Project of control software and antennas for an indoor UWB localization system

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Abstract

In the last decade, the Real-time Localization Systems (RTLS) have been increasingly relevant. Simple and efficient solutions for indoor tracking are important for several real-world applications. The objective of this work is to provide a fully functional UWB indoor localization system making use of four Time Domain PulsOn P400 ranging modules for which a corresponding controlling software and antenna were developed. The software implements techniques based on Non-Linear Least Squares, Taylor Series approximation and other linear methods that were reviewed. After a careful analysis to the gathered results in a real ranging scenario, it was concluded that the implemented algorithms have achieved an accuracy between 60mm and 156mm for 90%precision. Also, after evaluating the proposed UWB antenna performance in a real ranging scenario using the described modules, it has been observed that the variance of the measurements has faintly decreased compared to the existent antennas. However, the Received Signal Strength increased on average by 2.2dB, which encourages the application of this antenna in ranging systems.
Keywords: Indoor localization systems, Real-time Localization Systems (RTLS), Ultra Wide Band (UWB) Antenna, tracking, UDP, ranging

1. Introduction

Since the inception of wireless propagation, but specially in the last 10 to 15 years, there has been a non-stop development in the area of location techniques. Antennas are one of the most important components in a localization system. They are the entrance and exit points for information when it's transmitted wirelessly. Improvements in the area are almost limitless and there is still a lot of research to be done. Alongside the development of a localization system there's the need for developing software that analyses, processes and presents the user with human readable and useful information. The purpose of localization systems is vast and concerns many scientific fields and services such as medical and healthcare monitoring, inventory location, global positioning or even personal tracking. The objective of this work is to provide a fully functional Ultra Wide Band (UWB) indoor localization system making use of four Time Domain PulseOn P400 ranging modules linked together in an Ethernet network for which a corresponding controlling software and antenna were developed.

The proposed control software consists of a Graphical User Interface (GUI) developed in Visual C# 2012 which communicates via User Datagram Protocol (UDP) packets with the PulsOn P400 modules which are capable of determining distance between themselves by request using a Roundtrip Time of Flight (RToF) protocol via UWB pulses. Positioning, localization and visual post-processing of data algorithms were developed with the aid of the Math.NET Numerics toolkit and MATLAB R2015a which then are used by the software via shared pre-compiled libraries provided by the MATLAB Runtime software package. For intra-module communication a unidirectional, UWB antenna (optimized for the band 3.1 to 5.3 GHz) was developed and tested in an indoor localization scenario. Moreover, the validity of existing Time of Arrival (ToA) localization estimation algorithms is tested in the scope of the developed indoor Real-Time Localization System (RTLS).

This paper is structured as follows. First, the main localization techniques are reviewed. Special importance is given to ToA, which is the method studied in this work. Also, the implemented algorithms in the software are presented. Moreover, in section 3, the proposed UWB antenna is presented and tested. Furthermore, the software and the implemented algorithms are tested in a real ranging scenario. Finally, the conclusions of this work are presented.

2. Indoor localization

A location or localization system is a set of operational devices which possess specific hardware and software to compute and locate the position of a moving or stationary object in a given site. These systems are made of nodes that can represent devices to be located (unknown nodes, dark nodes or target nodes) or reference points whose location is known (reference nodes or base stations). The goal of such systems is to provide a more-or-less precise and accurate location of the object depending on its characteristics and function. A system that does this in real-time is called a RTLS. It is also important to define the rigour of a location estimation system. In the literature, by introducing the concept of Accuracy and Precision, it can be classified how well the location estimation system behaves [5]. Accuracy, or granularity, denotes how close an estimation is to the real value. In the case of location systems, a higher accuracy (finer granularity) means a lower spatial error margin relative to the true location. It is expressed in units of length and it usually arises in the form of a range of values. The precision denotes how likely it is for the estimated value to lie within a certain accuracy interval or above a threshold.

2.1. Indoor localization techniques

Localization techniques are practical and analytical methods to handle different types of measurement information. In what follows, several of the most used localization techniques are introduced.

- **Received Signal Strength Indicator (RSSI)**. This technique uses signal strength (or a measure proportional to it) to identify target position. For RSSI data processing, Fingerprinting based algorithms can be used [8].

- **ToA**. By measuring signal propagation time between nodes, the physical distance between them can be inferred. Target localization can be performed via Trilateration.

- **RToF**. Distance determination by measuring the interval between sent and reflected signal.

- **TDoA**. Distance determination by measuring the difference in signal arrival times sent simultaneously by two different base stations. Target localization can be performed via Multilateration.

- **Angle of Arrival (AoA)/Direction of Arrival (DoA)**. Target position estimation by signal angle of arrival. Target localization can be performed via Triangulation.

- **Proximity**. Target position determination by association with a base station location.

In this paper it is given special attention to the ToA technique as it is the method applied by the developed localization system.

2.1.1 ToA - Time of Arrival

The distance between two nodes can also be measured in terms of the time it takes for the signal to travel between them. Supposing v is the propagation speed of the signal, then $d = v \times (t_2 - t_1)$ where d is the distance between the nodes and t_1 and t_2 are the times at which the signal was sent and received, respectively. However, the calculation of d requires the times t_1 and t_2 to be measured by different nodes in the network. This implies time stamp information transfer between devices as well as prior clock synchronization of the network. These aspects will rise hardware complexity and system cost.

ToA measurements merely infer the time it takes for a signal to arrive at a node so that a distance can be computed. However, the direction of signal arrival is still unknown. Trilateration is a technique for locating an unknown point based on distances to other points whose location is known. Trilateration makes use of at least three distance measurements (in 2D) to three reference nodes. The distance estimates are obtained through ToA or RSSI measurements, for example.

The estimated distance d_i between the target node and the i-th reference node is given by

$$\begin{aligned} ct_i = d_i = f_i(x_i, y_i) + \epsilon_i \\ \text{with} \quad i = 1, 2, \ldots, M \end{aligned} \tag{1}$$

where t_i is the actual ToA measurement, c is the speed of light, ϵ_i denotes the measurement error or noise and

$$\begin{aligned} f_i(x_i, y_i) = \sqrt{(x - x_i)^2 + (y - y_i)^2} \\ \text{with} \quad i = 1, 2, \ldots, M. \end{aligned}$$

Equation 1 is actually a system of equations where (x_i, y_i) are coordinates of the i-th reference node, M the number of reference nodes and (x, y) the coordinates of the target node. For $\epsilon_i = 0$, when three of these circumferences intersect, a fixed location is obtained. This procedure is depicted in Figure 1. The location is obtained by solving the system for (x, y).

However, in a real system, reference node position and distance estimation inaccuracies occur. These are modelled by the noise variable ϵ_i. This variable introduces the probabilistic characteristic

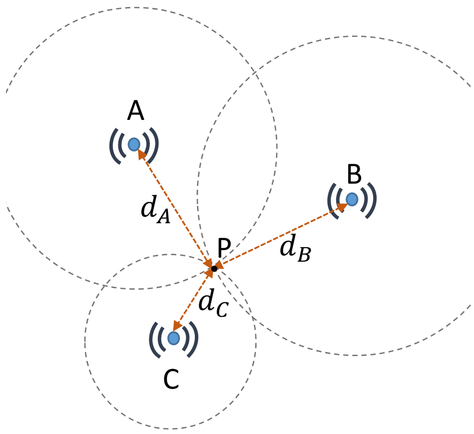


Figure 1: Positioning based on RSSI or ToA measurements.

of this problem and so a new approach has to be applied, i.e. the position (x, y) has to be estimated.

To solve this statistics problem the Maximum Likelihood (ML) method can be applied [3]. Under the assumption that the noise ϵ_i is normally distributed, has zero mean, variance σ_i^2, the estimator $\hat{\boldsymbol{\theta}}_{ML} = [\hat{x}, \hat{y}]^T$ asymptotically achieves the Cramer-Rao Lower Bound (CRLB) [1] [4]. In a real system, M will be finite so, in general, the ML estimator will be biased and have a non-optimal variance greater than the CRLB. The final expression for $\hat{\boldsymbol{\theta}}_{ML} = [\hat{x}, \hat{y}]^T$ corresponds to the following Non-Linear Weighted Least Squares (NLWLS) problem [3]

$$\hat{\boldsymbol{\theta}}_{ML} = [\hat{x}, \hat{y}]^T = \underset{x,y}{\operatorname{argmin}} \sum_{i=1}^{M} \frac{(d_i - f_i(x, y))^2}{\sigma_i^2}. \quad (2)$$

It is noteworthy that the variance of the noises ϵ_i (i.e. σ_i^2) are dependent on i. For each of i measurement there is a different variance because a different channel is used. However, σ_i^2 is also distance dependent, i.e. the noises are heteroeskedastic [6]. To improve performance, a basic variance model is developed for the location system developed in this work.

The absence of a closed form solution to the NLWLS problem in (2) implies the use of iterative and computationally intensive algorithms such as the method of Gauss-Newton, Leverberg-Marqvardt or other Descent methods. Although providing accurate results, these approaches require good parameter initialization to avoid diverging or converging to local minima and minimize iterative steps. Initialization parameters for these algorithms can be obtained via Simple Geometric Pinpoint (SGP) or via linearization techniques. The latter can also be used to obtain an approximate closed form solution to the NLWLS problem. Both SGP and linearization are discussed in detail further on.

[1]The CRLB expresses a lower bound to the variance of an unbiased estimator. It states that this variance is at least as high as the inverse of the Fisher Information matrix.

2.2. Indoor localization algorithms for ToA

Distance measuring in real-word localization scenarios is subject to inaccuracies that require the use of algorithms that try to mitigate the effects of errors in the measurements and deliver the best approximate result. The software developed in this work makes use of these algorithms to process target position estimation which can be separated into two main categories:

- **Linear approach**. Typically involves, but it is not limited to, linearized versions of the Least Squares method which produces fast results with a minimum of mathematical operations. In this paper two linear approaches are presented.

- **Non-linear approach**. Non-linear approaches generally involve iterative algorithms that may reach the correct solution to the non-linear problem within a few steps given proper initialization. Although accurate, these algorithms are computationally intensive. In this paper two non-linear approaches are presented.

2.2.1 Linear approaches

A. Simple Geometric Pinpoint (SGP)

The SGP is a simple and direct positioning method. For three base stations, the case of interest, it consists in finding the target position based on the centroid of the triangular shape formed by the three most closed points, known as cluster points, corresponding to the intersection of the range circles provident from a ToA based range estimation.

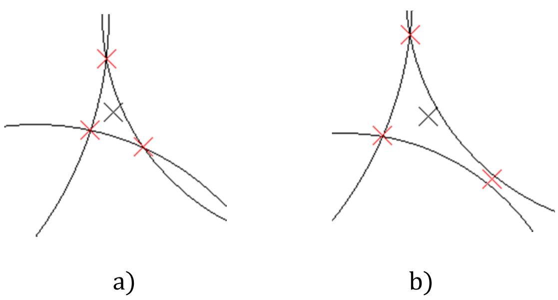


Figure 2: Two possibilities of cluster configuration on a ToA estimation.

The intersection points of two ToA circles are obtained by solving the following system of equations

$$\begin{cases} r_1^2 = (x - x_1)^2 + (y - y_1)^2 \\ r_2^2 = (x - x_2)^2 + (y - y_2)^2 \end{cases}$$

Where (x_1, y_1) and (x_2, y_2) are base station coordinates and r_1 and r_2 are distance estimates to target. The solution set (x_{c1}, y_{c1}), (x_{c2}, y_{c2}) exists when both circles intersect and both points are candidates to cluster points, Figure 2 a). To determine which of the two intersections belongs to the cluster, the distance differences from the two intersection points to the circle defined by the measurement of the third base station are computed. The point whose distance difference is the smallest belongs to the cluster. In case the ToA circles only intersect at one point, there is only one solution to the system of equations and the corresponding point (x_c, y_c) is automatically a cluster point. The third case, Figure 2 b), occurs when two ToA circles don't intersect at all. In this case the cluster point is a point where the distance to either circles is minimized.

The centroid of the triangle formed by the cluster points can be found by averaging the x and y coordinates of the cluster points. Let x_{c1}, x_{c2}, x_{c3} and y_{c1}, y_{c2}, y_{c3} be the x and y coordinates of the cluster points, respectively. Then, the centroid denoting target final position (x_T, y_T) is:

$$x_T = \frac{x_{c1} + x_{c2} + x_{c3}}{3} \qquad y_T = \frac{y_{c1} + y_{c2} + y_{c3}}{3}$$

The SGP can be applied to any system where the Base Station (BS) number is larger than 1 and is useful for course localization measurements that don't require much accuracy. The fact that it has a closed form solution, makes this a low resource method which is favourable for computation time. The points provided through SGP may serve as initialization points for more advanced and computer intensive statistical approaches like Least Squares (LS). Still, it is not guaranteed that SGP points will be close to the optimal LS solution which can increase computational requirements compared to other initialization techniques.

B. Linearized Least Squares Approximation (LLS)

Linear solutions consist on linearizing the involved equations (1) so that they depend linearly on the parameters to be estimated, in this case x and y, the position coordinates of the target.

Following the linearization proposed in [2], squaring both sides of (1) gives

$$\begin{aligned} xx_i + yy_i - \frac{1}{2}R^2 &= \frac{1}{2}(x_i^2 + y_i^2 - f_i^2) \\ &\text{with} \quad i = 1, 2, \ldots, M. \end{aligned} \tag{3}$$

with $R = \sqrt{x^2 + y^2}$.

Writing the system of equations in (3) in the matricial form $\boldsymbol{A}\vec{\gamma} = \vec{b}$:

$$\boldsymbol{A} = \begin{bmatrix} x_1 & y_1 & -\frac{1}{2} \\ x_2 & y_2 & -\frac{1}{2} \\ \vdots & \vdots & \vdots \\ x_M & y_M & -\frac{1}{2} \end{bmatrix}, \vec{\gamma} = \begin{bmatrix} x \\ y \\ R^2 \end{bmatrix},$$

$$\vec{b} = \frac{1}{2} \begin{bmatrix} x_1^2 + y_1^2 - f_1^2 \\ x_2^2 + y_2^2 - f_2^2 \\ \vdots \\ x_M^2 + y_M^2 - f_M^2 \end{bmatrix}.$$

The system $\boldsymbol{A}\vec{\gamma} = \vec{b}$ can be solved recurring to the known standard least squares estimation

$$\hat{\vec{\gamma}} = \underset{\hat{\vec{\gamma}}}{\operatorname{argmin}} (\boldsymbol{A}\hat{\vec{\gamma}} - \vec{b})^T (\boldsymbol{A}\hat{\vec{\gamma}} - \vec{b}) = (\boldsymbol{A}^T\boldsymbol{A})^{-1}\boldsymbol{A}^T\vec{b} \tag{4}$$

In case there are only three measurements (one from each base station, ie. $M = 3$) the system $\boldsymbol{A}\vec{\gamma} = \vec{b}$ is determined and has a trivial solution which is given by $\vec{\gamma} = \boldsymbol{A}^{-1}\vec{b}$.

Although simple, the method in (4) still has two problems. First, the restriction $R = \sqrt{x^2 + y^2}$ is not accounted for and secondly, in case $M > 3$, the variance of the errors σ_i^2 is also ignored. Also the value of f_i is unknown and will have to be replaced by d_i for implementation.

To improve the estimator, the variances of the errors can be taken into account. According to [1], the best linear unbiased estimator is given by the following Linear Weighted Least Squares (LWLS) estimator

$$\begin{aligned} \hat{\vec{\gamma}} &= \underset{\hat{\vec{\gamma}}}{\operatorname{argmin}} (\boldsymbol{A}\hat{\vec{\gamma}} - \vec{b})^T \boldsymbol{W} (\boldsymbol{A}\hat{\vec{\gamma}} - \vec{b}) = \\ &= (\boldsymbol{A}^T\boldsymbol{W}\boldsymbol{A})^{-1}\boldsymbol{A}^T\boldsymbol{W}\vec{b} \end{aligned} \tag{5}$$

with

$$\vec{b} = \frac{1}{2} \begin{bmatrix} x_1^2 + y_1^2 - d_1^2 \\ x_2^2 + y_2^2 - d_2^2 \\ \vdots \\ x_M^2 + y_M^2 - d_M^2 \end{bmatrix}$$

and

$$\begin{aligned} \boldsymbol{W}^{-1} &= diag(f_i^2\sigma_i^2, ..., f_M^2\sigma_M^2) \\ &\approx diag(d_i^2\sigma_i^2, ..., d_M^2\sigma_M^2). \end{aligned} \tag{6}$$

2.2.2 Non-linear approaches

A. Non-Linear Least Squares (NLLS)

As discussed in section 2.1.1 for ToA, the optimal solution to the target position (x, y) in the problem (1) can be estimated through the Method of Maximum Likelihood which degenerates into a Non-Linear Least Squares (NLLS) problem given by

$$S = \frac{1}{2}\sum_{i=1}^{M} W_{ii}\epsilon_i^2. \tag{7}$$

where

- M is the number of measurements.
- W_{ii} is a weighting diagonal matrix equal to $1/\sigma_i^2$. Is it important to note that the errors are assumed to be uncorrelated which is generally accepted for ToA estimation [3].
- ϵ_i is the residual error and $\epsilon_i = d_i - f_i(x, y)$ where d_i is the measured distance and $f_i(x, y) = \sqrt{(x - x_i)^2 + (y - y_i)^2}$ where (x_i, y_i) are the position of the base stations to which the i-th measurement was taken.

The goal of the Least Squares method is to find the values of (x, y) that minimize the sum of the squares of the residuals, i.e. minimize the quantity S. Defining $\vec{\gamma} = (x, y)^T$ and computing the derivative of S with respect to γ_j where $j = 1, 2$ and setting it to zero gives

$$\frac{\partial S}{\partial \gamma_j} = \sum_{i=1}^{M} W_{ii}\epsilon_i J_{ij} = 0 \tag{8}$$

where $J_{ij} = \partial\epsilon_i/\partial\gamma_j$ is the Jacobian matrix.

In contrast to the trivial linear least squares, the matrix $\boldsymbol{J}$ actually depends on the parameters to be estimated so there is no closed form solution to (8). Evaluating $\boldsymbol{J}$ gives,

$$J_{ij}(x, y) = \begin{bmatrix} -\frac{x - x_1}{h_1} & -\frac{y - y_1}{h_1} \\ \vdots & \vdots \\ -\frac{x - x_M}{h_M} & -\frac{y - y_M}{h_M} \end{bmatrix} \tag{9}$$

where $h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2}$.

As opposed to the linear approaches and the Taylor-Series approximation described next, the software developed in this work makes use of the already programmed and optimized iterative non-linear least squares solver available in the Optimization Toolkit which can be accessed via the MATLAB Runtime package to solve equation (8) - this is the only employed localization method which needs external software. The command for the used solver is the known MATLAB command *lsqnonlin* with the default iterative algorithm Trust-Region Reflective, since there are no constraints on the parameters (x, y) and the system is overdetermined. To reduce the amount of function evaluations within the execution of the command, each time the solver is called, the Jacobian (9) is computed beforehand and provided to MATLAB Runtime engine each time a location estimation is carried out.

B. Taylor Series Approximation (TS)

The Taylor Series Approximation (TS) for ToA is an iterative method that locally linearizes the function

$$f_i(x, y) = \sqrt{(x - x_i)^2 + (y - y_i)^2} \qquad i = 1, 2, \ldots, M \tag{10}$$

in the neighbourhood of an initial target position estimate (x_e, y_e), which can be obtained through SGP or other Linear Least Squares approach. Approximating (10) by a first order Taylor series expansion gives

$$f_i(x, y) \approx f_i(x_e, y_e) + \theta_x \frac{\partial f_i(x, y)}{\partial x}(x_e, y_e) + \\ + \theta_y \frac{\partial f_i(x, y)}{\partial y}(x_e, y_e) \tag{11}$$

where $\theta_x = x - x_e$ and $\theta_y = y - y_e$ and where

$$\frac{\partial f_i(x, y)}{\partial x}(x_e, y_e) = \frac{x_e - x_i}{h_{ei}}$$
$$\text{and } \frac{\partial f_i(x, y)}{\partial y}(x_e, y_e) = \frac{y_e - y_i}{h_{ei}}$$

with $h_{ei} = \sqrt{(x_e - x_i)^2 + (y_e - y_i)^2}$, equation (10) can be expressed as

$$\boldsymbol{A}\vec{\theta} = \vec{b} \tag{12}$$

where

$$\boldsymbol{A} = \begin{bmatrix} \frac{x_e - x_1}{h_{e1}} & \frac{y_e - y_1}{h_{e1}} \\ \vdots & \vdots \\ \frac{x_e - x_M}{h_{eM}} & \frac{y_e - y_M}{h_{eM}} \end{bmatrix}, \vec{\theta} = \begin{bmatrix} \theta_x \\ \theta_y \end{bmatrix},$$
$$\vec{b} = \begin{bmatrix} f_1(x, y) - f_1(x_e, y_e) \\ \vdots \\ f_M(x, y) - f_M(x_e, y_e) \end{bmatrix}.$$

According to (1), and since the value of $f_i(x, y)$ is unknown, it is replaced by $d_i - \epsilon_i$. Updating $\vec{b}$ and defining $\vec{p} = [\epsilon_1, ..., \epsilon_M]^T$ gives

$$\vec{b} = \begin{bmatrix} d_1 - f_1(x_e, y_e) \\ \vdots \\ d_M - f_M(x_e, y_e) \end{bmatrix}$$

also the system in (12) becomes

$$\boldsymbol{A}\vec{\theta} + \vec{p} = \vec{b} \tag{13}$$

The minimum amount of measurements is $M = 3$, since there are three base stations, which means the system in (13) is always overdetermined. Moreover, $\vec{p}$ is a random vector whose covariance matrix is given by

$$\boldsymbol{C_p} = \mathbb{E}[\,\vec{p}\vec{p}^T\,] = diag(\sigma_1^2, ..., \sigma_M^2) \tag{14}$$

where $\mathbb{E}[\;]$ is the expectation operator and, once again, the errors are assumed to be uncorrelated [3].

According to [7], the best linear unbiased estimator for $\hat{\vec{\theta}}$ in (13) is given by the following LWLS problem

$$\begin{aligned}\hat{\vec{\theta}} &= \underset{\hat{\vec{\theta}}}{\operatorname{argmin}}(\boldsymbol{A}\hat{\vec{\theta}} - \vec{b})^T \boldsymbol{C}_p^{-1}(\boldsymbol{A}\hat{\vec{\theta}} - \vec{b}) = \\ &= (\boldsymbol{A}^T\boldsymbol{C}_p^{-1}\boldsymbol{A})^{-1}\boldsymbol{A}^T\boldsymbol{C}_p^{-1}\vec{b}.\end{aligned} \tag{15}$$

Equation (15) is then solved using QR decomposition. The variances of equation (14) are obtained through the noise model suggested next.

2.3. Noise model

The variance of distance measurement between a base station and a target depends on several factors such as system bandwidth, clock jitter - which remain constant - and distance dependent ones such as the Signal-to-Noise ratio (SNR). This means that the expected measurement variance actually depends on the parameter being estimated. There are several methods to address this problem [3, 6] that are based on SNR variation applied to indoor path loss models. A variance or noise model is important when using Weighted algorithms as it should be given less importance to more noisy measurements so that target detection occurs more precisely. The hardware (Time Domain P400 modules) used to produce distance measurements is part of a commercial product, so the post-processing algorithms used internally are not available to the user and no noise model is given. As a result, a more empiric approach had to be employed in order to develop a simple noise model for this system. Two modules were placed front to front and 1000 distance samples between the target and the base station were taken in 0.3m steps from 0.6m to 4.8m. The variance is estimated by a set of these samples for each distance and is plotted in Figure 3. The antenna used was the stock 3dBi omni-directional monopole antenna. The polynomial Least Squares fit carried out in MATLAB is plotted in Figure 3 as well and it is given by (16). Measurements under 300mm are considered to have a constant 19mm standard deviation.

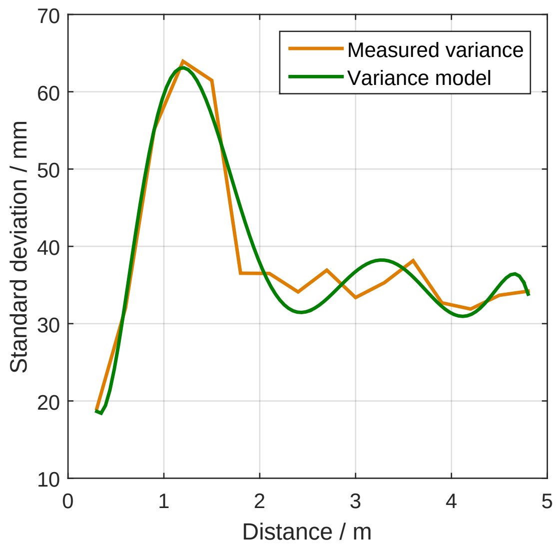


Figure 3: Measured standard deviation and interpolated noise model.

$$\sigma(d) = \begin{cases} 19, \text{ if } d \leq 0.3m \\ \\ (-0.01d^7 + 0.2d^6 - 1.5d^5 + 5.5d^4 \\ -11.5d^3 + 11.1d^2 - 4.4d + 0.8) \times 10^2, \\ \text{ if } d > 0.3m \end{cases} \tag{16}$$

3. UWB reflector antenna

The original stock 3dBi omni-directional antennas [10] for each module are variations of a UWB monopole, which offers a practical 3dBi gain in all directions perpendicular to the antenna. This omnidirectional radiation characteristic is optimal when orientation of the target is not known or when signals are expected to arrive from any direction, which is the case. However, for static base station antennas, their spacial orientation can be set and remain unchanged throughout the operation of the system. Consequently, a UWB monopole may not be the optimal antenna for a static base station if the target remains in a confined area. To improve SNR and possibly decrease measurement variance, a more directional and high gain antenna is developed and tested. Additionally, the more directivity, the less multipath effects on received and sent signals.

The main idea behind the development of the proposed high gain, directive UWB antenna relies on the use of a reflector metallic plane placed near the antenna so that the radiated power can be narrowed down to a specific direction. The proposed antenna is shown in Figure 4. The side view with reflector plane dimensions is shown in Figure 5.

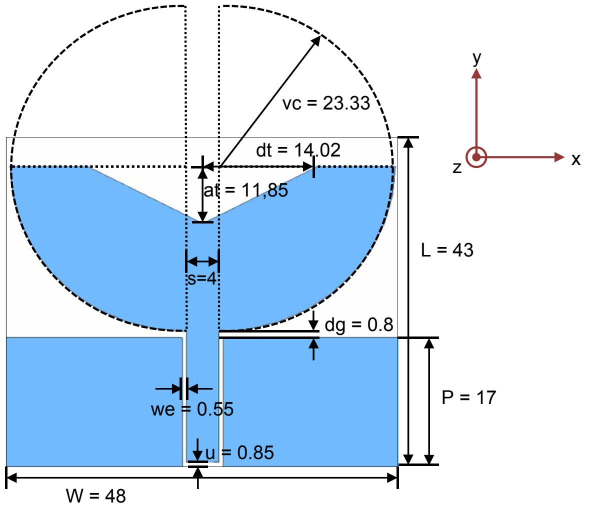


Figure 4: Base model for the proposed UWB antenna design - reflector plane and SMA connector not shown (dimentions in mm).

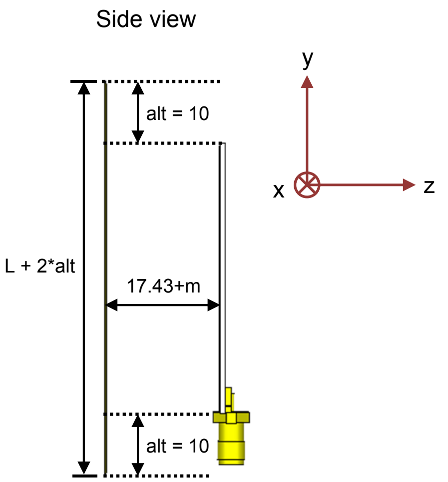


Figure 5: Perspective and side view of the antenna model with reflector plane and SMA connector (dimensions in mm).

The antenna is fed by a Coplanar Waveguide (CPW). In this feeding technique, the ground conductors and the feed line are on the same plane. The substrate used is the Rogers 5880 laminate with 0.787mm thickness and dielectric constant $\epsilon_r = 2.2$. All metallic parts and surfaces (conductors, connector and reflector plane) are modelled by lossy copper with conductivity 5.8×10^7 S/m. The software tool used to simulate antenna behaviour is the CST Microwave Studio 2015 and the simulated and measured reflection coefficient S_{11} are plotted in Figure 6. Simulated antenna directivity for the z-direction (perpendicular to antenna plane) is plotted in Figure 7.

By analysing the obtained results, it can be concluded that the antenna is matched for the band 3.3GHz to 10GHz which corresponds to the simulated results except for the lower frequencies. The lower band of the prototype in contrast to the theoretical model, can be explained by several factors not accounted for in the simulation. The submillimetre precision required to get optimal experimental results cannot be reached in practice, therefore the results are subject to error. Moreover, coaxial cable to connector mismatch will affect input impedance which will in turn worsen S_{11} results. Furthermore, substrate misalignments relative to the ground plane will also negatively influence results. At the beginning of the band of interest (3.1GHz) the antenna prototype as an S_{11} equal to -7.5dB which is an acceptable value nonetheless. As for antenna directivity, it can be seen in Figure 7 that above 6GHz the antenna ceases to be directive in the z direction and is no longer optimal for ranging applications.

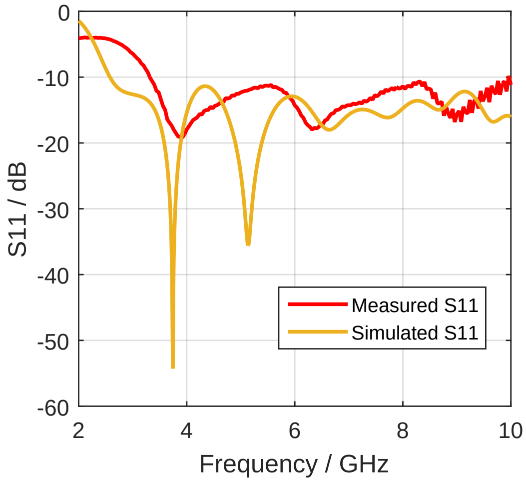


Figure 6: Simulated and measured S11.

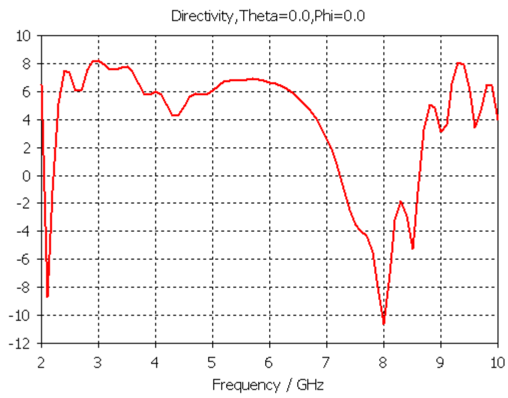


Figure 7: Simulated directivity.

3.1. Performance measurement in a ranging system

To evaluate performance in a real ranging system, three PulsOn P400 modules were used: One target and two base stations. The proposed antenna was attached to one of the base stations. The other two modules use the stock 3dBi omni-directional monopole antenna [10], which will act as the reference antenna. The measurement set-up is depicted in Figure 8.

The objective of this test is to compare distance measurement variance between antennas as well as to obverse the change in RSSI for both base stations. To achieve this, 1000 distance samples between the target and the base stations were taken in 0.3m steps from 0.6m to 4.8m. Measurement variance was computed and plotted in Figure 9.

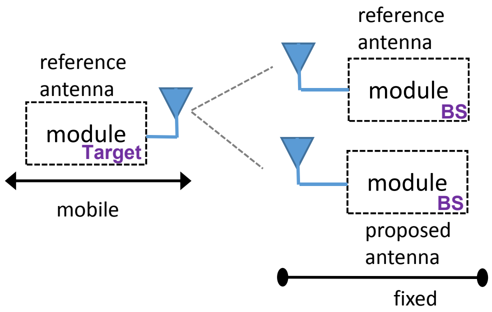


Figure 8: Scheme of measurement setup.

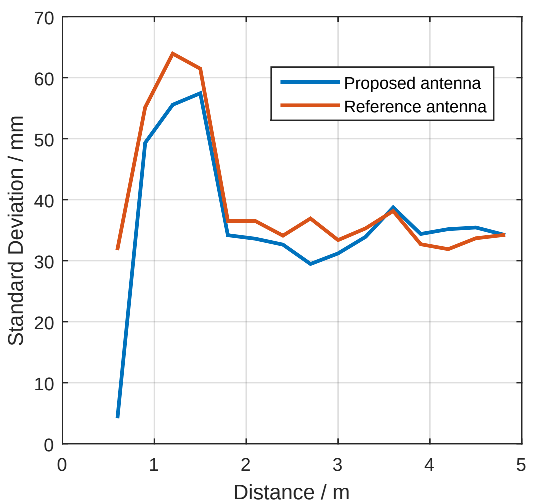


Figure 9: Variance comparison for proposed and reference antenna.

In can be seen that the proposed antenna manages to slightly improve measurement variance specially for small distances when compared to the reference antenna. In Figure 10, the difference in RSSI in dB from both base stations is plotted. It can be seen that the proposed antenna improves RSSI at the target up to 3.3dB. On average, RSSI increases 2.27dB. This result indicates system range improvement as well as higher capability and compatibility for application in RSSI based localization systems.

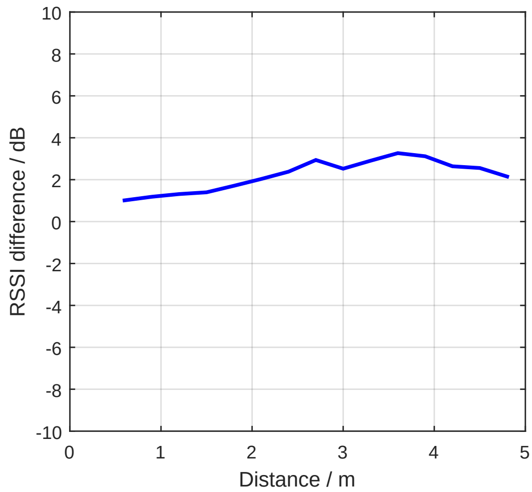


Figure 10: RSSI difference between proposed and reference antenna.

It is worth to mention that the presented results only apply for the commercial system in study. Performance may vary if the proposed antenna is used in other systems. This is because signal post-processing algorithms vary from system to system. In this specific case, they are not known to the user and they too have influence on measurement variance. Moreover, UWB pulse distortion caused by the antenna will also affect variance results. Antenna fidelity factor [9] measurements were not carried out due to time constraints.

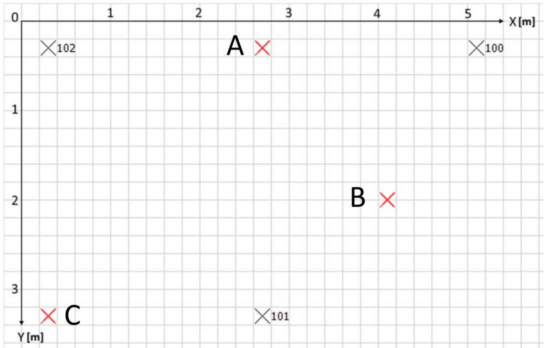
4. Software and algorithms performance

In this test the goal is to obtain an estimation of the system accuracy and mean error depending on the algorithm and initializer used. Also, the influence on target position relative to the base stations is analysed. All measurements were carried out with three different target positions. The obtained results were processed by the developed software.

Figure 11 depicts base station layout and true target positions with a red cross.

Location of target points A, B and C were chosen strategically so that every limit location of the base station layout could be tested. Unfortunately, due to space limitations, points outside the rectangle defined bu the base stations could not be tested although the system is prepared to do so, depending only on the employed solver algorithm. The antennas used for the this test were the stock omni-directional monopoles.

The studied algorithms were tested and its performance measured in terms of the accuracy of measurements with 90% precision and the Mean Distance Error (MDE). MDE is computed as the mean



Target	X [m]	Y [m]	B.S.	X [m]	Y [m]
A	2.7	0.3	100	5.1	0.3
B	4.1	2	101	2.7	3.3
C	0.3	3.3	102	0.3	0.3

Figure 11: Base station layout and target test positions.

euclidean distance between position samples and the true target position and is expressed by

$$MDE = \frac{1}{M} \sum_{i=1}^{M} \epsilon_i \qquad (17)$$

where

- M denotes the amount of successful measurements.
- $\epsilon_i = \sqrt{(x_p - x_r)^2 + (y_p - y_r)^2}$ where (x_p, y_p) are the coordinates of the estimated position and (x_r, y_r) are the real coordinates of the target.

For each combination of algorithm and initializer, 700 samples were taken. Additionally, for the applicable algorithms, two Measurements per Sample (mps) were taken for comparison purposes. The results for the points A, B and C are presented in Tables 12, 13 and 14 respectively, where T.A. time stands for *Tracking Algorithm* execution time. The T.A. time is the time it takes for the sequential distance measurement from the three base stations and execution of initializer and solving algorithm.

Analysing the results, it can be concluded that the performance of the linearized models (including SGP) differs significantly from point to point, which was expected due to the validity of the linear models depending on target position. Also, there was no significant difference on iterative Weighted vs. Non-weighted algorithms. The LWLS, although it is a Weighted algorithm, performed better than Linear Least Squares (LLS) due to the fact that it needs 2mps. It is noteworthy though, that system noise will depend on channel propagation conditions and can differ substantially in indoor scenarios, so Weighted algorithms could make a difference if the system were to be tested in other conditions, other base station configuration and employing other noise models. Another important point to be noted is that system sampling frequency is limited by the mean Tracking Algorithm (T.A.) time, which includes 3 (at 1mps) and 6 (at 2mps) sequential measurement requests to the base stations each one taking around 50ms. This time is hardware inherent and cannot be overcome by the developed software - also, T.A. mean time remained relatively constant on all three tested points for each evaluated algorithm.

POINT A	** Not aplicable		-- Not computed					
Algorithm / Init.	Mean T.A. time [ms]		MDE [mm]		Maximum error [mm]		Accuracy 90% pre. [mm]	
	1 mps	2 mps	1 mps	2 mps	1 mps	2 mps	1 mps	2 mps
SGP	151	**	67	**	222	**	156	**
LLS	150	**	40	**	124	**	80	**
LWLS	**	301	**	35	**	105	**	65
TS/LLS	154	309	35	25	130	70	61	44
NLLS/LLS	164	--	35	--	148	--	73	--
NLWLS/LLS	164	--	34	--	134	--	72	--

Figure 12: Data for point A.

POINT B	** Not aplicable		-- Not computed					
Algorithm / Init.	Mean T.A. time [ms]		MDE [mm]		Maximum error [mm]		Accuracy 90% pre. [mm]	
	1 mps	2 mps	1 mps	2 mps	1 mps	2 mps	1 mps	2 mps
SGP	152	**	64	**	159	**	105	**
LLS	152	**	40	**	151	**	71	**
LWLS	**	317	**	29	**	94	**	50
TS/LLS	154	308	36	29	100	70	65	55
NLLS/LLS	163	--	36	--	102	--	63	--
NLWLS/LLS	163	--	35	--	106	--	61	--

Figure 13: Data for point B.

POINT C	** Not aplicable		-- Not computed					
Algorithm / Init.	Mean T.A. time [ms]		MDE [mm]		Maximum error [mm]		Accuracy 90% pre. [mm]	
	1 mps	2 mps	1 mps	2 mps	1 mps	2 mps	1 mps	2 mps
SGP	152	**	67	**	141	**	130	**
LLS	150	**	53	**	214	**	100	**
LWLS	**	303	**	44	**	118	**	70
TS/LLS	154	307	36	32	116	91	65	60
NLLS/LLS	164	--	41	--	136	--	64	--
NLWLS/LLS	163	--	42	--	154	--	66	--

Figure 14: Data for point C.

5. Conclusions

The main objective of this work was to provide a software control interface for a UWB indoor localization system based on commercially available wireless modules (TimeDomain P400) capable of distance measuring via an RToF protocol. A UWB antenna reflector antenna to be used with this system is also proposed.

The main goal of the proposed antenna was to investigate if a high gain and directional antenna has influence on distance measurements variance of a UWB ranging system. In the band of interest (3.1 - 5.3GHz), the developed antenna also achieves a theoretical maximum directivity of 8.1dBi. The model was then prototyped and tested in a real scenario. There was a slight discrepancy between the measured and theoretical S_{11} in the lower frequencies of the band, which can be explained by poor coaxial connector matching properties as well as prototype manufacturing imperfections. Additionally the antenna was tested in a real ranging system scenario and its performance compared to 3dBi stock UWB omni-directional monopole antennas. After evaluating the antenna performance, it has been observed that the variance of the measurements is on average 9mm lower when compared to the reference omni-directional monopole up to a distance of 3.8m. However, the most improvement is in Received Signal Strength Indicator (RSSI) readings, which reached up to 3.3dB.

The developed software was also tested in a real scenario where the accuracy (for 90% precision) and Mean Distance Error (MDE) were measured for various algorithm combinations in various point targets. It can be concluded that the Taylor Series Approximation (TS) algorithm establishes a fair compromise between *Tracking Algorithm* time and consistent results in terms of MDE and accuracy. The developed software is able to provide an intuitive user interface that controls the modules via UDP packets, processes distance information, applies verified and tested localization algorithms - all in a stand alone application. Furthermore, it provides a Simulation Console where algorithm performance can be tested in different base station configurations and target behaviour without actually setting up a laboratory measurement. Moreover, the software provides a real time target location visualization as well as linear position interpolation. At the end of each tracking sequence, a report containing the gathered data and tracking statistics is presented to the user.

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