Indoor positioning using Ultra-Wide Band (UWB) technologies: positioning accuracies and sensors' performances

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***Abstract* — Positioning in indoor environment is one of the most important and interesting topic in navigation system that still present numerous open problems to investigate. Many researchers are attempting to investigate on technologies able to reach valid location in an indoor space, where the well-known GNSS positioning systems are not able to operate. Among the many solutions proposed for location-based services, several wireless communications technologies have the potential to be employed for indoor positioning. In this paper, an Ultra-wideband (UWB) indoor positioning commercial system is presented which exploits two-way time of flight (TWTF) to compute range measurements. These measurements are used in multi-lateration method to compute the position of a trans-receiver (TAG). Firstly, the calibration results have been shown, comparing the internal IMU sensor of UWB system with a mass-market one, using the angles measured thanks to the total station as reference. Secondly, we also have statically analysed the positioning and the ranging capabilities of the system in a favourable environment, as an indoor office room. The average 3D accuracy obtained from the test is 100 ± 25mm. Also the ranging measurements has been analysed as the raw data from which the Pozyx® inner algorithm starts to compute the positions. It has been demonstrated that the range accuracy is about 320 ± 30mm. After these first tests, the system has also been tested in a harsh environment in a narrow corridor where a horizontal accuracy of about 87.4 mm is obtained with a maximum ranging error of ±225 mm. The system and algorithms tested in this report gave almost similar performances in both environments.**

Keywords — Indoor Positioning; Ultra-wide-band; integrated positioning; tracking.

I. Introduction

In recent years, the technological advance in the field of ubiquitous computing (everyday objects interconnected able to collect data and provide services) is opening tremendous opportunities for a large number of novel application that promise to hugely increase the quality of our lives. Among the many possibilities, one of the most important and interesting topic in the field of navigation and positioning is that of location-based services (or context-aware mobile computing) (Schiller et al, 2004). Such systems combines the location information of the end user with intelligent application in order to provide related services [1].

As is well known, GNSS receivers are everyday tools used by a large number of users for various outdoor applications: from navigation to high-precision positioning [9]. Thanks to the accuracy, the availability, the integrity and the continuity of these systems, the use of outdoor location-based services have been increased, in particular for pedestrian navigation, object tracking, emergency management, behavior analysis, context advertising, social networking, augmented reality and more [10]. It is clear, however, that many of these applications require seamless positioning in all condition, in order to be extended to mass-market products.

In this context, a current research topic is the search for a valid alternative to the GNSS for indoor positioning, where the visibility of the satellites is prevented by occlusions and this system is no longer able to operate. In the past decade, indoor positioning has become a focus topic of investigation, creating an heterogeneous system's panorama, in which the type of sensors, the location technology and the physical quantity measured generate different classification methods and different hierarchical levels between systems. The investigated technologies include a wide rande: from image-based systems [8] and [5], through the inertial navigation systems [12], even considering Infrared [20] and Wi-Fi [4] positioning.

Recently, ultra-wide band technology (UWB) [18] has been considered and adopted, which are namely a radio frequency based system consisting of fixed anchors and mobile antennas (TAGs), which again uses the principle of trilateration, enabling indoor positioning even without GNSS. These systems use different positioning and tracking methods such as distance estimation with waves reflection (RADAR principle), active measurements for distance estimation based on time of flight (ToF), time of arrival (ToA, TDoA), angle of arrival (AoA) principles or even with fingerprinting (RSSI mapping). The advantages of the UWB technology in approaches based on active systems is that the estimation of the distance is directly correlated to the signal bandwidth and because the UWB use large frequency bandwidth (>500 MHz) this permit high resolution in time and consequently in range [17]. It is evident that this technology is quite suitable for precise indoor

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positioning. UWB is especially useful for environment where multipath is high, because the wide bandwidth facilitates the detection of multiple time delayed version of signal sequences (occlusion, furniture, wall effects). Also, the development of international wireless communication standards that adopt UWB technology has encouraged R&D effort on UWB. The reasons why the UWB has not entered strongly in the mass market is the requirement for a dedicated infrastructure with all the related problems (costs, coverage area, number of users, scalability and more).

In literature, there are several example of application of UWB technology in indoor positioning, navigation and tracking. Some commercial solution are already implemented for mass-market users. Examples of commercial available UWB solutions is based on a combined TDoA and AoA approach are [19], [21] and [7] solutions.

In this paper, it has been tested the performances of the “low cost” commercial system Pozyx® (2017). Based on UWB technology, this system is able to provide a complete indoor navigation solution: position, attitude and power [6]. The system is composed by a network of radiofrequency modules with f=500MHz, which allows to reach 10-15cm of precisions. The system is comprised of a trans-receiver TAG (rover) that transmits a data packet to a set of ANCHOR (fixed) installed in the environment with a well-known position. Using a two way ranging TWR approach and a multilateration method, the system is perfect for indoor positioning and navigation. The TAGs also have an IMU system, consisting of three accelerometers, gyros and magnetometers. This allows to estimate angular value and than to implement integrated solutions based on different estimation procedure. In the next chapters it will be described the performances of the systems applied in real indoor environments.

II. UWB POSITIONING

Ultra-Wideband (UWB) is a radio technology for short-range, high-bandwidth communication used in distance estimation, localization and tracking thanks to Time of flight (TOF) measurements and multilateration techniques. A radio wave signal is sent from a module called tag to another called anchor and back and measure how long it takes the trip (TWR, two way ranging). The value of distance between the two antennas used in the triangulation algorithm is obtained simply divided the time of flight measured from the anchor by the speed of radio waves (speed of light c = 299792458 m/s).

$$d = TOF / c \qquad (1)$$

The use of large frequency bandwidth (>500 MHz) permits high resolution in time and consequently in range. In fact, in a single nanosecond, a wave travels almost 30 cm. The achievable range resolution, in the case of UWB can be approximated with:

$$rr \approx c / 2b \qquad (2)$$

Where c is the speed of the wave front and b the bandwidth. E.g. Considering f=500 MHz and a propagation in free space (assuming speed of light) it is rr ≈ 0.5c / 500MHz = 299 mm).

The most commonly used method of positioning uses basic geometry to estimate the position. By measuring the distance to a number of anchors with a known position it is possible to obtain your own position. Measuring a certain distance, it is possible to know that the unknown point will be in a circle of that radius around the anchor. Making distance measurements with 3 anchors, the position is uniquely determined by the intersection of the three circles [2]. This method is called trilateration (or multilateration if more than 3 anchors are used). The difficulty of this approach lies in the fact that the measurements are not perfect. There will always be some noise on the measurements and because of this, the circles will not intersect at exactly one point. To circumvent this issue, to estimate the point that is closest to all circles it is used the linear least squares algorithm.

In the UWB systems, the high resolution time is measured with different techniques like Time of Arrival (ToA), Two Way Ranging (TWR), Time Difference of Arrival (TDoA). All these techniques rely on time measurements which can be divided into three different principles [14]: Continuous wave, impulse radio and pseudo noise modulation. The most used principle is the impulse radio. Combining multiple signals with a slightly different frequency, it’s possible to create a 'pulse' with more defined timing, i.e., the peak of the pulse.

The range of frequencies that are used for this signal is called the bandwidth Δf. Using Heisenberg's uncertainty principle could be roughly determine the width Δt of the pulse, given a certain bandwidth Δf'.

$$\Delta f \, \Delta t \geq \tfrac{1}{4} \pi \qquad (3)$$

It’s evident that, in order to have a narrow pulse, necessary for accurate timing, it is needed a large bandwidth. It is very hard to determine the peak of a wide pulse accurately; moreover the reflections coming from the signal scattered onto object (wall, ceilings, closets, desk, etc.) are also captured by the receiver and may overlap with line of sight pulse. With pulse of 4ns wide, (Δf = 20MHz) any object within 1.2m of the receiver or the transmitter will cause an overlapping pulse. Because of this, ranging with Wi-Fi using time-of-flight is not suitable for indoor applications. In the UWB systems, the duration of the pulse is in the order of nanoseconds or even less, that means a bandwidth of more than 500MHz and the capability to distinguish reflections of the signal.

Unfortunately, all wireless communication systems use the frequency spectrum. In order to avoid interference with other radio services, the Federal Communications Commission (FCC) in the USA has limited the unlicensed use of UWB to an equivalent isotropic radiated power density of -41.3 dBm/MHz and restricted the frequency band to 3.1 GHz - 10.6 GHz (respectively 6.0 GHz - 8.5 GHz in accordance to the European Communications Committee (ECC)). Fig. 1 illustrates how UWB coexists with other Radio Frequency (RF) standards.

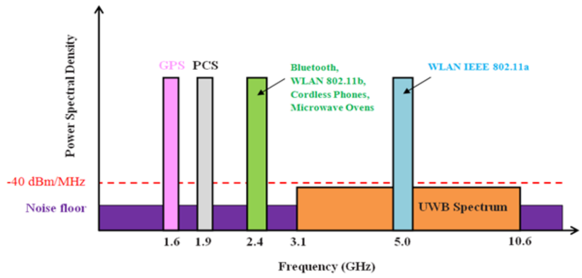

Fig. 1. Regulated UWB spectrum

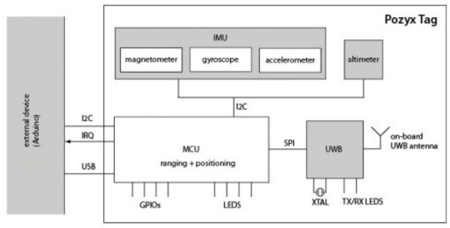

Fig. 3. Device diagram (source: https://www.pozyx.io/)

III. System Design

Pozyx® accurate positioning is a UWB-based hardware solution able to provide position and motion information. The system consist in a network of radiofrequency E/R modules with a very low power consumption. The bandwidth f 500MHz used by this system permit to send a pulse of 0.16ns wide, permitting accurate range measurements with an accuracy of about 30 cm. The network is composed by one tag, that transmit the package of data, and a series of anchors with well-known position. Another tag can be added to this configuration in order to set a master-rover configuration for the emitter module (Fig. 2).

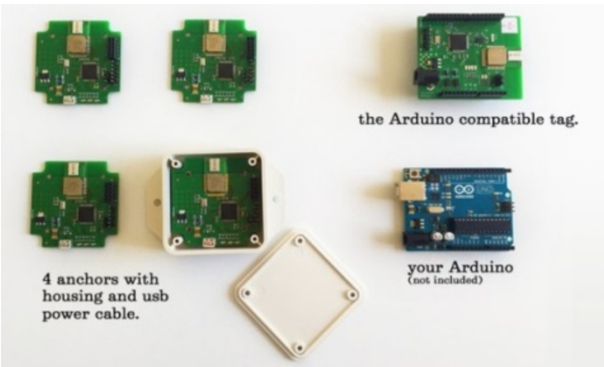

Fig. 2. Pozyx system. (source: https://www.pozyx.io/)

These system transmit with a power spectrum density below -41.3dBm/MHz a train of pulse that accumulated permit to the signal received to rise above the noise level. The maximum update rate for a single tag is currently as high as 80Hz (locally) or around 40Hz (remotely). With more tags the remote update rate must be divided by the total number of tags. Pozyx® tags are also equipped with an accelerometer, gyroscope and magnetometer (Fig. 3). With these sensors it is possible to obtain the orientation of the device. However, separately these sensors all have their flaws. For example, the accelerometer is noisy and the gyroscope is biased. Together these flaws can be mitigated. Pozyx offers 9-axis sensor fusion (3 axes for every sensor) to get the best possible measurements. These tags can be connected to any computational external device, like Raspberry Pi and Arduino boards, permitting to interact with the microcontroller unit (MCU).

IV. Performances Evaluation

In order to validate the accuracy of the system, in term of positioning, ranging and navigation, some test are been performed and some statistical values are been extracted with respect to reference solutions. The datasheet of Pozyx® describes some extensive factory-made test and shows the accuracy of the system. The test were performed both indoor and outdoor, with line-of-sight (LOS) conditions and non-line-of-sight condition, and using two different algorithm (UWB_ONLY and TRACKING) that allows to compute position by multilateration for the first and using previous position for the second. The tests were performed within an office space of 7m x 9m, using four anchor placed at the edges of the area at roughly 2 m height. Test were made using ultra-wideband channel 5, preamble length 1024, prf 64 MHz, and bitrate 110 kbps. For both algorithms, the average horizontal error in LOS is 92 mm and 140 mm in NLOS.

Other tests were performed to compare the measured range with the Pozyx® device against a millimeter accurate ground truth, using the same previous settings of the system. 7000 range measurements were collected and the results are shows an accuracy of about 30 cm. The datasheet of Pozyx® doesn't show any accuracy information about the inertial measurements unit installed on the TAG board.

Similar test were performed in order to verify the statistical value exposed in the datasheet and to stress the system in less advantageous situation. To do this, tests were performed in different environment and changing the configuration of the system. In outdoor scenario, the maximum range measurable by a single anchor was checked together with the performances of the inertial sensors. In an office room, the maximum positioning capability was evaluated. Finally in a narrow corridor, positioning and tracking accuracy, continuity of the signal, emission power and other performances were computed.

- Outdoor test: This simple evaluation of the system permit to define the maximum distance between an anchor and a tag to guarantee the signal exchange. An anchor was placed on a tripod in the middle of a courtyard, while a person holding the tag upwards in his hand moving far from the anchor. The interruption of the streaming of the signal data coincide with the maximum measurable distance. This point was measured with a tape measure. The maximum distance between a single anchor and a tag is about 40 meter.

Another test is conducted to check the internal competence of the system by examining the information provided by the sensors. In this test, the motion information acquired from this system is compared with the sensor information acquired from MicroStrain Inertial measurement unit (IMU) (model 3DM_GX3-35). These two systems are fixed on the platform which is placed on the top of the total station as shown in Fig. 4. The total station is used for the reference for both systems in this test. The main objective of this test was to compare orientation information acquired from both systems in terms of precision, accuracy and sensitivity.

Fig. 4. Inertial sensors fixed on a total station

- Indoor room test: This test was performed within an office space of 6.44 m x 4.91 m (Fig. 5). Four Anchor board were placed with different height in the four corner of the room and the positions were measured with a measure tape fixing one of the four anchor with 0 X, 0 Y and 0 Z coordinate. The room is selected to avoid too many obstacles to assess maximum positioning capabilities of the system. Inside the room several points are marked in the centre that maintains line-of-sight (LOS) from all the anchors. On the floor of the office were materialized several points that maintains line-of-sight (LOS) from all the anchors in order to verify the variations in precision and accuracy changing the position. Also a 6-anchors configuration was tested. Moreover two different algorithms (UWB-only and Tracking) are tested for both static and kinematic positioning.

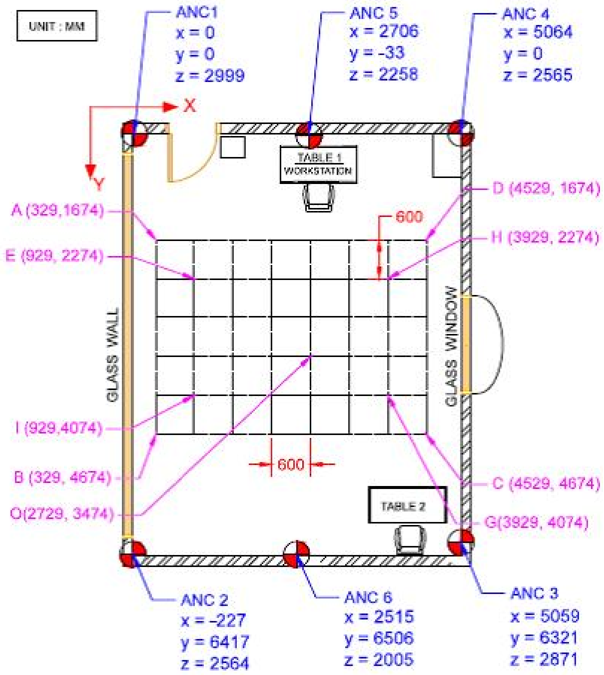

Fig. 5. Indoor room test

- Indoor narrow corridor: In this test, system is examined in a narrow corridor in the presence of numerous obstacles such as glass windows, metallic rail, power socket and narrowness of the passage to check its competence in a harsh environment (Fig. 6). In this site, anchors are installed in 4-anchor and 6-anchor configuration in a short network of 1.8m x 6.8m dimension. Five different points are marked in the test field for positioning. Two different algorithms UWB-only and tracking are tested for static positioning in this environment. Various tests have been performed, changing the geometrical configuration of the anchor, the positioning algorithms and increasing the number the Pozyx® boards. The main goal of this test was to assess system performance in an extreme environment by identifying accuracy and precision in both positioning and range measurements.

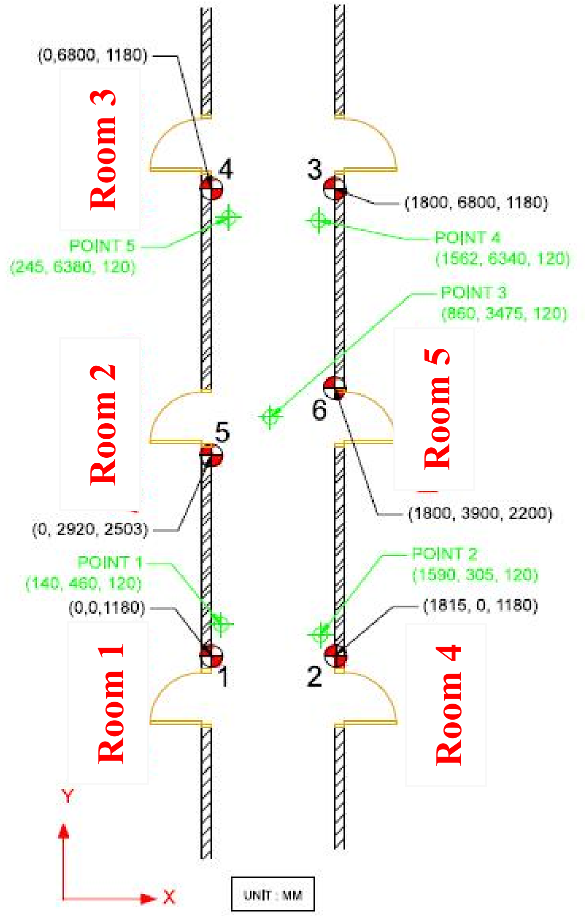

Fig. 6. Narrow corridor test

V. EXPERIMENTAL RESULTS

A. Outdoor test

In the first test, the Roll Pitch and Heading orientation of the TAG is compared with the Microstrain. Acquiring different raw angle measurements each 50 deg, it was observed that both systems use different scale for Roll and Heading. So, after aligning the orientation angles to a common scale, the maximum absolute difference in the orientation for each Roll, Pitch and Heading is computed and compared (Fig. 7).

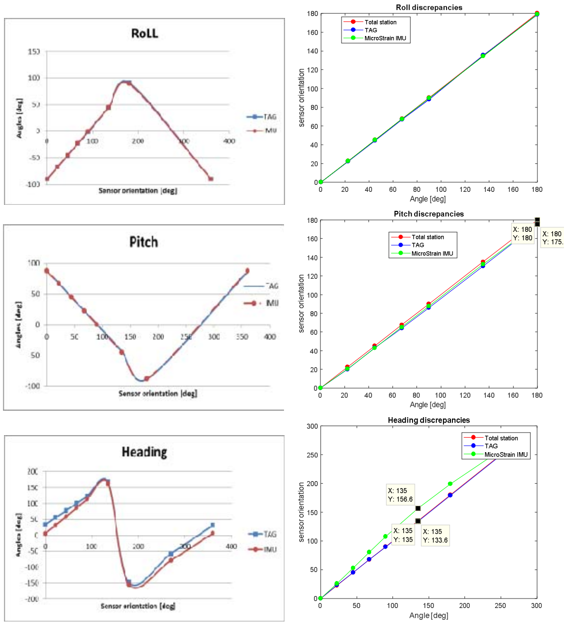

Fig. 7. Orientation comparison between TAG and MicroStrain, and discrepancies comparison

In Table 1, it is possible to see that for the heading, the TAG orientation is quite coherent with with the orientation of the total station while MicroStrain orientation is deviating with a maximum absolute difference of 21.6º. This behaviour could be due to the not correct IMU calibration. Nevertheless, the overall results of this analysis show that the IMU sensors accuracy installed in the TAG board is about the same order of the MicroStrain.

TABLE I. *MAXIMUM ABSOLUTE DIFFERENCE IN ORIENTATION*

	Roll [deg]	Pitch [deg]	Heading [deg]
TAG - Ref	1.7	4.63	1.4
MicroStrain - Ref	0.8	4.43	21.6
TAG – MicroStrain	1.52	1.93	20.2

B. Indoor room test

In the Indoor room test, four anchors have been placed on each corner of the room with different heights. Accuracy and precision in both position and range measurements for the several marked points in static condition is evaluated. The accuracy is interpreted as the difference between the true value of a certain point (measured with the millimeter tape) and the computed one obtained by the system for both position and the range measurement. As it has been described in chapter 4, two different algorithm (UWB_ONLY and TRACKING) are implemented for the positioning. Nevertheless on static condition the two algorithm give the same results, than we will describe only the results which are referred to UWB_ONLY algorithm. The planner view of the test field is as shown in Fig. 8.

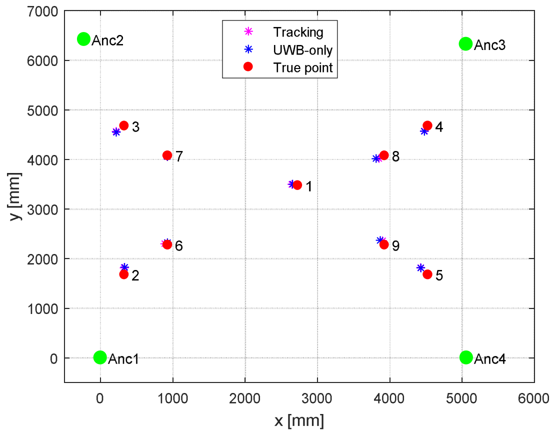

Fig. 8. XY plotting of algorithm positions

Regarding the precision of the system i.e. the spread around the mean value of a set of direct or computed measurements, Fig. 9 show the statistical value obtained for raw ranges and computed position. It appears that the ranges z component is bit noisier though it is remains less than 32 mm for all the points. The average precision in 3D position is 25 mm.

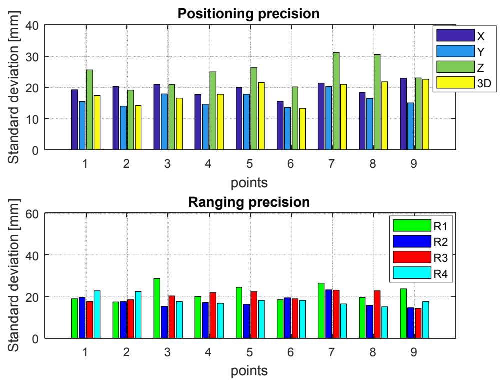

Fig. 9. Position and Range precision

Fig. 10 gives the statistical information about the accuracy in the range measurements. It is observed that the ranges from the anchor 2 (R2) are least accurate except for point 3 and point 4. Moreover, the mean accuracy of the range measurement is less than 320 mm for all the points with the standard deviation of around 30mm. This are the results expected checking the datasheet of the system.

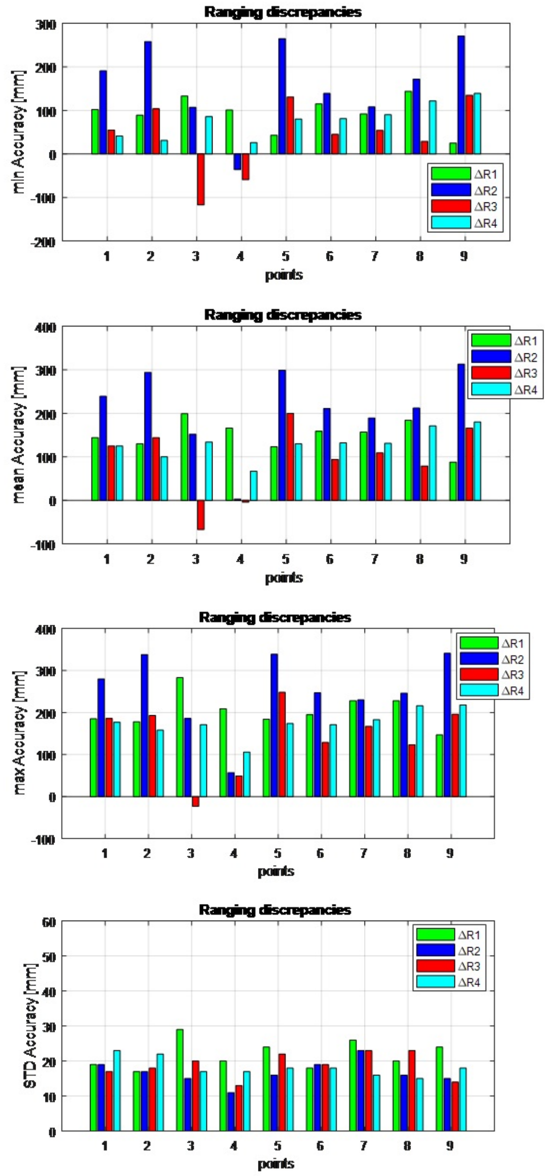

Fig. 10. Ranging accuracy

Fig. 11 provides the information about the accuracy in the positioning. Here the z-component is the least accurate and from the trend it appears that it is effected by the systematic error which could be due to the network configuration. Observing the data it is possible to state that the absolute 3D position accuracy of the system in this test for all the point is around 100 ± 25mm.

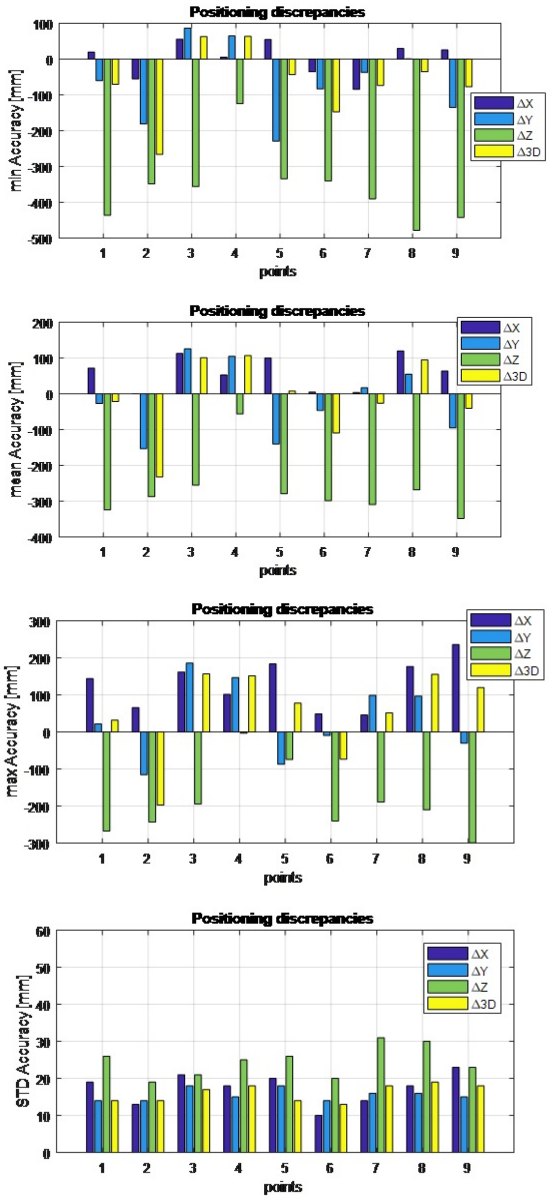

Fig. 11. Positioning accuracy

The same test has been performed upgrading the number of anchor from 4 to 6 in order to verify an increase on the positioning accuracy. The results shows that the discrepancies between the real value and the computed one for both the configurations, follow a quite random behavior. In some of the point the accuracy is improved while in other it remains almost the same or has reduced. So keeping the same configurations and addition of two more anchors does not significantly change the accuracy of the system. Seems that increasing the number of input information in the positioning algorithm don't give back a better estimation.

In the same environment, a kinematic test was performed. The rover is moved on the marked points to assess the system for kinematic positioning. Here along the line AB it is possible to observe the deviation from the true track (in black in Fig. 12) which could be due to the presence of a thick glass wall along this path that causes reflections thus reduces the accuracy.

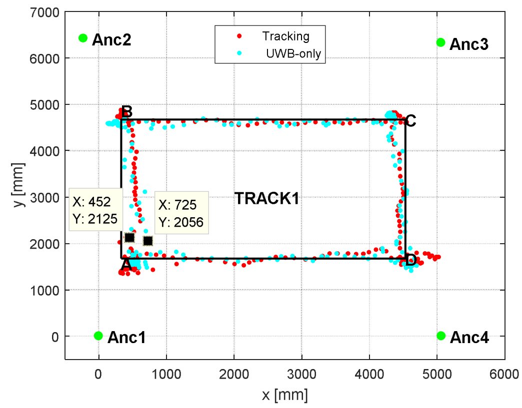

Fig. 12. Kinematic positioning plotting

In Fig. 13 the PDOP values are compared with two different configurations. By increasing 2 anchors in the 4-anchors configuration PDOP values have improved in each point.

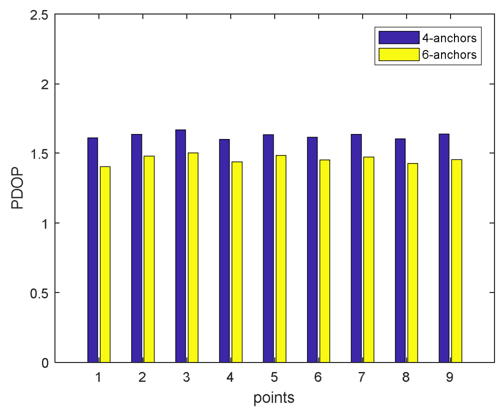

Fig. 13. PDOP comparison

C. Narrow corridor test

In this test, 4 anchors are placed in a narrow corridor with a small network of 1.8m x 6.8m dimension. The planner view of the test field is as shown in Fig. 14. Here the accuracy and precision in the position and range measurements for several marked points in static condition have been analysed. The points are selected in such a way that they are close to each of the anchor and one in the centre of the network. UWB_ONLY algorithm is implemented for positioning meanwhile true points are measured with millimeter tape.

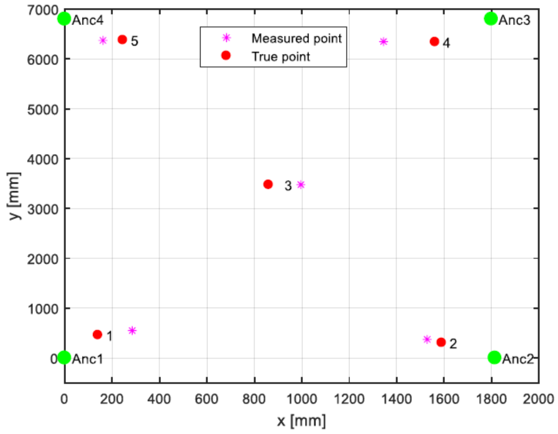

Fig. 14 Planimetric view of the test site

Fig. 15 provides the statistical information about the precision in both range and position measurements. Here in both range and the position measurements the standard deviation has increased in comparison with the results obtained in the room in test 2. It appears that the z component is very much effected and have reached to around 100mm for point 4. Moreover, on average the precision in 3D position is around 25mm mean while standard deviation in the range measurements on maximum reached to 60mm.

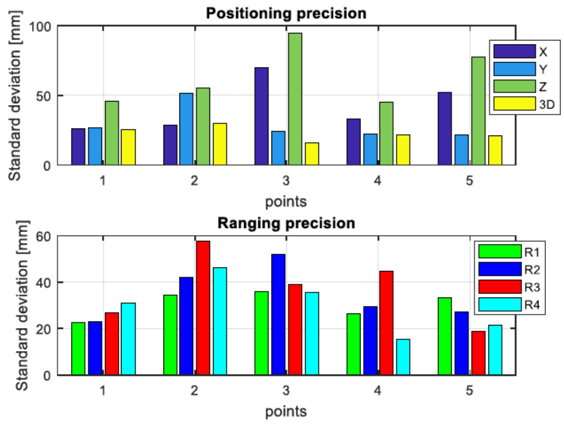

Fig. 15. Position and range precision

Fig. 16 gives the information about the accuracy in the range measurements. Moreover, the absolute mean accuracy of the range measurement is around 150mm ± 50mm.

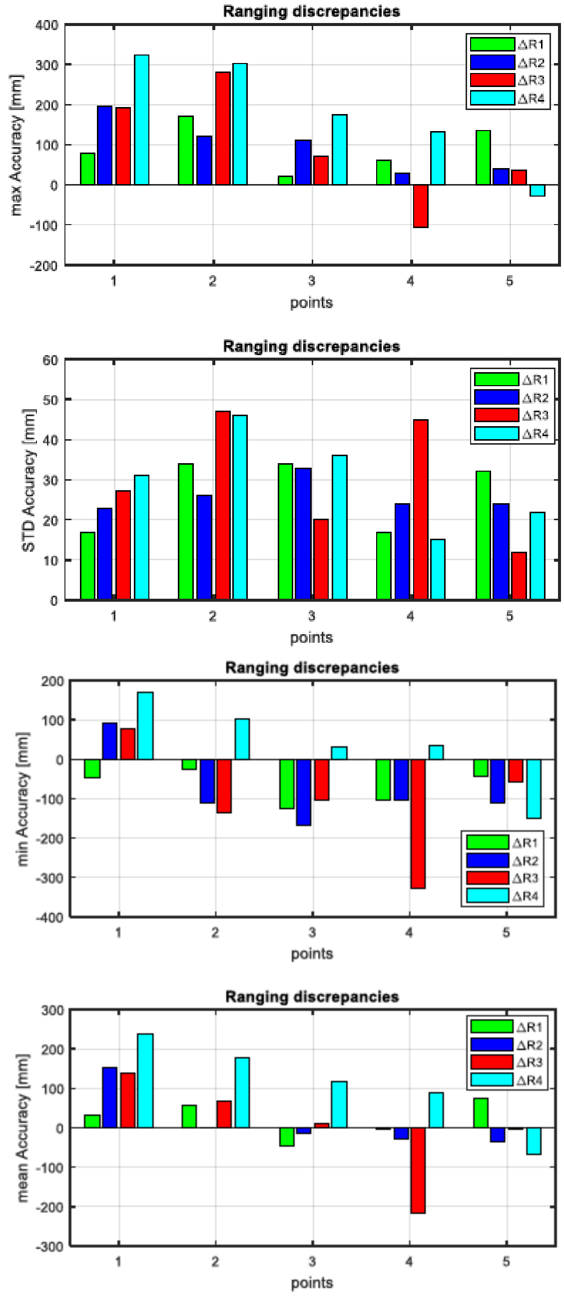

Fig. 16. Ranging accuracy

Fig. 17 gives the information about the accuracy in the positioning. Moreover, the mean absolute 3D position accuracy of the system in this test for all the point is around 60mm ± 45mm.

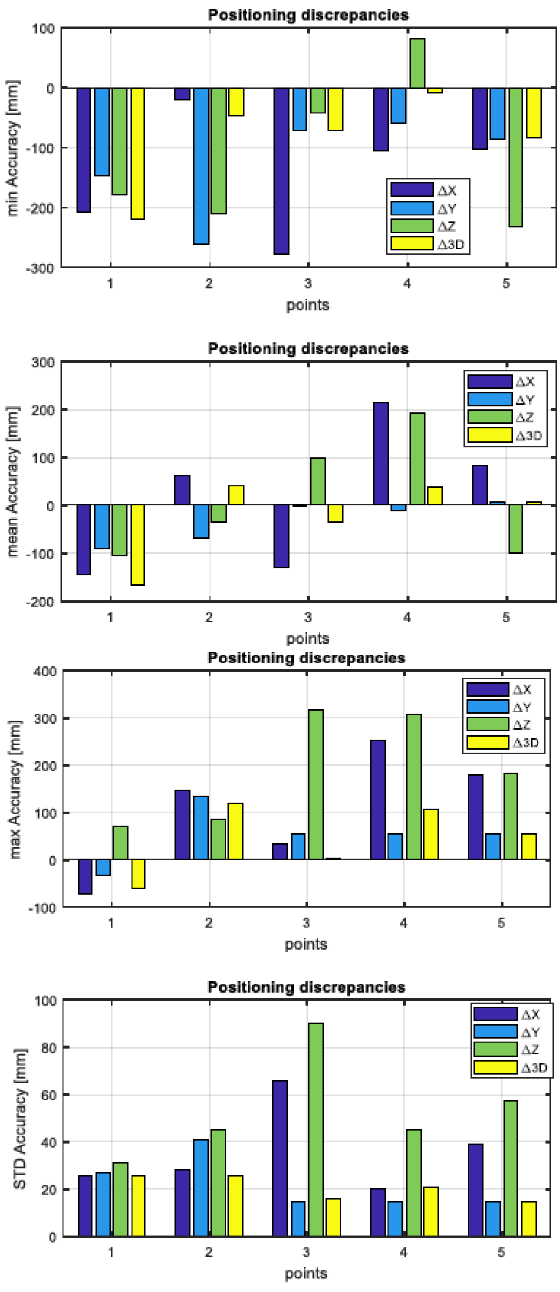

Fig. 17. Positioning accuracy

VI. CONCLUSIONS

Positioning in indoor environment is one of the most important and interesting topic in navigation system that still present numerous open problems to investigate. Numerous research are attempting to investigate on technologies able to reach valid location in an indoor space, where the well-known GNSS positioning are not able to operate. Among the many solution proposed for location-based services, several wireless communications technologies have the potential to be employed for indoor positioning. In this paper, an Ultra-wideband (UWB) indoor positioning system which exploits two way time of flight (TWTF) to compute range measurements has been presented. These measurements are used in multilateration method to compute the position of a trans-receiver (TAG). This kind of system have the advantage to provide high accurate positioning (around 10 cm from the state of art) as well as having low power consumption, high level of multipath resolution, high data rate and more.

In particular, the present research is focused on testing and evaluate the performances of a commercial solution called Pozyx®, an UWB network solution which exploit also other sensors measurements like inertial chipsets, magnetometers and altimeter.

In this report, quality of the system in term of precision and accuracy has been analysed in different environments. Firstly, the calibration results have been shown, comparing the internal IMU sensor of UWB system with a mass-market one, using the angles measured thanks to the total station as reference. The obtained results have shown that both roll and pitch angles are comparable to those estimated through the total station, while for the heading the maximum absolute difference of 21.6°.

Secondly, we also have statically analysed the positioning and the ranging capabilities of the system in a favourable environment; an indoor office room. The average 3D accuracy obtained from the test is 100 ± 25mm. Also the ranging measurements has been analysed as represent the raw data from which the Pozyx® inner algorithm compute the position. It has been demonstrate that the accuracy is about 320 ± 30mm. Later the system has been tested in a harsh environment in a narrow corridor where the horizontal accuracy of 87.4 mm is obtained with maximum ranging error of ±225 mm. The system and algorithm tested in this report gives similar performances in both environments.

In the next steps, other configurations will be tested, considering also more reference anchors in order to increase the accuracy values and the reliability of the solution. In addition, it should be nice to process the raw data acquired by the system in order to obtain a more accurate solution, thanks to an Extended Kalman Filter.

From the results of these test, is possible to state that this kind of system could reach easily a decimetre level of accuracy, a level of accuracy interesting for a large panorama of application. Unfortunately, these systems pretends an network installation in order to provide the position and this could represents a limitation in term of cost, time and infrastructure requirements.

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