Evaluation of positioning and ranging errors for UWB indoor applications

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Abstract. Nowadays location information is a common requirement for numerous application fields like Location Based Services (LBS), Intelligent Transport Systems (ITS), precise agriculture, augmented reality and more. Most common navigation systems rely upon Global Navigation Satellite System (GNSS) which is by far the most cost-effective outdoor positioning system. Unfortunately, when the operation is moved indoor, the radiofrequency signals broadcasted by the satellites network are not able to achieve the receiver on the earth and the positioning is no longer available. So, dealing with GNSS- denied environment makes it necessary to use alternative solutions to aid navigation. Among the numerous solutions for indoor positioning, Ultra-Wide Band (UWB) systems are particularly interesting due to their signal characteristics. UWB signal allows high accuracy in ranging estimation, it doesn't interfere with other RF signal like GNSS and Wi-Fi and the hardware it is easily producible and therefore low-cost. In this work some commercial UWB systems are statistically analysed regarding positioning and ranging capability. Also attitude estimation from an inertial platform embedded in one system is validated. The systems are tested in different environments in order to consider the importance of network geometry, environmental noise and motion of the body. The results confirms the capability of these systems to perform centimetric-level positioning and navigation in standard indoor environments like office room or narrow corridor.

Keywords: UWB, indoor navigation, ranging, positioning.

1 Introduction

Estimate the position of people, objects and vehicles, navigate them through an unknown environment and monitoring them during their transfer are fundamental requirements in most relevant application fields (robotics, logistics, smart cities, big data, internet of things and more).

GNSS is the infrastructure that allows to define position, velocity and time of the user when it moves in outdoor environment. Indoor, several technologies have been investigated in recent years, exploiting different physical quantities, different methodologies and different hardware. Moreover, most of the research on indoor localization systems is devoted to providing low cost solutions with high accuracy even in harsh environments.

Ultra-Wideband systems (UWB) are very popular indoor positioning and navigation systems based on impulse radio frequency carrier-less signals, whose characteristics give major advantages in position estimation with respect to other indoor localization techniques [1]. Firstly, the very short pulses used in transmission results in a wide spectrum band due to the inverse relationship between time and frequency. This means the capability of the system to measure and discretize transmission and reception time with high accuracy. High time resolution means also precise range measurements and consequently good potential in positioning estimation. However, some limitations are present when RF-based technologies are used. These are signal degradation, multipath effect and interferences. The presence of obstacles, near surfaces and radiation pattern directionality can affect the capability of these systems to discretize between line of sight (LOS) and non-line-of-sight (NLOS) signal, can cause wrong detection of the first path in channel impulse response or produce low power signal that can't reach the receiver antenna. In these situations, the accuracy and robustness of these systems are strongly affected, and some mitigation procedure are required [2].

Considering the environmental dependency of the ranging error distribution, the present work tries to characterize some low-cost UWB positioning systems observing different response changing the scenario, the network geometry, the motion of the body and the number of anchors. Similar tests have been performed in [3] and [4] where different sensors have been characterized. Statistical analysis allows to validate the performance of these systems in term of position and range accuracy and precision.

2 Experimental Analysis

The goal of the experimental analysis was to evaluate the performances of the UWB technology in performing ranging and positioning estimation. Characterizing observations behavior and positioning accuracy with different algorithms and changing the scenario, it is possible to define methodologies to hybridize these systems with aiding sensors for efficiently navigating in GNSS-denied environments. To do so, a set of commercial UWB sensors has been chosen and tested both indoor and outdoor. Several on-field variables have been considered: inter-visibility conditions, number of sensors, scale of application, type of environment, dynamic of the motion and geometry of the configuration. The position estimation was performed with proprietary algorithms, which usually are black box, and with more robust algorithms like weighted least mean square and extended Kalman filter. For this research two low-cost UWB solutions have been tested in several condition and compared in specific applications. We chose the Pozyx "Ready to Localize" development kit and the TREK 1000 evaluation kit from DecaWave.

2.1 Ranging measurements

UWB sensors manufacturer declares ranging capabilities of their systems which usually do not reflect real case applications. Therefore, LOS ranging measurements were performed in an open area ensuring no obstacles between two UWB sensors. For this test, an anchor was placed on a fixed position while a person holding the tag upwards in his hand has moved away from the anchor. The true distance between the anchor and the tag was continuously measured with a measurement tape. Fixed steps were established for acquiring some minutes of measurement in static condition. The steps were increased till reaching the maximum measurable distance which correspond to the interruption of signal communication. 13 measurements were performed at 5, 6, 7, 8, 9, 10, 20, 30, 40, 50, 60, 70 meters and for each step about 2 minutes of observations were recorded. From the data acquired, outlier rejection was performed to remove recursively the measurements away from a fixed threshold. The number of samples acquired in each step ranged from a minimum of 200 to a maximum of 1200 in function of the data rates and packets. For each step the distribution of the ranging errors was analyzed. To verify how the errors are distributed, the skewness and the kurtosis were computed (table 1).

Table 1. Pozyx and TREK1000 statistical analysis.

Reference distance [m]	Mean Error [m]		RMSE [m]		Skewness		Kurtotis	
	Pozyx	Trek	Pozyx	Trek	Pozyx	Trek	Pozyx	Trek
5,000	-0,214	0,010	0,02	0,013	0,160	-0,166	3,32	3,22
6,000	-0,223	0,020	0,023	0,012	-0,198	-0,218	3,19	3,09
7,000	-0,226	0,036	0,019	0,011	-0,330	-0,260	2,58	2,79
8,000	-0,249	0,061	0,021	0,012	-0,197	0,181	3,61	3,11
9,000	-0,239	0,084	0,025	0,015	0,023	-0,003	2,78	2,79
10,000	-0,248	0,101	0,024	0,016	0,241	0,041	2,00	2,89
20,000	-0,279	0,047	0,108	0,023	-0,063	0,006	2,76	2,92
30,000	-0,339	0,002	0,083	0,027	0,045	0,061	3,18	3,16
40,000	-0,265	0,007	0,096	0,040	-0,090	1,022	2,78	5,78
50,000	-0,333	0,041	0,053	0,030	0,244	0,214	3,40	3,40
60,000	0,290	0,034	0,057	0,038	0,200	0,201	2,75	2,75
70,000	-0,285	-0,207	0,042	0,053	0,389	0,280	3,28	3,29

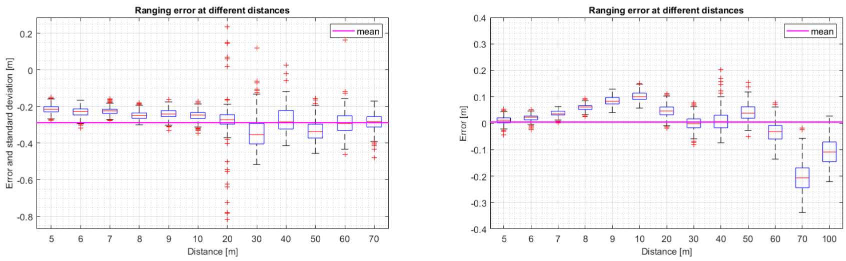

Fig. 1. Ranging precision and accuracy in LOS conditions for Pozyx and TREK1000. The box-plot shows the 25th and the 75th percentiles. The red crosses are outliers.

Observing the results in figure 1 and table 1, it is possible to state that the behavior is mainly gaussian with some exceptions related to some accidental movement of the sensors. The results showed that both the error and the standard deviation increase with the distance, although not in a linear way, mainly due to the signal fading. The maximum error is always less than 35 cm while the maximum standard deviation is around 10 cm. Similar results were obtained for the TREK 1000 sensor. In this case the system performs better with a mean error of 20 cm at least (at 70 meters distance) and standard deviation always under few centimeters, due to the presence of the external UWB antenna. For both sensors the distance from which the data communication is completely lost has been measured. The maximum operational range in LOS for Pozyx UWB system is 120 m while for TREK1000 is 157 m.

2.2 Static and Kinematic Positioning

Testing the positioning capabilities of different UWB sensors consist in evaluating the response of the system in different environmental conditions [5]. The parameters that influence the response of these systems are:

1. Geometry configuration: The configuration of the UWB network changes the geometric precision as for the GNSS system;
2. Number of anchors: the number of anchors can both increase the positioning accuracy of the systems or, in some cases, inject noise and decrease the performances;
3. Type of environment: the presence of furnitures, the passage of people, reflective or absorbing surfaces are environmental conditions that can affect the range measurements and consequently the positioning behavior;
4. Body motion: also, the motion is a variable to take into account as the system could perform differently in static or in kinematic condition;
5. Estimation algorithm: trilateration techniques or minimization procedures lead to different results.

Several tests were made changing above parameters in order to stress the system in different environments. Anchors were located in office rooms and in narrow corridors to evaluate the influence of geometric network configuration. The anchor number has been increased and decreased to observe changes in accuracy and precision. The provided inner algorithms were used to perform both positioning and navigation together with some more robust estimation procedure. Finally, one system was tested outdoor. In this work only the office room test is presented in detail, while only statistical results are reported for narrow corridors and the outdoor environment.

Several tests were conducted in an office room of 6,44 x 4,91 m. This environment was selected to reduce multipath and blocking effects from furniture, people and walls. The network of fixed anchors was located in the room at different eight and measured accurately with a topographic survey. On the floor, several reference points were materialized and measured with millimetric level of accuracy. The coordinates of these points were used to compute estimation errors of the tag located statically on those points for several seconds. Moreover, raw ranges were acquired during the test to perform comparison between proprietary algorithms and external post-processing estimation procedures. Table 2 provide the results of the numerical analysis in terms of accuracy and precision of the system, both for 2D and 3D estimation. The UWB systems allows to select two different algorithms for pose estimation, the UWB-ONLY, which compute positioning with multilateration algorithm, and the TRACKING algorithm, which integrates also the IMU measurements in the estimation and is recommended for kinematic scenarios. The results of these two inner algorithms were compared with a NLLSE which was developed using raw ranges measurements acquired during the test. Observing the results is evident how in static conditions the three algorithms give almost the same estimation results. Moreover, it is possible to observe how the Tracking algorithm, which relies on the integration of other sensors, inject some noise on the observables so that the RMSE increase of about 10 cm with respect to the other two algorithms. Although, it is possible to observe a major accuracy of the Tracking algorithm in the three-dimensional test mainly due to the integration of the pressure sensor in the positioning estimation which affect the Z direction. Finally, the inner "UWB-only" algorithm and the NL-LMS estimation provides the same results, so it is possible to conclude that also the Pozyx system use the same approach of the authors.

Table 2. Overall statistical parameters of 2D and 3D positioning errors in office room. Results are reported for three different algorithms.

Error	UWB-only		Tracking		NL-LSE	
	2D	3D	2D	3D	2D	3D
Min [m]	0,006	0,103	0,004	0,103	0,003	0,102
Max [m]	0,293	0,502	2,743	2,837	0,218	0,415
Mean [m]	0,120	0,303	0,130	0,256	0,123	0,307
Median [m]	0,128	0,317	0,110	0,235	0,134	0,322
RMSE [m]	0,052	0,064	0,162	0,166	0,050	0,063

Figure 2 shows the statistical analysis (mean error and RMSE) for each point materialized on the floor of the office. Comparing this plot with the floorplan of the office it is possible to observe the absence of a geometry relation between the location of the points in the environment and the accuracy of the system. Although it is evident that this relation exists, in this case the environmental conditions affect more the results. Moreover, the power emission has been taken into account, especially observing point 4, but no correlation was found.

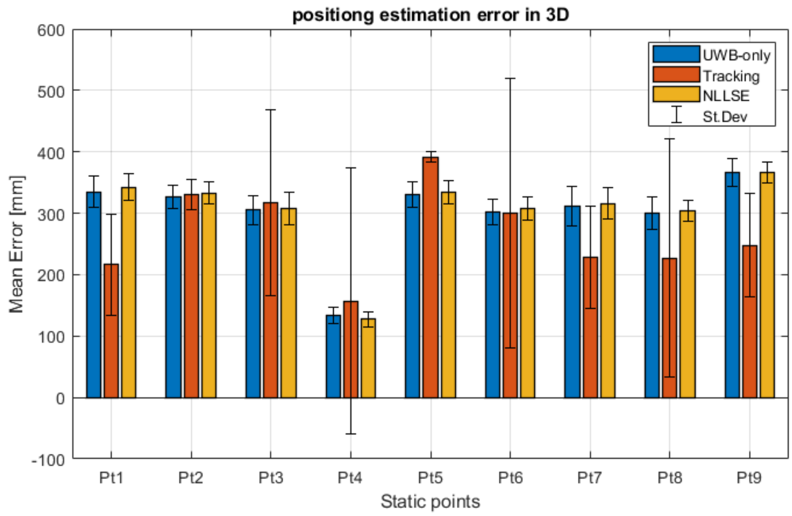

Fig. 2. Mean error and relative RMSE of each algorithm applied in different points spreads in the environment.

In the same environment, a kinematic test was performed. Two different paths were followed again with both 4 and 6-anchors configuration. The acquired observations were used to compare the results of the NL-LMS estimation ("UWB-only) and the KF ("Tracking"). The results are reported in table 3 and represented graphically in figure 3. What is possible to observe is the smoothness of the KF solution and a major error estimation along the vertical lines of the path. This is due to the presence of glass walls which generate strong multipath effects.

Table 3. Overall statistical parameter for both used algorithms in kinematic test (3D Error).

	Outer Track		Inner Track	
Algorithm	*UWB-only*	*UWB+IMU*	*UWB-only*	*UWB+IMU*
Min [m]	0,001	0,000	0,002	0,003
Max [m]	0,538	0,340	0,351	0,442
Mean [m]	0,203	0,146	0,137	0,134
Median [m]	0,211	0,156	0,114	0,106
St.D. [m]	0,127	0,082	0,105	0,100

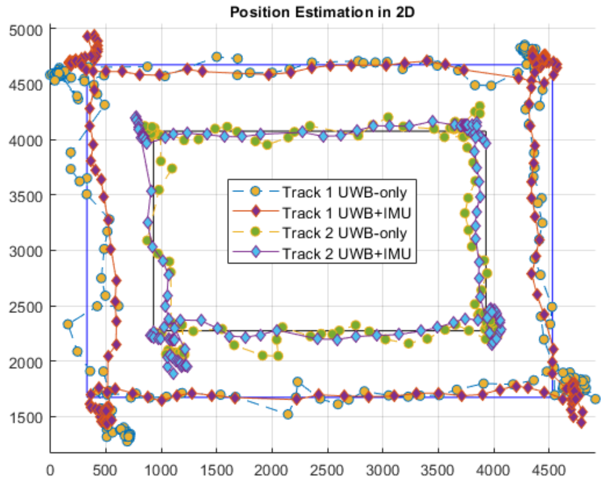

Fig. 3. 2D positioning estimation.

In order to check the Pozyx system competence in a harsh environment, several tests were made in a narrow corridor, which present an unfavorable geometric configuration. In this test, the anchor network was installed in a corridor of 1,8 x 12 m dimension. Again, several points were materialized and accurately measured to perform analysis on the estimation algorithms. The results proposed in tables 4 are referred to a 6-anchor configuration, comparing the NL-LMS and the Tracking solutions both for planimetric and three-dimensional position estimation. The typical 2D accuracy of the system in this kind of environment is around 15 cm with a precision less than 10 cm.

Table 4. Overall statistical parameters of 2D and 3Dpositioning errors in narrow corridor. Results are reported for two different algorithms.

	UWB-only		Tracking	
	2D	3D	2D	3D
Min [m]	0,003	0,013	0,004	0,02
Max [m]	5,919	6,304	2,178	5,71
Mean [m]	0,157	0,484	0,177	0,47
Median [m]	0,096	0,581	0,110	0,58
St.D. [m]	0,118	0,213	0,069	0,13

3 Conclusions

To evaluate the performances of UWB ranging capability and positioning estimation, several tests were made changing environmental characteristics and estimation procedures. Two commercial sensors (Pozyx and TREK1000) were used to acquire several ranging samples at different distances in order to characterize the behavior of the error distribution. This analysis in fundamental to design a data fusion algorithm. From the analysis of the ranging measurements acquired, it is possible to affirm that the external UWB antenna of the TREK1000 hardware allows to provide more accurate and precise ranging with respect to the Pozyx system and his onboard antenna. This increment in accuracy is in most of cases around 20 cm. The accuracy decreases with the distance although not in linear way. The distribution of the measurements is mainly gaussian, as demonstrated by the skewness and kurtosis parameters although some environmental factor can produce a gaussian mixture behavior.

Regarding the position capability, the Pozyx system has been evaluated in different indoor scenarios, an office room and a narrow corridor. Several tests were made considering the geometry of the network, the number of anchors, the environmental noise and the tag motion. The most relevant results were reported in this work also considering different algorithms. The Pozyx can provide better than 50 cm accuracyso in the harshest conditions. In favorable environment the best accuracy obtained was of 15 cm with a RMSE of 10 cm.

Thanks to all the performed test it is possible to affirm that UWB technology is a suitable solution for positioning and navigation purposes in indoor environment. Although it works well as stand-alone solution, major benefits are achieved with the hybridization with other sensors. The low-cost and the scalability of the system are great advantages. Further research should evaluate considering the multi-floor behavior, the material effect to the ranges and the data transmission capabilities.

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