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Horizontal dilution of precision-based ultra-wideband positioning technique for indoor environments

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Abstract: Ultra-wideband (UWB) technology provides considerable performance in many indoor localization problems thanks to its very wide spectrum and high-resolution characteristics. In this paper, we propose using the horizontal dilution of precision (HDOP) to decrease the localization error in indoor environments for UWB localization systems. To achieve this aim, first we determine the positioning accuracy of a commercially available UWB positioning system using laboratory experiments. Next, the results of the position estimations obtained by the HDOP are compared with the experimental results acquired by the UWB positioning system. Finally, we investigate a detailed comparison with the least squares (LS), nonlinear regression (NLR), and iterative nonlinear regression (INR) techniques. In terms of the mean position estimation error, the proposed HDOP technique increases the performance of the UWB positioning system and the LS algorithm by approximately 10% and 3%, respectively. In addition, while the proposed HDOP technique provides localization for all of the test points, both the NLR and INR algorithms perform below the expected levels at the same points.

Key words: Wireless networks, ultra-wideband, localization, dilution of precision, least squares techniques, linear regression

1. Introduction

Wireless communication systems acquire practical solutions to today's communication problems with many successful applications [1–3]. In addition, they seem to be the systems that follow the technological improvement closely [2]. With the help of the advantageous and practical solutions to problems that they provide, wireless communication systems draw the attention of researchers and lead them to contribute to the solutions of localization and real-time tracking. In the literature, there are different studies for various environments to estimate a user's position and follow the user when it is needed [3]. While the Global Positioning System (GPS) [4] is accepted as the most important and accurate solution among the presented solutions for outdoor environments, there is no commonly accepted method for indoor environments. Studies have been focused on ultra-wideband (UWB) technology, which has better signal resolution compared to traditional radio technology [5]. High-bandwidth UWB radio transceivers transmit data faster and with a small error probability by minimizing the effects of multipath interferences. This yields a faster and more reliable wireless communication environment between wireless equipment in indoor environments [6].

UWB systems transmit at prespecified power levels [7] in order to not be affected by the interferences caused by systems using the same frequency spectrum. Thus, UWB signals, which are at prespecified power

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levels and have high bandwidth, provide some advantages, such as high precision localization, transmission of data with high speed, and designing of radio transceivers at a lower cost and power. In this sense, UWB positioning methods are separated into 2 categories, the direct and 2-step methods, according to the transmission between the nodes [6]. While direct localization methods estimate the position using the transmission between the nodes, 2-step positioning systems first determine specific parameters from radio signals and then estimate the position according to the signal parameters. Two-step positioning is preferred much more in UWB-based methods due to its lower computational complexity compared to direct positioning. Using these methods, some useful parameters, such as the received signal strength (RSS), angle of arrival (AOA), time of arrival (TOA), and time difference of arrival (TDOA) can be determined. Next, localization is carried out according to these signal parameters. There are 2 prominent positioning schemes for the localization process [8]: the first based on geometrical relations and the second based on statistical approaches.

In the literature, there are numerous positioning methods using these algorithms differently [9]. In order to carry out localization, geometrical methods are among the simplest and easiest methods that predict the direct dissolving of quantity set in real time, which is supported by the measurements of radio signal parameters, such as the RSS, AOA, TOA, and TDOA [8]. These quantities are derived from geometrical models that provide an intersection of the different geometrical shapes. Measurement of the TOA or RSS is used to determine the distance between the target and the receiver that defines a circle for the target's possible position. The intersecting points of the circles and the target's position can be estimated with the help of these measurements [10]. Otherwise, the position of the target is determined by 2 AOA measurements between the receiver and the target [11]. In addition, with the existence of 3 reference points in the other geometrical method, the target position can be determined according to the hyperbolas' intersecting point, which is obtained from 2 TDOA measurements with respect to 1 reference point being used [12]. Moreover, there are some methods in which both of the aforementioned solutions can be used at the same time [13]. Although these geometrical methods provide a foresight for localization when measurements without noise signals are done, they cannot provide a systematic and safe approach when measurements with noisy signals are done.

A few other positioning methods employed in UWB systems are based on using optimization and statistical approaches [6]. With the help of ample position data, which are obtained by parameters using noisy or nonnoisy measurements, these methods can produce theoretical solutions to localization. According to the amount of noisy measurements, the methods in which they can use 2 or more parameters, such as the AOA, TOA, RSS, and TDOA, are divided into 2 types: parametric or nonparametric [8]. While localization is done by knowing the probability density function of the noise in parametric methods, in methods that are not parametric, localization is done without any information about the noise [5]. In the literature, in addition to these methods, there are some others that use these methods for different environments [6,14–16].

Commercially produced UWB positioning systems can be used for many applications of health, security, military, and emergency management [17–19]. Localization error under the limit of 1 m is usually expected for the positioning of targets, changing according to the applications. A positioning method in which the UWB system can be used for this target is chosen according to precision, complexity, stability, scalability, and computational cost. According to the literature, UWB positioning products, which could not provide desired and sufficient performance indoors until a few years ago [8], have recently provided more definite positioning with the help of performance improvements [20–22].

In this study, the settling of a commercially produced UWB positioning system in a laboratory environment and evaluation of the positioning performance are implemented. Additionally, it is suggested that experimental location estimations, which are obtained by the UWB positioning system, can be improved with horizontal dilution of precision (HDOP), generally used outdoors in the GPS system [23]. For this reason, HDOP is presented to be used as a filter by making a threshold value definition. In order to use this method, it is necessary to have HDOP maps of the area, which are measured according to the different numbers of receivers. A detailed explanation of the positioning system, which uses the UWB method, as well as the obtaining and evaluating of experimental results for known static test points are presented in Section 2. HDOP, which is used for improving the predictions of the UWB system, and the least square (LS) [24], nonlinear regression (NLR) [14,25], and iterative nonlinear regression (INR) [26] methods, which can be used as positioning methods in the literature, are explained in Section 3. Localization performances, including a comparison of all of the methods, are shown in Section 4. Finally, the discussion and conclusions are given in Section 5.

2. UWB positioning system

In a common UWB positioning system, there is a transmitter, typically called a tag, that emits UWB signals whenever it is alerted by the system and is under the control of the system, and more than one receiver receiving the UWB signals. Currently available UWB positioning systems can make both static and dynamic measurements [20]. There are some positioning and monitoring products from different companies to address different problems on the wireless market [9]. The UWB positioning system considered in this paper is a positioning platform based on the traditional time division multiple access control channel and uses AOA and TDOA signal parameters for the positioning procedure. The receivers, which can work in the frequency band range of 6–8.5 GHz, have been mounted on stable and considerably higher positions according to the measurement area in the building. Since reflections in the building cause attenuation on the direct path, it is difficult to arrange the signal time clearly on traditional radio frequency signals. However, a direct path with UWB signals can separate them from the reflections. Therefore, it is easier to arrange the signal time clearly. The receivers, whose positions are fixed in 3-dimensional spaces, are connected to the same network by a network cable. A central computer in the network contains the positioning software, which is the third component of the UWB positioning system (the first is the tag and the second is the receiver). This software is used for setting up the whole system and calibrations and for performing the localization by the receiver measurements and specific algorithms. The system fixes an AOA vector for each receiver in the localization process. In addition to this, each receiver creates the TDOA graph. The intersecting point of these graphs shows the position of the tag. The position of the tag can be decided by any of these signal measurements. Hence, it is necessary that at least 2 receivers have measurements on the position of the tag. The receivers' calibrations and orientations should be performed carefully in order for all of the receivers to work at the same time and carry out positioning more reliably. In this process, the receivers are manually and thoroughly fixed in a 3-dimensional coordinate system, and these coordinates should be entered correctly into the software of the central computer within the same network. The sensitivity of the values of these coordinate points directly affects the performance of the positioning.

The UWB positioning system that we set up has a total of 6 receivers, measuring 15 m $\times$ 9 m, in a laboratory environment, 4 of which are in the same room while the other 2 are in 2 different rooms, as seen in Figure 1. All of the receivers are placed in the corners of rooms that have a height of nearly 2.30 m. A total of 21 static measurement points (12 in the big room, 6 in the hallway, 1 in the first small room, and 2 in the other small room) are determined. By fixing the tag on a tripod at heights of 0.75 m and 1.51 m, positioning is implemented at 2 different heights. In the process of positioning, a waiting time of nearly 2.5 min is applied before going from each point to another measurement point.

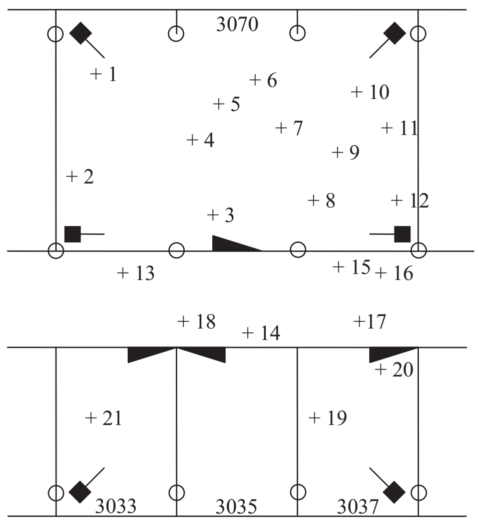

Figure 1. Position illustration of the UWB receivers and the measurement points in the laboratory plan.

In Figure 2, the estimation points, which the UWB positioning system fixes for each of the measurement points that have been provided by the receivers for 2 tags of different heights, are shown. The UWB receivers are drawn in the corners of the figures. When the height of the tag is 1.51 m, it is clear from the estimations that the error in the 19th measurement point is much greater than that of the others. The reasons for these faulty

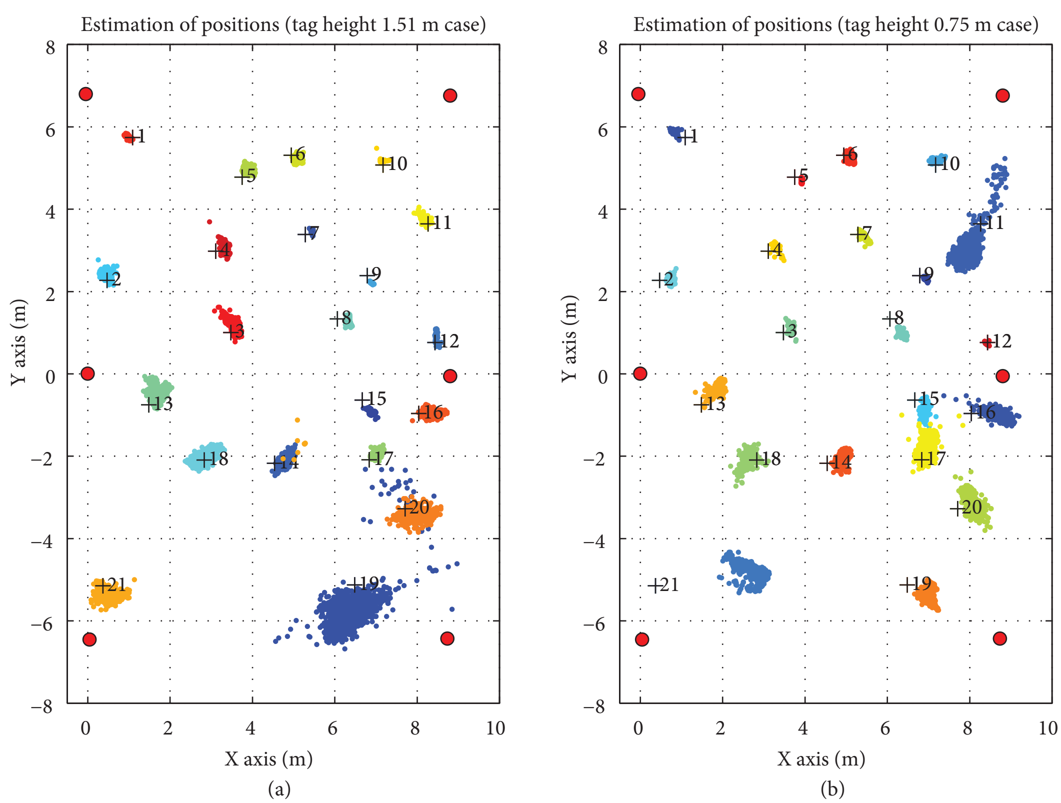

Figure 2. Illustrating the locations of 21 test points for the tags at different heights in the UWB positioning system.

estimations can be the receivers' calibration, not carrying out the placement and measurement at the same time during the measuring process, or being exposed to the effect of more attenuation since the measurement point is in a small room. It is clear that the UWB system carries out an average estimation for all of the other test points, except for this one. It is observed that the estimations of the 11th and 21st test points can be faulty when the measurement height of the tag is 0.75 m. While the reason for the faulty estimations for the 11th test point is a time synchronization problem in the measurement process, the reasons for the faulty estimations for the 21st test point can be listed as faulty tag placement and much more attenuation effect. While the average estimations for all of the test points, except for these 2 points, are done, the error of the test points in the big room, where the multipath and attenuation effect is less particular, is considered less than that of the test points in the corridor and other rooms.

The cumulative distribution of the localization error of the UWB positioning system yields from 2 different test points is shown in Figure 3. When the tag height of the 21st test point in Figure 3a is 1.51 m, 98.7% of the positioning error is under the limit of 0.56 m, and when the tag height is 0.75 m, the positioning error is between the values of 1.57 m and 2.77 m. However, location estimations that belong to the 21st test point are seen near the 14th test point when we look carefully for the positioning error at 1.51 m. Thus, these estimations show that the error increases at over 6 m for 1% of the test points. In Figure 3b, the location estimations of the 12th test point are under the limit of 0.35 m for 2 tag heights. The average and maximum (95%) errors for the 2 tag height localizations, which are taken from the data of the UWB positioning system, are shown in Figures 4a and 4b, respectively. According to the mean localization errors, when the height of the tag is 1.51 m, the results are better than with the other tag results in general. Corresponding to the results, most of the mean localization errors are generally under the limit of 0.5 m for both tag heights. For the tag heights of 0.75 and 1.51 m, positioning errors of 0.42 m and 0.24 m are obtained by the mean of all of the location estimations and test points. While the maximum localization error is nearly 6 m at the height of 1.51 m, it is not more than 2.78 m at the tag height of 0.75 m. It can be said that the maximum localization errors can be generally fixed as 1 m for both tag heights.

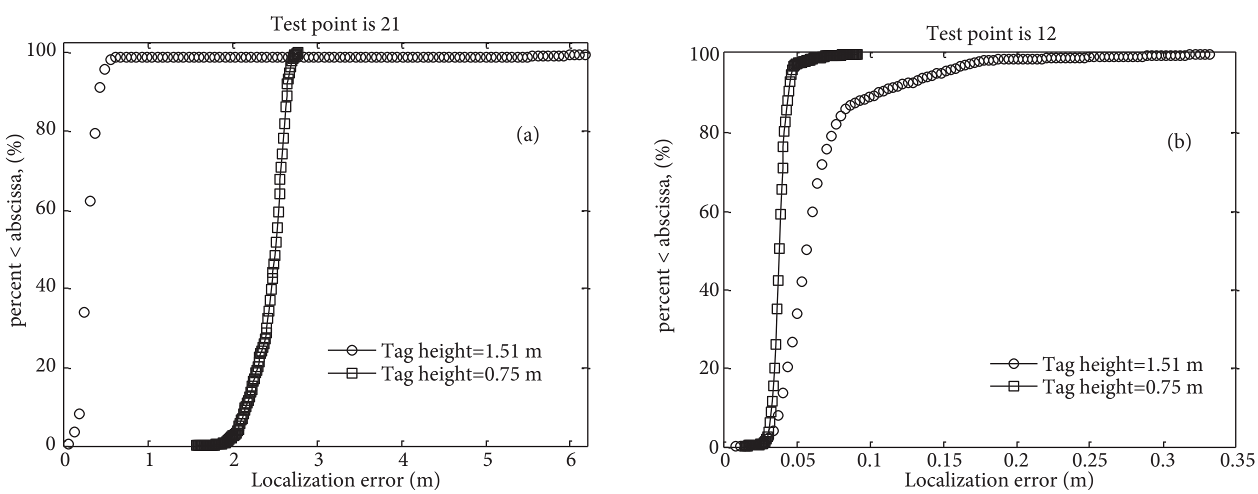

Figure 3. Cumulative distribution functions of the 12th and 21st test points' localization errors determined by the UWB positioning system.

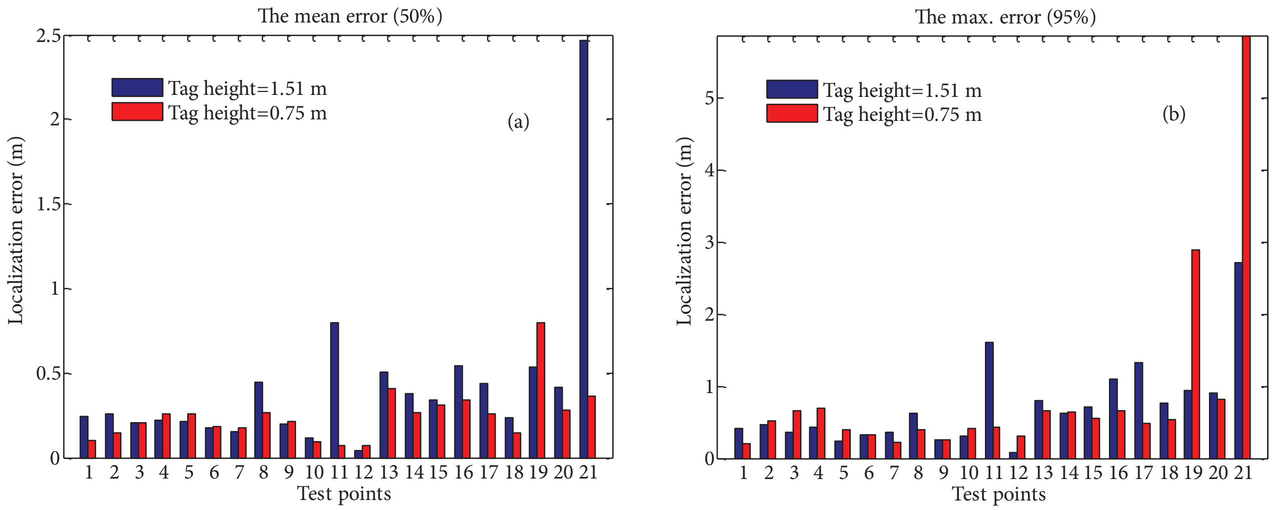

Figure 4. The mean and maximum (95%) localization errors of whole test points fixed by the UWB positioning system.

3. Positioning methods

3.1. Horizontal dilution of precision

The GPS has been the subject of much research about wireless communication owing to its advantages. This system should make a decision about whether the satellite geometry is suitable for positioning or not, in order to undertake a high-precision positioning process. To make this decision, dilution of precision (DOP) is generally used in the literature [4]. The reliability of the positioning process that is carried out using the DOP is determined. If the measured DOP value is high, this means that the satellite geometry is not good, and whenever it is low, the satellite geometry is like desired. Different types of DOP can be expressed, such as the HDOP. HDOP is used for the positioning process at a horizontal plane and it can be mathematically counted by the geometry of the satellites. In order to count the HDOP value mathematically, the 3-dimensional position of the satellites is used, and the distance of the receiver, the position of which has been estimated, is fixed to each satellite and then is counted using Eq. (1).

$$R_i = \sqrt{(x_i - R_x)^2 + (y_i - R_y)^2 + (z_i - R_z)^2} \tag{1}$$

Here, R_i represents the distance between the satellite and estimated point. R_x, R_y, and R_z represent the 3-dimensional positioning data of the receiver, the position of which has been estimated, and terms x, y, and z describe the satellites' position. Directed derivatives are taken for each satellite using the distance data and the formulas of Eq. (2).

$$Dx_i = \frac{x_i - R_x}{R_i}, Dy_i = \frac{y_i - R_y}{R_i}, Dz_i = \frac{z_i - R_z}{R_i}, Dt_i = -1 \tag{2}$$

Dt can be used when we make a process about the satellite time (time DOP). These data, which confirm the position estimation of the receiver, are set on a matrix (G) for all of the satellites sequentially. Using this covariance matrix, the DOP records are carried out. The covariance matrix is obtained as in Eq. (3):

$$(\mathbf{G}^T\mathbf{G})^{-1} = \begin{bmatrix} \sigma_{xx}^2 & \sigma_{xy}^2 & \sigma_{xz}^2 & \sigma_{xt}^2 \\ \sigma_{yx}^2 & \sigma_{yy}^2 & \sigma_{yz}^2 & \sigma_{yt}^2 \\ \sigma_{zx}^2 & \sigma_{zy}^2 & \sigma_{zz}^2 & \sigma_{zt}^2 \\ \sigma_{tx}^2 & \sigma_{ty}^2 & \sigma_{tz}^2 & \sigma_{tt}^2 \end{bmatrix}. \tag{3}$$

The diagonal parts of this covariance matrix represent the variance of the user position, which is estimated for each axis and the user time. Using the parts of the matrix, the HDOP value is fixed as below:

$$HDOP = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2}. \tag{4}$$

The HDOP value should be mathematically computed and the level should then be fixed in order to use this dilution as a filter. For this reason, HDOP analysis should be implemented in the whole sensor field. As a result of this analysis, a HDOP threshold level ($HDOP_L$) is determined by the mathematical expression in Eq. (5).

$$\mu_{(HDOP_B)} + \sigma_{(HDOP_B)} \leq HDOP_L \leq \mu_{(HDOP_W)} - \sigma_{(HDOP_W)} \tag{5}$$

Here, $\mu_{(HDOP_B)}$ and $\mu_{(HDOP_W)}$ represent the averages of the HDOP value, which are respectively found when the satellite geometry is the best or the worst one, and $\sigma_{(HDOP_B)}$ and $\sigma_{(HDOP_W)}$ represent the standard deviations. It is envisaged that with the help of this threshold level computation, the qualities of the 6 receivers' measurements in the UWB positioning system are determined, and, after the elimination of poor-quality measurements, the performance of the position estimation is increased.

3.2. Least squares

The LS algorithm, used with many signal processing algorithms in the literature, is one of the most traditional algorithms. It is used for making the problem linear and reducing the error. Here, the distances of an estimated point to the receivers are inserted in an equation system [24]. Taking into consideration the intersecting infinite spaces means making it linear. The intersecting point of these spaces can be determined with the LS algorithm. By definition, given that the receiver positions are $(x_i,\ y_i,\ z_i)$, the points are $(x_j,\ y_j,\ z_j)$, and the distances of the estimated point to these receivers are $(d_i,\ d_j)$, these spherical equations can be written for the target's position:

$$\begin{aligned}(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2 = d_i^2 \\ (x_j - x)^2 + (y_j - y)^2 + (z_j - z)^2 = d_j^2.\end{aligned} \tag{6}$$

If we subtract one equation from the other, we can get the equation below for the space intersecting between the 2 spheres:

$$2(x_j - x_i)x + 2(y_j - y_i)y + 2(z_j - z_i)z = d_i^2 - d_j^2 - x_i^2 - y_i^2 - z_i^2 + x_j^2 + y_j^2 + z_j^2. \tag{7}$$

When we put values in the state of $(i,\ j)$ in the equation above, the continuous linear equations that are shown below can be obtained:

$$\mathbf{RP} = \mathbf{O}, \tag{8}$$

$$\mathbf{P} = \left[\begin{array}{ccc} \hat{x} & \hat{y} & \hat{z} \end{array}\right]', \quad \mathbf{R} = \left[\begin{array}{ccc} 2(x_0 - x_1) & 2(y_0 - y_1) & 2(z_0 - z_1) \\ 2(x_0 - x_2) & 2(y_0 - y_2) & 2(z_0 - z_2) \\ 2(x_0 - x_3) & 2(y_0 - y_3) & 2(z_0 - z_3) \end{array}\right], \tag{9}$$

$$\mathbf{O} = \left[\begin{array}{c} d_1^2 - d_0^2 - x_1^2 - y_1^2 - z_1^2 + x_0^2 + y_0^2 + z_0^2 \\ d_2^2 - d_0^2 - x_2^2 - y_2^2 - z_2^2 + x_0^2 + y_0^2 + z_0^2 \\ d_3^2 - d_0^2 - x_3^2 - y_3^2 - z_3^2 + x_0^2 + y_0^2 + z_0^2 \end{array}\right]. \tag{10}$$

Finally, the position of the target point is computed as below:

$$\mathbf{P} = \left(\mathbf{R}^T\mathbf{R}\right)^{-1}\mathbf{R}^T\mathbf{O}. \tag{11}$$

Three-dimensional positioning for the position that is estimated is provided using this formula. Moreover, in order to use this formula, the rank of the **R** matrix is considered [24].

3.3. Nonlinear regression

NLR can be characterized with an estimation equation that is supported by one or more nonlinear unknown parameters [14,25]. Since it minimizes the total of the residual errors' square, this method, in which the estimated distances are used easily, can generally present suitable solutions for positioning. With the application of NLR at once, a positioning estimation, which is supported by all of the input measurements, is carried out. When the receiver position is $(x,\ y,\ z)$ and the tag position is $(u,\ v,\ w)$, there is a certain measurement error between the receiver and tag position. In this situation, the distance that contains the measurement error between the 2 points is measured using Eq. (12):

$$r_i = \sqrt{(x_i - u)^2 - (y_i - v)^2 + (z_i - w)^2} + \varepsilon_i. \tag{12}$$

Here, i is the number of receivers and ε_i represents the measurement error. In addition to this, the distance of the estimated point to the receiver can be expressed as follows:

$$d_i = \sqrt{(x_i - \hat{u})^2 - (y_i - \hat{v})^2 + (z_i - \hat{w})^2}. \tag{13}$$

Using these 2 distance equations, the position estimation is obtained by determining the standard residual error, as shown below:

$$\sigma^2 = \frac{1}{N}\sum_{i}^{N}(r_i - d_i)^2. \tag{14}$$

Here, r_i represents the distance of the point to the receiver, which contains the measurement error; d_i represents the distance of the estimated point to the receiver; and N symbolizes the estimation number of this point. By eliminating the measurements over the standard residual error, the others can be used as the position estimation.

3.4. Iterative nonlinear regression

INR, which is one of the forms of NLR, restarts the regression process and repeats this process continually by reducing the dimension of the input dataset in each step. This means that INR removes some measurements that have a bigger residual error from the input dataset [26]. This process goes on until either there are not enough measurements, which means that the model is unsuccessful, or the standard error decreases to under the limit of the desired threshold, which means that the model is successful. If the model is successful, the standard error value can be used as the estimation error value. Moreover, estimating the standard error is the most important point of this method. In the literature, there are some different suggestions for this estimation. The equation [26], which is one of these suggestions and uses the residual error for the standard error (s) value, is as below:

$$s = \sqrt{\frac{\sum_{i=1}^{n}(r_i - d_i)^2}{n - c}}. \tag{15}$$

Here, n represents the number of receivers used in NLR and c represents the least number of necessary receivers. By comparing the standard error estimation, which is obtained by Eq. (15), with the standard residual error, improvement of the position estimations is provided.

4. Position estimation results

The positioning experimental results are obtained for 21 different test points of 2 different tag heights with the help of the UWB positioning system. When the tag height of the test points is 1.51 m, the UWB positioning system estimates between 1529 and 2219 position estimations for the test points, and when the tag height of the test points is 0.75 m, it estimates between 1518 and 2220 position estimations. These estimation numbers are carried out with a reading at nearly 100 ms. These estimations are used for the performance evaluation of the positioning algorithm.

First, fixing of the HDOP level is done in a situation when attaining data from different numbers of receivers in a laboratory environment for the method that is applied for the experimental results, and the HDOP level is used as a filter. According to this, Figure 5a shows the HDOP levels when data are given from all of the receivers in the whole area, and Figure 5b shows the HDOP levels when data are given from only 3 receivers. These results are used in the choice of a specified HDOP threshold value for the area where the test measurements are implemented. According to Figure 5a, when data are given from all of the receivers, the value is between 0.96 and 1, as a result of the HDOP measurement, and it is described as ideal for outdoor positioning. When data are given from all of the receivers, the receiver geometry of the positioning process is the best one. If we look at Figure 5b, the HDOP value is between 1.5 and 5 when it is far away from the nearest points of receivers. Although this level is acceptable, it also means that the receiver geometry is not always good. According to these results, in the process of improving the UWB system's experimental results, the HDOP threshold level is determined as 1.5 using Eq. (5).

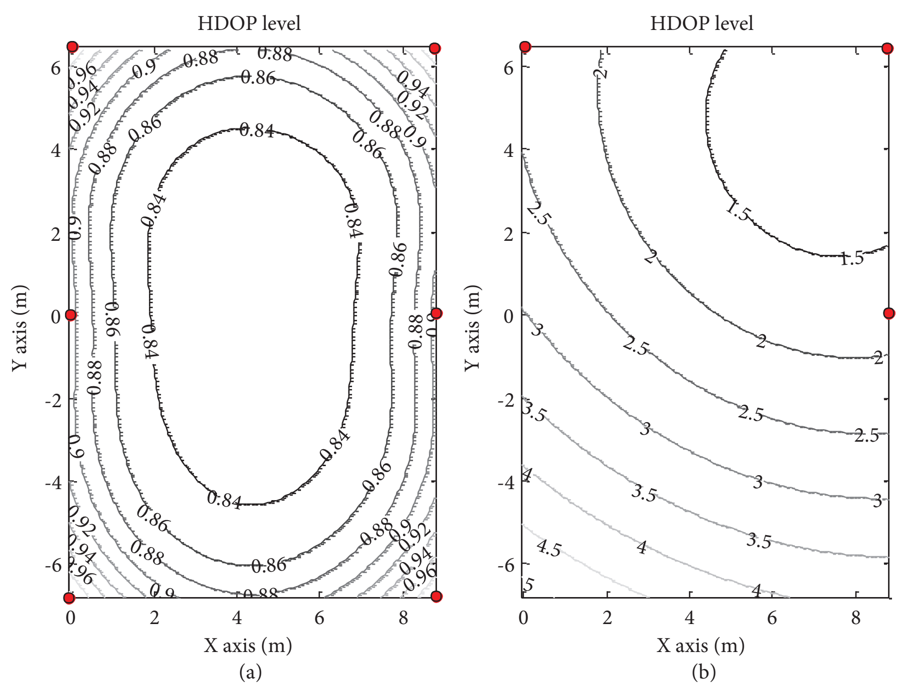

Figure 5. a) Computed HDOP levels for the whole test area when a signal is given from all of the receivers and b) computed HDOP levels for the test area when a signal is given from only 3 receivers.

Figure 6 shows the eliminated measurements of the test area according to the HDOP value. When the tag height is 0.75 m, by eliminating 97% of the measurements for the 11th test point in Figure 6a, the average of the estimations is 0.47 m and there is a 41% improvement. In Figure 6b, nearly 96% of the 21st test point's measurements are over the HDOP level. There is a 12% improvement of the average error by filtering the measurements. When the tag height is 1.51 m for the 16th point, the average error, which is 0.33 m in Figure 6c, is fixed as 0.20 m by eliminating 1417 of the 1570 test measurements. Finally, 5 of the 1576 measurements are below the desired HDOP level for the 13th test point in Figure 6d. The average error of these 5 measurements is fixed as 0.32 m.

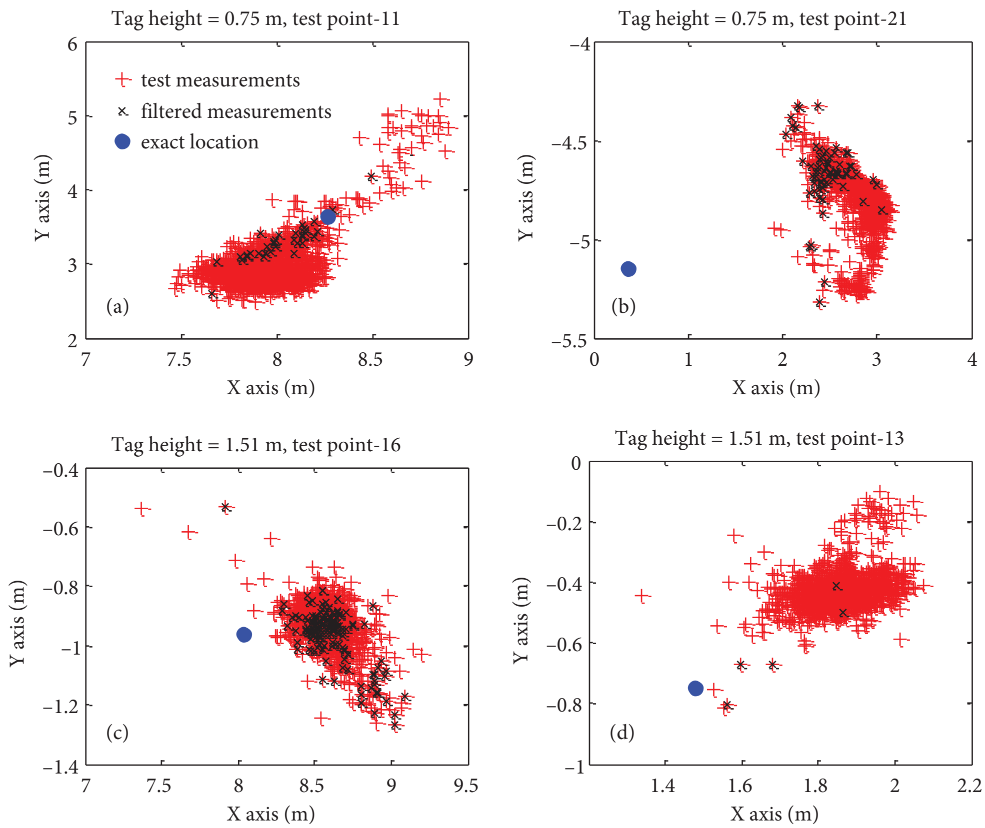

Figure 6. Measurements of the test points in the laboratory by filtering with the HDOP level.

After the process of filtering that uses the HDOP threshold level, the average position errors of all of the test points and the height of each tag are shown in Figure 7. According to these results, when the tag height is 0.75 m, all of the test points' average position errors, except for the 21st test point, are under the limit of 0.6 m. For the tag results of 1.51 m, it is fixed as 0.4 m, except for the 19th test point. If these results are compared to the untreated measurements, it is seen that the average position error, which is 0.4249 m for all of the test points and a tag height of 0.75 m, decreases to 0.3719 using the HDOP threshold level. When the tag height is 1.51 m, it is 0.2271 instead of 0.248. Figure 8 shows the positions that are obtained by the UWB positioning system and the cumulative distribution of the new position estimation results, which are taken by applying the other positioning methods. In Figure 8a, while the experimental measurements have a 0.87 m error in 60%, it is fixed as 0.45 m by the LS, 0.29 m by NLR, and 0.28 m by INR according to the results of the 0.75 m tag height. While the position errors of the NLR and INR are close to each other in this part, they are 0.96 m for the NLR and 0.36 m for the INR in 100%. In addition to this, according to the results of the 21st test point in Figure 8b, whose tag height is 1.51 m, it is seen that the INR algorithm is unsuccessful for this test point and there is no improvement between the other 2 algorithms in 99%. The positioning error, which is nearly 6 m and obtained by the UWB, could be done away in only 1%. According to these results, it can be said that the performance improvement cannot be provided without improving the position estimation for some test points and eliminating all of the position estimations, or cannot be provided in the situation where the INR algorithm does not work.

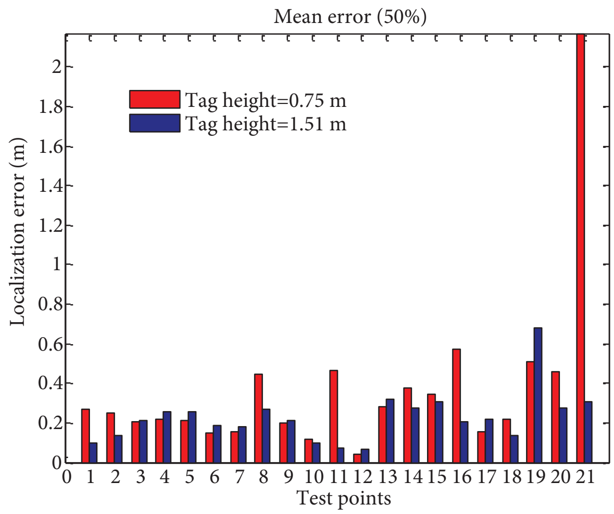

Figure 7. The average position errors that were obtained as a result of filtering all of the test points by the HDOP level.

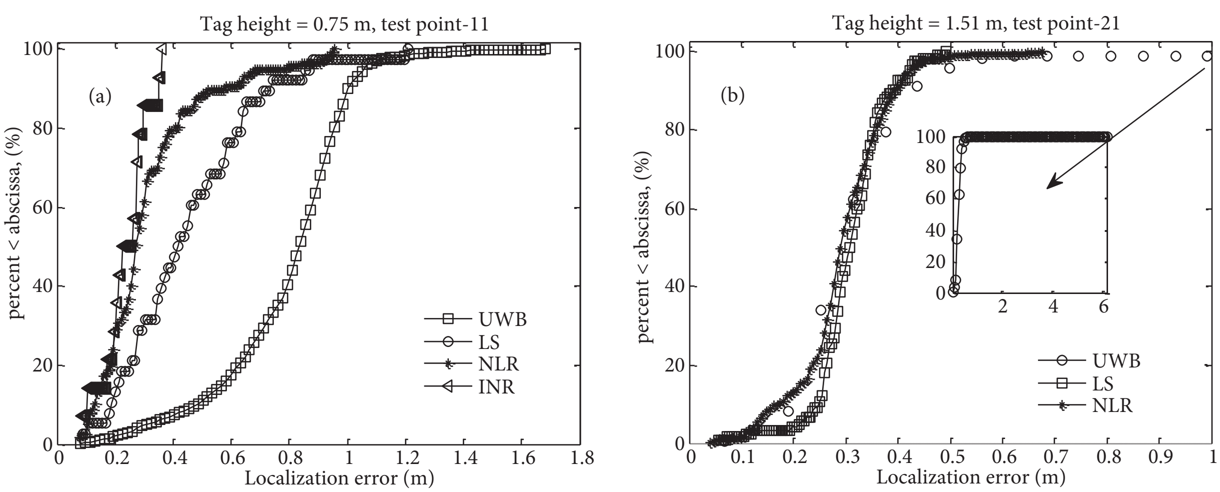

Figure 8. Contrary to the UWB positioning methods, the cumulative distributions of the new position estimations that were obtained by the LS, NLR, and LNR algorithms: a) the test point is 11 and tag height is 0.75 m and b) the test point is 21 and tag height is 1.51 m.

The experimental measurements of the 12th test point and position estimations of these measurements, which are obtained as a result of filtering by the LS, NLR, and INR algorithms, are shown in Figure 9. In the experimental UWB measurements of Figure 9a, when the tag height is 0.75 m, no measurements can determine the real position 100% correctly, but a definite number of measurements can give a 100% real position by the other tag height. In Figure 9b, where the performance of the LS algorithm is shown, it is seen that the estimations, which are far from the real position, are filtered. In Figure 9c, except for the estimations that are closer to the real position, the number of position estimations decreases nearly 70% for each tag height. Finally, it is seen in the position estimation results, which are filtered by the INR in Figure 9d, that not only those that are far away from the real position but also those that are close to the real position are eliminated. The number of position estimations (30) decreases, especially for the 0.75 m tag height.

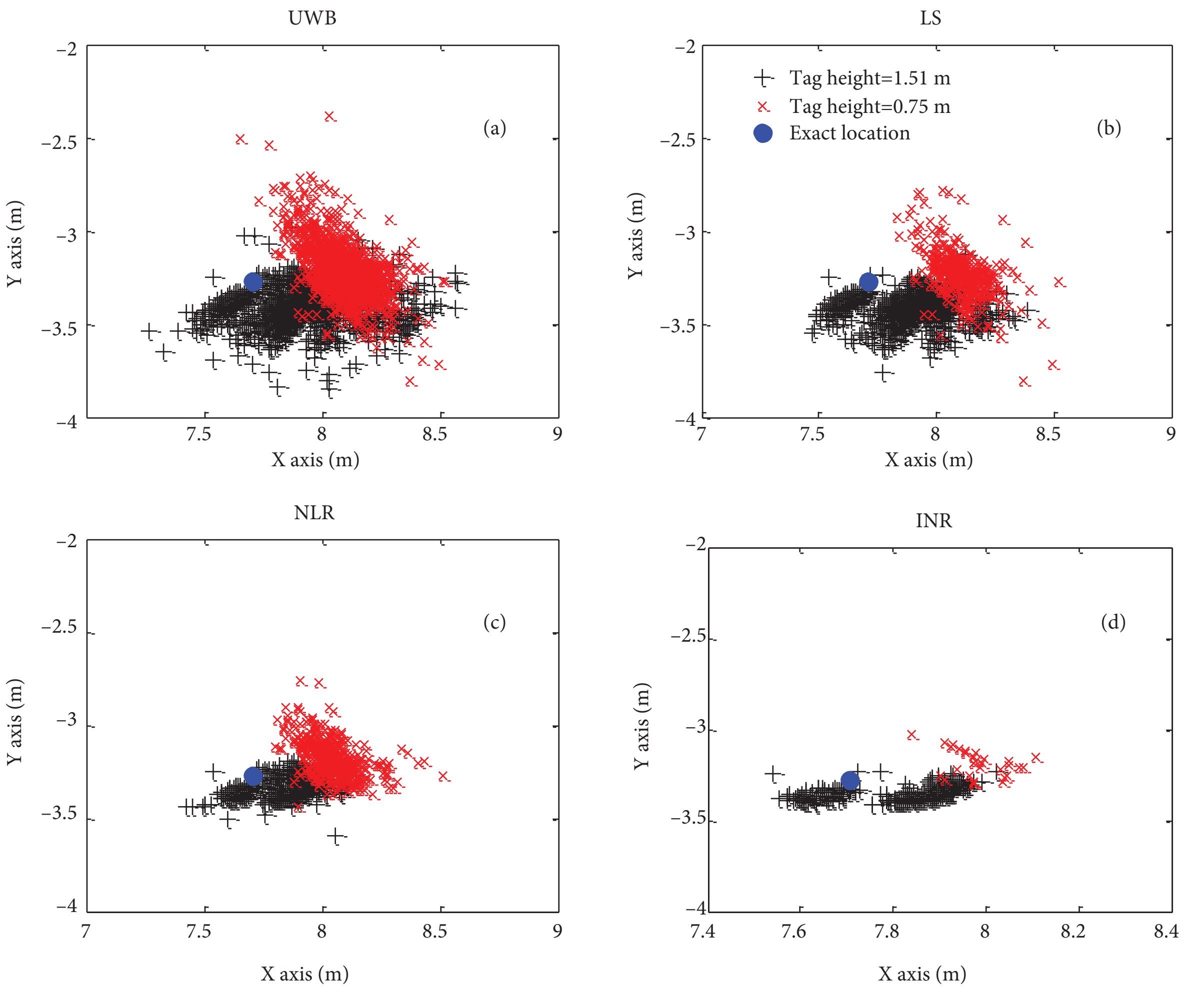

Figure 9. Position estimation after filtering by the algorithms of the 21st test point's position estimations with the UWB positioning method: a) UWB, b) LS, c) NLR, and d) INR.

Figure 10 shows the position errors of the LS, NLR and INR algorithms for the 20th test point and each tag height at the frequency axis. In Figure 10a, the LS algorithm fixes a 0.22 m position error most in 57 times. The position error increases until 0.7 m in the LS algorithm. The NLR algorithm determines 0.15 m and 0.22 m position errors in 21 times. The position error is fixed most at 0.46 m by the NLR algorithm. While the INR algorithm fixes 0.15 position errors in 14 times, this error is fixed most at 0.32 m. According to the results of the 0.75 m tag height in Figure 10b, the LS, NLR, and INR algorithms make position estimation extremely well at 0.44 m in 19 times, 0.34 m in 25 times, and 0.28 m in 3 times in sequence.

In Figure 11, the comparison of experimental measurements and average error performances, which are obtained as a result of improvement with the HDOP method and other algorithms, are presented. According to the results of the 1.51 m tag height in Figure 11a, it is seen that the LS algorithm cannot carry out position estimation of the 16th test point, it cannot provide any improvement of test points such as the 1st and 7th, and

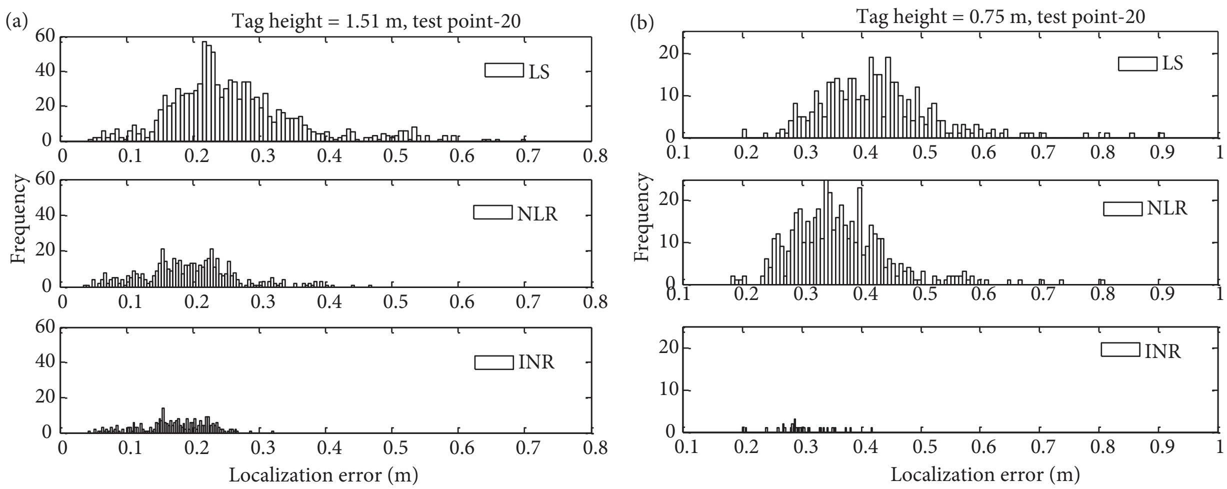

Figure 10. Illustrating the new position estimation errors of the 21st test point, which were obtained by the LS, NLR, and INR algorithms, at frequency axis: a) tag height is 1.51 m and b) tag height is 0.75 m.

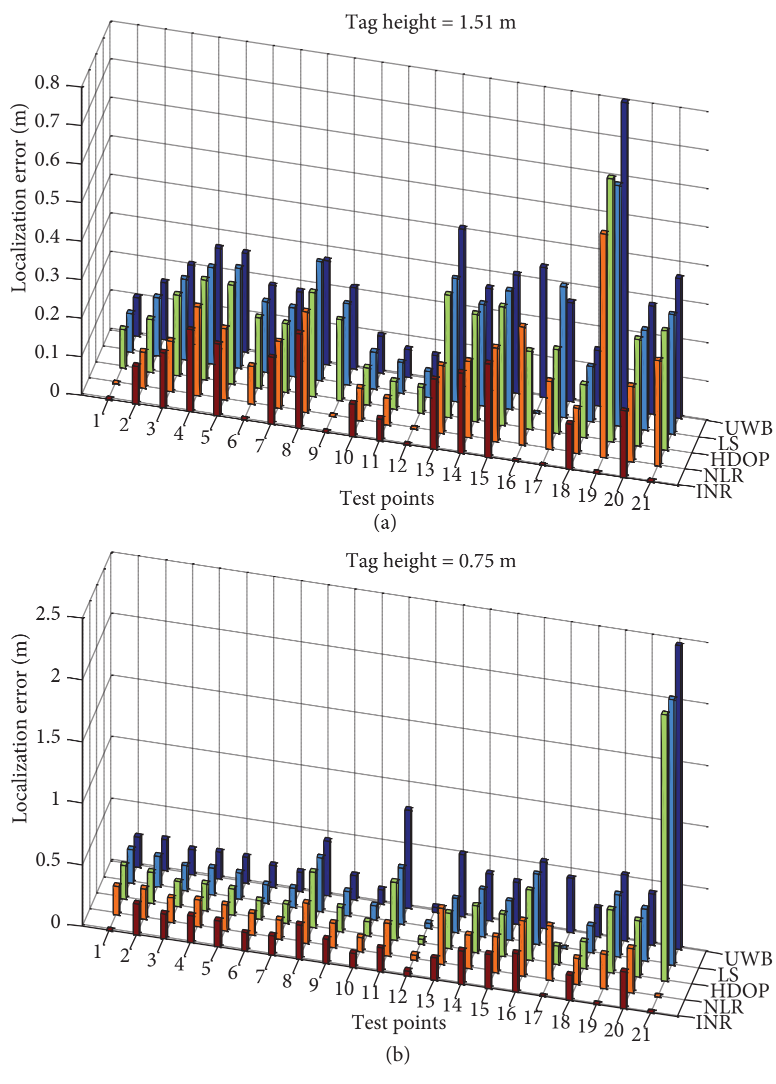

Figure 11. Contrastive average of the position estimation performance of the LS, NLR, and INR methods with position estimations of the UWB system: a) tag height is 1.51 m and b) tag height is 0.75 m.

the performance of some test points, such as the 2nd and 8th, are worse. However, the HDOP method could carry out position estimation for all of the points. In addition to this, while the HDOP method produces better performance for some points like the LS algorithm, it can also carry out some estimations that have a higher error than the UWB system measurements for some points. The NLR algorithm's position estimation performance, which is shown as better than that of the LS and HDOP methods, cannot reach the performance of these methods because the position estimation is not carried out for 3 test points. Hence, while the INR algorithm provides better average positioning performance than the others, it cannot carry out the position estimation of 8 test points. According to the results of Figure 11b, where the tag height is 0.75 m, all of the methods provide nearly the same estimation average (0.039 m) for the 12th test point. According to the average of errors, the INR algorithm, which has the best performance, has the highest percentage of not estimating positions. According to these results, the suggested HDOP method has the best performance by estimating for all of the test points.

According to all of the results and performance evaluations, a general positioning evaluation is given in the Table. According to this, for the tag heights of 0.75 m and 1.51 m, the LS algorithm increases nearly 11% and 6% in performance in sequence by not carrying out 4.6% of the position estimations. While the suggested HDOP method provides better positioning performance than the LS algorithm and worse performance than the NLR and INR algorithms, it is the best one since it can carry out position estimation for all of the test points. The positioning errors, which are decreased by the NLR and INR algorithms, produce undesired performance by increasing the number of test points that cannot be estimated.

Table. Performance improvements provided by the algorithms at average errors and rates for all of the test points and tag heights.

		Rates of improving localization		Rates of the test points that are not estimated	
		0.75 m	1.51 m	0.75 m	1.51 m
Algorithm	LS	11.06%	6.12%	4.76%	4.76%
	HDOP	12.47%	8.42%	0%	0%
	NLR	39.35%	19.39%	4.76%	14.28%
	INR	50.50%	44.07%	19.04%	38.09%

5. Conclusions

In this study, in addition to obtaining the experimental indoor positioning performance of a commercially available UWB positioning system, an improved method of position estimation performance, which is based on the use of the HDOP scale, is presented. In addition to this, in a laboratory environment, the performance improvements of the LS, NLR, and INR methods that are in the literature and position estimations, which are obtained by 2 different tag heights with a UWB positioning system that has 6 receivers, are presented contrastively.

Due to calibration and orientation problems of the receivers, the UWB positioning system can give worse positioning results for some test points than the system's general performance. Thus, this value can be fixed at over 2 m at a 0.75 tag height for the 21st test point. When the position estimations of the UWB positioning system are improved with a positioning method, which is suggested as the HDOP scale and can be fixed as a threshold for that, performance improvements of nearly 10% can be obtained based on the whole performance evaluation. It is guaranteed that this method produces the performance of position estimation for all of the test points, except for the suggested threshold level fixing. However, in accordance with the LS algorithms in the literature, the method using the HDOP scale has better results for each tag height in the performed comparison of performance. According to the NLR and INR algorithms, which are used as the other 2 methods, the high rate of average positioning error that the HDOP method possesses is considered as a disadvantage, since these algorithms cannot make position estimation for the test points of the high rate. The threshold, which is chosen according to that suggested in Eq. (5) for the HDOP scale, is chosen as closer to the upper limit in order to increase the degree of reliability of the results. The rate of performance improvement that is obtained by the HDOP scale can be increased by choosing this value closer to the lower limit.

Adaptively obtaining each test point of the threshold level value, which is used for the DOP scale, and improving faulty measurements, which are based on the calibration and the orientation of the UWB positioning system, with the help of the Kalman filter, will be discussed in future studies.

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