. The main purpose of this assessment is to decide whether the system can assure robust UAV positioning during emergency situations in GNSS-denied areas. The proposed system is rapid to deploy, cost-effective, and requires minimal hardware and software configuration, making it suitable for emergency response scenarios. The 3D trajectory estimated by the UWB positioning system is evaluated against ground truth positioning data provided by a VICON motion capture system. The system is tested in an uncontrolled indoor environment, with obstacles and NLOS conditions. In order to produce the best possible trajectory estimate, offline filtering techniques such as Kalman Filter, Savitzky-Golay filter and Rauch–Tung–Striebel smoothing are applied. The main purpose of these filters is to mitigate noise and the impact of outliers, and obtain a smoother and more reliable trajectory. A comparative analysis of Kalman Filter, Savitzky-Golay filter and Rauch–Tung–Striebel smoothing is presented by computing the Root Mean Square Error (RMSE) on each axis between the UWB measurements and the ground truth trajectory both before and after applying the offline filtering techniques.

Keywords: Indoor positioning, Unmanned aerial vehicles, Accuracy, Offline filtering

Introduction

These days, satellite navigation systems play a major role in the safe navigation and tracking of automobiles, ships and airplanes, as well as the positioning and monitoring of personal devices. Indoor localization has several uses in various domains, such as industry, mainly for asset tracking, emergency situations management and surveillance. Indoor positioning systems also represent crirtical infrastructure for some uprising concepts, such as internet of things (IoT) (Faheem Zahari, 2019). As people spend more time indoors, the main issues that occur concerning positioning services are related to their stability, accuracy and availability. In an urban setting, the GNSS receiver fitted on a modern mobile device can provide its location with an accuracy up to 7-13 meters (Krista Merry, 2019).

Additionally, tall buildings can block GPS signals, which leads to a multipath effect causing considerable positioning errors; thus, it often becomes difficult to determine whether the mobile terminal is located inside or outside the structure (Gyula Simon, 2021). Since the creation of contemporary smartphones, interest in developing more high-performance indoor positioning systems (IPS) has increased (Faheem Zahari, 2019), (Samama, 2019). Under high-stress, dynamic conditions, the rapid and precise positioning of people and certain goods can be critical. Previous research has investigated navigation solutions for GPS-denied environments, particularly through the integration of MEMS-based inertial navigation systems with GPS (Grigorie, 2017); however, such approaches typically provide only short-term positioning capability during signal outages, highlighting the continued need for reliable indoor positioning systems for sustained navigation in GNSS-denied scenarios. Thus, non-GNSS navigation systems must not only provide exact and continuous coordinates, but must also be resistant to certain error-inducing external factors. Based on signal type, IPS can be separated into two main categories: radio-based and non-radio based. Among the most widely-used radio-based technologies are Wi-Fi, BLE (Bluetooth low energy), and ultra-wideband (UWB), while non-radio technologies involve cameras, ultrasound, IMUs and other types of sensors (Tesfay Gidey Hailu, 2024). Reference (Jiahao Huang, 2024) provides a comprehensive review of indoor localization technologies and positioning algorithms and summarizes positioning accuracy achieved by different technologies: UWB provides centimeter-level accuracy, magnetic plus inertial fusion yields an accuracy of 1-2.8m, while ultrasonic localization can offer a median error of 15 cm.

UWB systems are among the best alternatives to GNSS navigation in areas where the access to satellites is denied or difficult. The IEEE 802.15.4a standard was the earliest to incorporate UWB standards in 2007 (Eirini Karapistoli, 2010). Due to its very narrow time-domain pulses, UWB can achieve very high positioning accuracy. UWB systems use time of flight (ToF) or received signal strength (RSS) measurements for computing the distance between the fixed anchors and the mobile tag. The majority of papers report centimeter-level accuracy for UWB systems used in indoor scenarios (Paolo Dabove, 2018), (Janis Tiemann, 2015). Futhermore, reference (Cristian Vidan, 2023) analyzes the RSS through different thickness walls in order to determine whether an ad hoc and low cost UWB indoor positioning system can enable reliable indoor localization for drones, proving that the UAV can safely navigate in soft NLOS scenarios.

Unmanned aerial vehicles (UAVs) have gained increasing popularity over the last years, as they have started to execute more varied and ambitious assignments, both in military and civilian fields. For many of these tasks, UAVs need to navigate safely in GNSS-denied environments, such as industrial infrastructure, or residential buildings during emergency scenarios. This paper aims to determine whether a low-cost and quick-to-deploy UWB IPS can allow safe UAV indoor navigation by providing reliable and accurate positioning in line-of-sight and disrupted LOS conditions. This will allow the UAVs to provide information to the first responders about the number and health status of the wounded and other hazards inside different infrastructures following an earthquake, explosion or other. The UAV could be equipped with chemical or other detectors, so that it could detect a large spectrum of possible toxic substances released into the atmosphere. This could assure a rapid response time, without risking the lives of the first responders. Furthermore, UWB infrastructure could be preinstalled in airports, warehouses and other industrial buildings, allowing for immediate UAV navigation in case of emergency. By enabling reliable indoor localization, UWB systems can facilitate UAV navigation in GNSS-denied ares, increase operator situational awareness, and enhance the safety and effectiveness of emergency response operations.

In this paper, the emphasis will be put on surveying the acccuracy and robustness of an UWB IPS under LOS and soft NLOS scenarios, in an uncontrolled environment. The accuracy of the 3D coordinates was demonstrated and evaluated in comparison to a MOCAP system; the results were quantified by computing the root mean square error (RMSE). By post-processing the collected data, respectively by applying offline filters, the overall performance of the UWB system was improved by ~8%. The novelty of this paper lies in the experimental evaluation of an indoor UWB positioning system for UAV applications employing the high-precision VICON mation capture data as ground truth, providing a realistic assessment of achievable 3D positioning accuracy in uncontrolled indoor environments. Furthermore, a comparative analysis of multiple offline filtering techniques, including Savitzky–Golay, Kalman, and Rauch–Tung–Striebel smoothing, is performed to quantify their influence on trajectory accuracy and to identify the most suitable method for improving UWB-based indoor localization performance.

System Description

UWB-based IPS

The UWB system consists of 4 anchors and one tag that was mounted on the UAV. One master tag will be connected to a laptop, in order to provide the coordinates, as well as other parameters of the slave tag installed on the UAV in real time, via the Arduino IDE. The anchors are powered by 4 external batteries and are arranged to make a rectangle, at different heights, in order to ease the process of establishing the coordinates of each anchor and minimize installation time. The distances between the anchors were accurately determined using a laser distance meter. The precision of the system greatly depends on the exactness of the anchor coordinates provided to the software.

The distance between the anchors and the tag at any given moment can be computed through multilateration; the time-of-flight between the tag and the four beacons can be computed through two techniques: time difference of arrival (TDoA) and two-way ranging (TWR). This paper uses the TWR method for two main advantages: clock synchronization between anchors is not required, unlike TDoA, making the system simpler and faster to deploy; furthermore, TWR systems do not require wired synchronization or a master clock, making them easier to install and maintain. For the TWR method, the tag sends a data packet to each anchor to start the positioning process, then waits for an acknowledgment signal from the anchors. The time of flight of the signal, respectively the time in which the signal moves for the transmitter to the receiver, is calculated using the following formula (Rakshit Ramesh, 2020):

$$ToF = \frac{t_{\text{total}} - t_{\text{reply}}}{2} \tag{1}$$

where t_{total} is described as the interval of time between the tag's initial data packet transmission to when the tag receives the data packet from the beacon; t_{reply} is the time difference from the moment when the anchor receives a signal to when it sends one.

The distance between the tag and the anchors is calculated using the following equation:

$$d = c \times ToF \tag{2}$$

where $c = 3 \times 10^8$ m/s is the speed of light and ToF represents the time of flight of the signal. After having computed the distance between the tag and at least 3 anchors for 2D positioning and 4 anchors for 3D positioning, the (x,y,z) set of coordinates of the tag can be deduced from the following system:

$$\begin{cases} d_A = \sqrt{[(x_A - x)^2 + (y_A - y)^2]} \\ d_B = \sqrt{[(x_B - x)^2 + (y_B - y)^2]} \\ d_C = \sqrt{[(x_C - x)^2 + (y_C - y)^2]} \end{cases} \tag{3}$$

The four UWB anchors were installed at different heights to ensure adequate 3D positioning observability within the test area. Each beacon has a hexadecimal ID. The coordinates of the anchor with the smallest hexadecimal ID, were set to be (0,0,0), before overlaying it on the origin point of the Vicon system, as seen in (Figure 1). This alignment enabled direct comparison between the UWB and VICON position measurements.

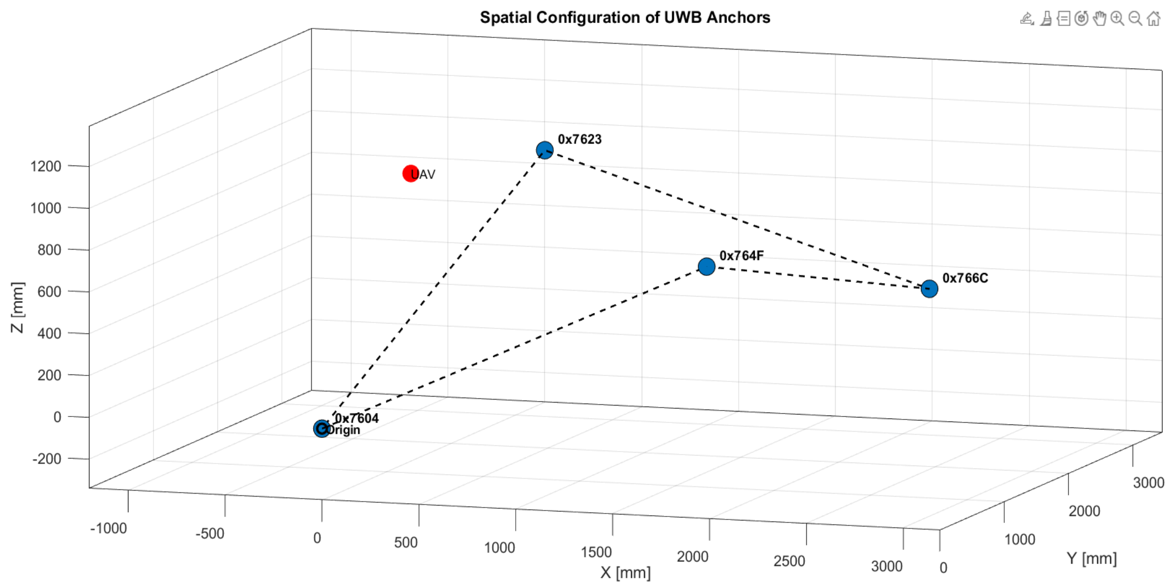

Figure 1. 3D layout of UWB anchors

VICON System

The ground truth position data used for accuracy evaluation was obtained using a VICON motion capture system. The Vicon MOCAP cameras emit infrared strobe lights once per frame. These lights are reflected by the retroreflective markers attached to the object to be positioned. The 3D position of the tracked object is constructed by triangulating the marker positions observed by multiple cameras at the same moment. The cameras are equipped with optical filters that ensure that only light with the same wavelength as the emitted light reflects back into the camera. The 16 MOCAP cameras had been installed and calibrated in a 60 m^2 room prior to the testing of the UWB system. The cameras provide good coverage for the whole room. The motion capture system provides sub-millimeter accuracy under optimal conditions (Vicon, 2020), making it suitable as a reference system for evaluating positioning accuracy. The maximum error at a given point during the experiment was 9 mm, with the majority of the errors having values below 2 mm. The VICON motion capture system is considered a reliable ground truth reference due to its very high positioning accuracy and stability. Furthemore, it is not affected by drift, as position estimates are obtained directly from optical measurements and not through integration. This ensures consistent position measurements throughout the entire experiment.

During the calibration process, the VICON system defines its own global coordinate system, with a fixed origin and axis orientation. In order to allow direct comparison bertween the UWB and VICON position measurements, the coordinate systems of both systems were aligned by colocating one of the UWB anchors with the origin of the VICON coordinate system. The VICON system operates at a much higher sampling frequency compared to the UWB positioning system, providing continuous and accurate trajectory measurements. This highlights the portions of the trajectory where UWB measurements are interrupted due to poor LOS between the tag and the beacons.

The retroreflective markers are placed on the extremities of the UAV. The trajectory of each marker can be followed separately, as well as the trajectory of the center of mass of the volume delimited by the markers. The spatial configuration of the VICON motion capture system is illustrated in (Figure 2). 16 infrared cameras are positioned around the experimental area to ensure full coverage of the capture volume and enable accurate 3D position tracking.

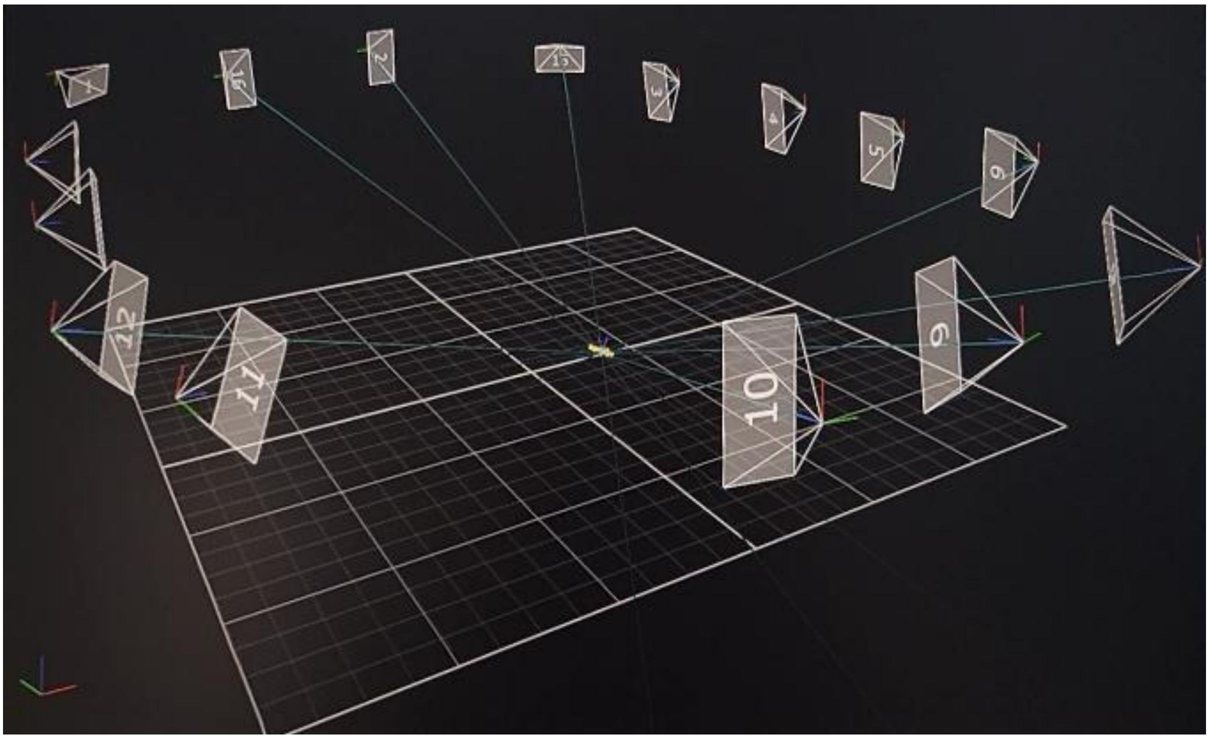

Figure 2. Spatial distribution of the VICON cameras

Experimental Setup

A UWB tag and reflective markers were attached to the UAV, allowing simultaneous tracking by both systems. The complete configuration of the UWB anchors and the VICON cameras is illustrated in (Figure 3). Position data from both systems were recorded simultaneously. Four UWB anchors were installed at fixed positions, within the capture volume defined by the VICON cameras. The UAV was moved along an arbitrary trajectory in order to evaluate positioning accuracy under dynamic conditions. The coordinate systems of the two IPS were aligned by colocating one of the UWB anchors with the origin of the VICON coordinate system. The UWB data was collected through Arduino, while the VICON Tracker software provides an Excel file containing the 3D coordinates for each frame.

One important issue for the accuracy testing was raised by the different update rates of the two systems. The Vicon Tracker software enables the user to manually change the refresh rate of the positions, with the usual update rates being between 200-300Hz, while the UWB system only allows refresh rates between 10-15 Hz. In order to ensure temporal consistency and enable accurate comparison, the VICON trajectory was downsampled to match the update rate of the UWB system.

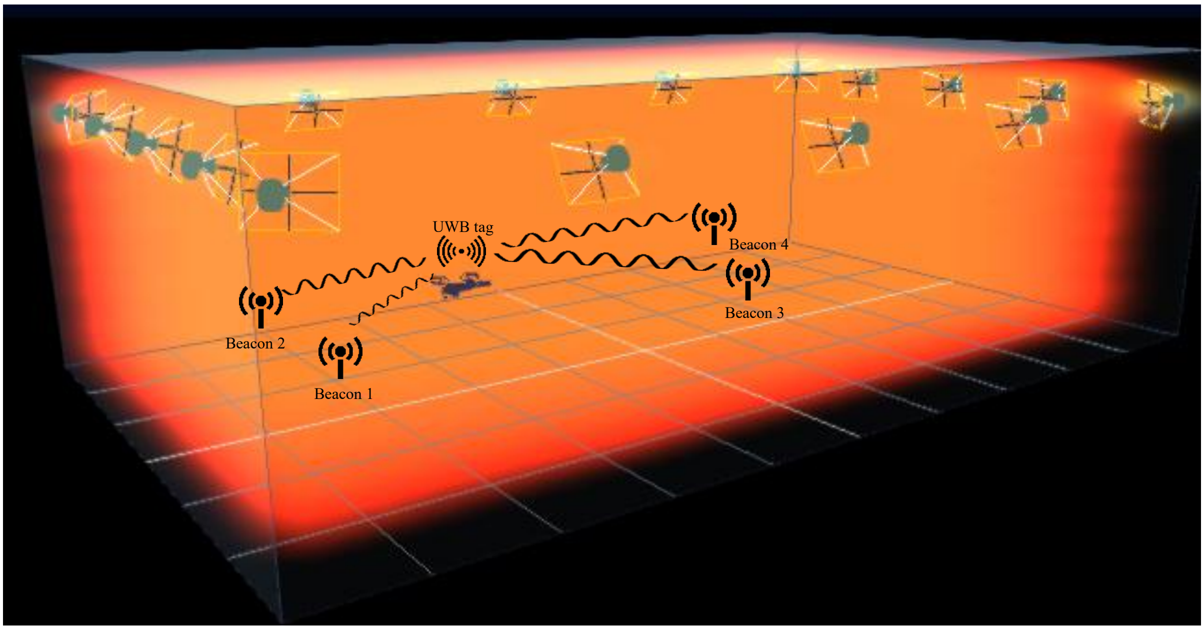

Figure 3. Experimental setup of the VICON and UWB systems

The coordinates were plotted against time, in order to obtain the trajectory of the UAV on all three axes. As the UWB generated coordinates were very affected by noise and other positioning errors, the main focus was to find a suitable filter, that would follow the trend of the trajectory while mitigating the problems generated by the noise and outliers.

Accuracy Testing

The positioning error was computed on each axis as the difference between the UWB position and the Vicon ground truth. To quantify the positioning accuracy, the RMSE was computed for each axis using the following formulas:

$$RMSE_x = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(x_{UWB}(i) - x_{VICON}(i)\right)^2}$$
$$RMSE_y = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_{UWB}(i) - y_{VICON}(i)\right)^2} \qquad (4)$$
$$RMSE_z = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(z_{UWB}(i) - z_{VICON}(i)\right)^2}$$

where N represents the total number of samples.

The UWB trajectory was compared to the VICON ground truth trajectory in order to visualize the positioning performance.

Figure 4. Shows the position of the UAV along the X, Y, and Z axes as a function of time, compared to the VICON ground truth trajectory. Figure 4. UWB and VICON trajectory comparison

The results show that the raw UWB coordinates generally follow the ground truth trajectory but exhibit noticeable fluctuations and outliers caused by measurement noise, propagation errors, and suboptimal system geometry. These effects cause positioning errors and reduce the accuracy of the estimated trajectory. However, the UWB system provides a centimeter-level accuracy. RMSE values for each axis are summarized in (Table 1).

Table 1. RMSE values for X, Y and Z axes

Axis	RMSE [mm]
X	625.8
Y	813.9
Z	322.0

The results show that the positioning error varies across the three axes, with the largest error being on the Y axis. This can be attributed to the geometric layout of the UWB anchors, which affects the positioning accuracy depending on the position of the UAV within the volume determined by the anchors. The spatial distribution of the anchors influences the geometric dilution of precision (GDOP), which leads to different accuracies on the axes. The geometric dilution of precision reaches a minimum value near the center of the measurement volume; as the UAV moves closer to the edges of the anchor distribution, the GDOP increases, resulting in larger positioning errors. Furthermore, part of the UAVs trajectory was beyond the anchor-delimited maesurement volume, thus proving that the UWB system is realiable even under degraded communication conditions and difficult line-of-sight scenarios. The Z axis is the most affected by noise, especially in the more dynamic section of the trajectory. Both the static and dynamic portions of the trajectory cointain noise and outliers, even though there are ares wehere the UWB coordinates math the ground truth.

These results are realistic for an emergency situation, where the rapid deployment of the system is critical. The suboptimal 3D layout of the anchors, as well as the obstacles in the room, which cause difficult propagation of the signals, are the main causes of the positioning errors. Despite these errors, the UWB system is able to provide continuous 3D position estimates and accurately track the overall motion of the UAV within the experimental area. These results demonstrate that the UWB positioning system provides reliable position information, even in uncontrolled environments, while also highlighting the presence of measurement noise and positioning errors that can be further reduced using filtering techniques.

Offline Filtering

Although the raw UWB coordinates follow the general shape of the ground truth trajectory, noticeable fluctuations and frequent outliers are observed due to measurement noise, multipath propagation, and inadequate geometry of the anchor configuration. These effects cause positioning errors that reduce the overall accuracy of the system. To mitigate these effects and evaluate the maximum achievable positioning performance, several offline filtering techniques were applied to the raw UWB trajectory. As it allows processing of the complete dataset, offline filtering is useful tool in experimental evaluation. Unlike real-time filtering methods, offline approaches have access to the entire sequence of measurements, enabling more effective noise reduction and trajectory smoothing. As a result, the motion of the UAV can be reconstructed more precisely and compared to high-precision ground truth data. In this study, three filtering methods were applied to the raw UWB trajectory: the Savitzky–Golay filter, the Kalman filter, and the Rauch–Tung–Striebel (RTS) smoother.

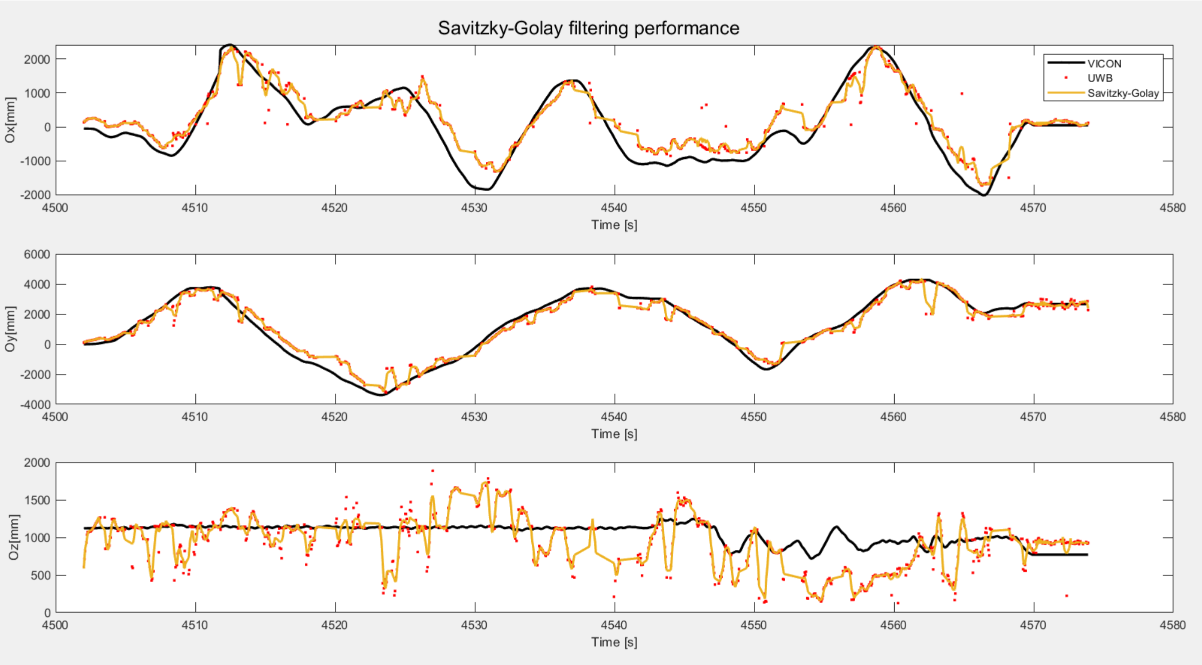

Figure 5. Savitzky–Golay filtering performance

The Savitzky–Golay filter was used as a signal smoothing technique to mitigate high-frequency measurement noise while preserving the general shape of the trajectory. This filter produces a smoothed output signal by fitting a low-order polynomial to a sliding window of data samples. The Savitzky–Golay filter improves trajectory smoothness and successfully eliminates the majority of outliers, as shown in (Figure 5).

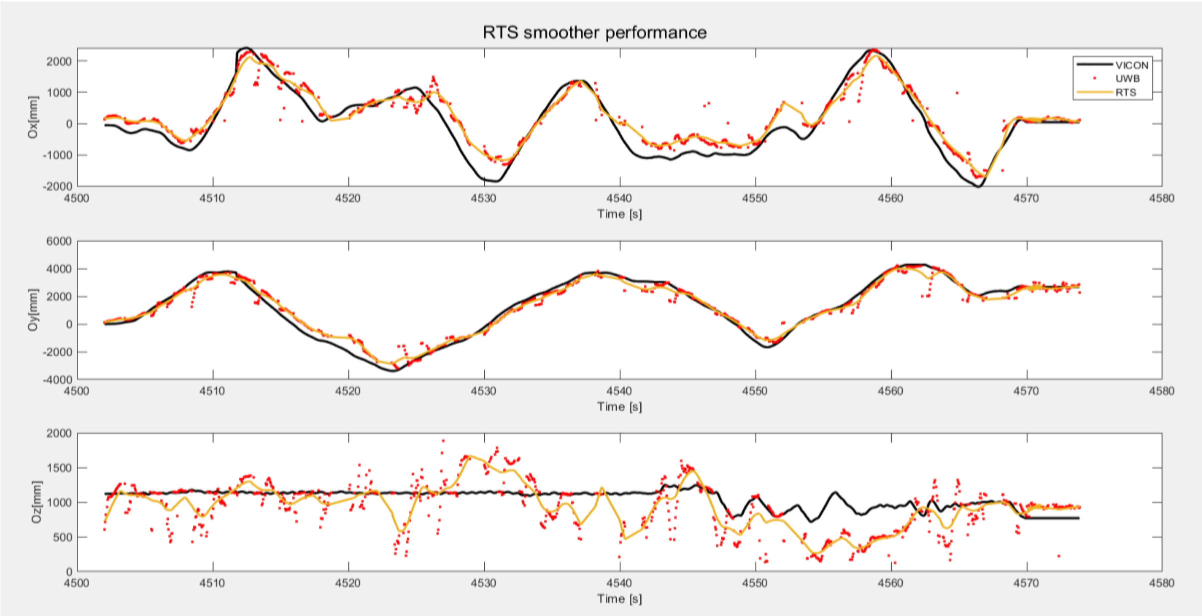

Figure 6. Kalman filter trajectory estimation performance

The Kalman filter was applied in order to improve position estimation by combining the UWB measurements with a dynamic motion model. The filter estimates both position and velocity and accounts for measurement uncertainty and the dynamics of the system. This approach improves trajectory stability and reduces the impact of measurement noise, resulting in more consistent and robust position estimates. However, the Kalman filter applied is a forward-only filter and cannot fully exploit the whole dataset, as it only uses current and past measurements to estimate the state of the system. (Figure 7) highlights the performance of the Kalman filter versus the ground truth trajectory.

While the Kalman filter offers good results, it is possible to further improve the trajectory estimation, by applying the Rauch–Tung–Striebel smoother as an offline extension of the Kalman filter. Unlike the standard Kalman filter applied, which operates in a forward direction, the Rauch–Tung–Striebel smoother performs an additional backward pass through the data, utilizing both past and future measurements. This allows more accurate estimation of the trajectory and provides improved noise reduction compared to forward-only filtering methods. Although this filtering method has no real-time applications, it is a useful tool in evaluating the maximum achievable positioning accuracy of the UWB system.

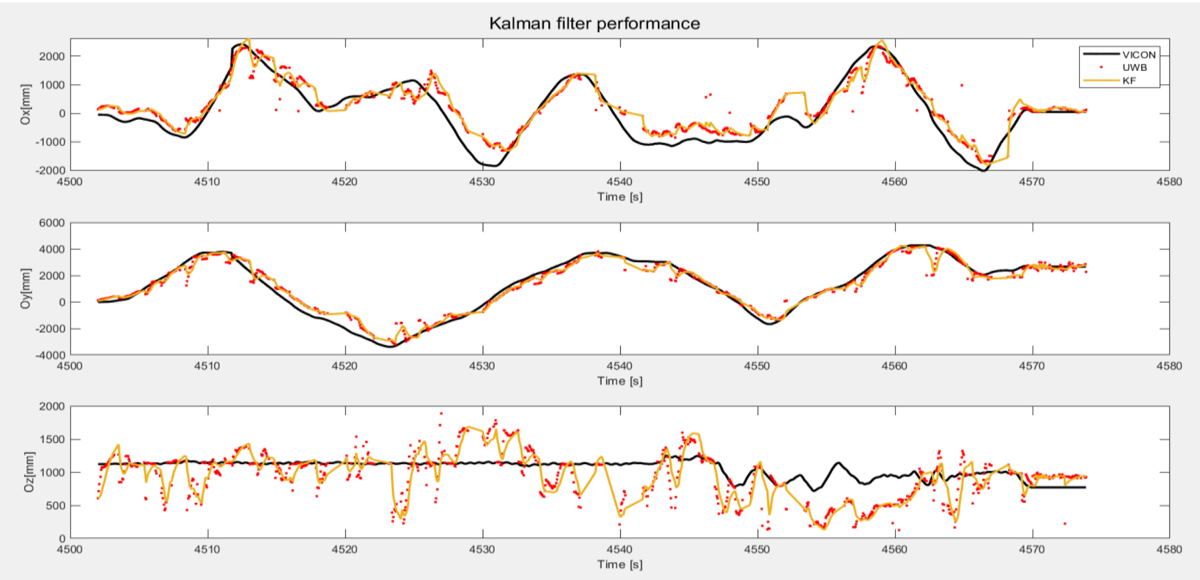

Figure 7. RTS smoother trajectory estimation performance

On the X and Y axes, the RTS smoother significantly reduces high-frequency noise and minimizes the oscillations more effectively than the Kalman filter. On the Z axis, although not all errors cuased by geometric constraints could be corrected, the RTS smoother visibly reduces random fluctuations compared to the raw data, thus improving the accuracy.

The performance of the filtering methods was evaluated by comparing the filtered UWB trajectories with the VICON ground truth and computing the RMSE for each axis. The results show that offline filtering significantly increases the positioning accuracy by reducing measurement noise and producing a smoother and more accurate trajectory estimate. Among the evaluated methods, the RTS smoother provides the best overall performance, achieving the lowest positioning error. (Table 2) summarizes the RMSE values on all three axes for the studied offline filters.

Table 2. RMSE comparison of offline filtering methods

Filter	RMSE X [mm]	RMSE Y [mm]	RMSE Z [mm]
Savitzky–Golay	610.7	802.9	306.5
Kalman Filter	622.4	804.9	307.7
RTS Smoother	591.6	764.4	259.9

The results demonstrate that offline filtering improves the positioning accuracy of the UWB system compared to the raw measurements. The Savitzky–Golay filter provides moderate improvements, reducing the RMSE by 2.41% on the X axis, 1.35% on the Y axis, and 4.81% on the Z axis. The Kalman filter achieves a similar performance as the SG filter, with improvements of 0.54%, 1.11%, and 4.44% along the X, Y, and Z axes. The most significant positioning improvement is obtained using the RTS smoother, which reduces the RMSE by 5.47% on the X axis, 5.71% on the Y axis, and 19.29% on the Z axis compared to the raw UWB measurements. The substantial improvement on the vertical axis highlights the advantage of smoothers that can exploit the whole dataset in mitigating noise and geometric limitations.

In terms of overall performance, the Savitzky-Golay filter achieves a 2.36% improvement compared to the raw UWB measurements on all the 3 axes, while the Kalman filter provides a 1.52% improvement. The RTS smoother provides the most significant enhancement, reducing the overall positioning error by 8.11%. The most important improvement is observed on the vertical axis, where the RTS smoother reduces the RMSE by 19.29%. Overall, the results confirm that offline smoothing techniques, particularly RTS, significantly increase trajectory accuracy and provide a more reliable representation of the UAV motion within the measurement volume.

Conclusions

The experimental evaluation confirms that the raw UWB positioning system is capable of tracking the overall UAV dynamics within the indoor environment with centimeter-level accuracy; however, the measurements are affected by noise, outliers, and geometric limitations due to the anchor configuration. These factors introduce deviations from the ground truth trajectory, most prominently along the vertical axis, where the GDOP has a stronger influence.

The Savitzky–Golay filter successfully removes high-frequency oscillations and attenuates outliers while preserving the overall trend of the trajectory. This improves the predicted trajectory's visual smoothness and produces modest improvements in RMSE on all 3 axes. The Kalman filter further improves trajectory stability by incorporating a dynamic motion model, producing consistent position estimates and reducing measurement noise. However, both methods operate using forward-only processing and therefore cannot fully exploit the whole trajectory dataset.The best performance is achieved using the Rauch–Tung–Striebel smoother, which applies bidirectional state estimation. By utilizing both past and future measurements, the RTS smoother significantly reduces residual noise and improves the accuracy of trajectory reconstruction. The results show an overall improvement of approximately 8% in the RMSE compared to the raw UWB data, with the most significant decrease observed on the vertical axis. This demonstrates the effectiveness of offline smoothing techniques in compensating for measurement noise and geometric limitations in indoor UWB positioning systems.

This study provides a comprehensive experimental validation of a UWB indoor positioning system for UAV applications using high-precision VICON ground truth data. The work evaluates positioning accuracy, analyzes the impact of anchor geometry, and compares multiple offline filtering techniques to determine their effectiveness. The main personal contributions include the design and implementation of the experimental setup, the alignment and synchronization of the two positioning systems, the accuracy analysis of the UWB system based on RMSE metrics, and the comparative assessment of filtering strategies for trajectory refinement and evaluation of the achievable accuracy of the UWB system.

Overall, the results demonstrate that UWB positioning, when combined with appropriate filtering techniques, represents a viable solution for indoor UAV navigation in emergency scenarios, in GNSS-denied areas where drift-free localization is required.

Scientific Ethics Declaration

* The author declares that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the author.

Conflict of Interest

* The author declares that there is no conflict of interest.

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