# ACCURACY IMPROVING ALGORITHM FOR WIRELESS 3D LOCATING SYSTEMS

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Abstract: In this paper we propose an approach to improve the object location accuracy and enable better attitude estimation for wireless locating systems. This method combines the position data of multiple tags placed on an object. The algorithm is independent of the technology used to measure the tags position or the methods of pre-processing the data. The algorithm has been tested experimentally with an Ubisense system based on ultra wide band (UWB) communication. It has been demonstrated that the accuracy can be improved by a factor of three down to a couple of centimetres. This improved accuracy allows estimating not only the location but also the attitude of an object.

## 1 INTRODUCTION

During the last years, applications involving wireless locating and real time positioning are being adopted by industry. Some examples are GPS technology used in agricultural applications to locate the machinery on the fields or the use of UWB Ubisense modules in the automotive manufacturing industry. When working in outdoor environments traditional location systems are used, for instance GPS. However, those systems are not available, reliable or accurate enough when working with indoor positioning. For this reason new solutions using other technologies have been developed.

Due to its large bandwidth and robustness against interferences, ultra-wideband technology (UWB) is an ideal candidate to provide positioning information in indoor environments (Dardari, 2009) (Gezici, 2005). The UWB location system of Ubisense consists of tags, location devices attached to an object that allow it to be located by broadcasting radio signals, and hubs, sensor devices which generate location data corresponding to tagged objects by measuring the time and angle of arrival of these radio signals. Based on these measurements, the position of the tags is next estimated. With this technique it is possible to get an accuracy of a couple of tens of centimetres, which can be enough for multiple locating applications.

Nevertheless, for some applications this accuracy may not be enough. Particular examples are the applications in which it is necessary to determine the attitude of an object. By placing three tags on an object, it is possible to estimate the orientation of the object in space. In this case, an error of some tens of centimetres for each tag means an unacceptable attitude error.

Some previous works, have tried to minimize the location error by improving the hardware and the applied locating technique itself (Zhang, 2008). Others have focused on time filtering methods (Muthukrishnan, 2009), which incurs a certain delay before giving an accurate response. In this paper we present a new real-time method that minimizes the location error by using multiple tags. Because this is independent of the technology used to measure the object location, it can be applied to any positioning measurement.

The paper is organised as follows. In Section 2, we first introduce the experimental set-up used to validate our approach. In Section 3, we analyze the initial data gathered with our set-up. In Section 4, we propose a novel algorithm to improve positioning accuracy for attitude estimation: first a geometrical approach and second an approach based on optimization. This method has been experimentally tested and validated and some initial results are shown in Section 5. Finally, Section 6 summarizes


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our major conclusions.

## 2 EXPERIMENTAL SET-UP

Before proposing our approach, data from previous works have been analysed and verified. To this end and also to validate our approaches, an UWB-based system from Ubisense has been used. This system consists of four hubs placed at different positions, the four corners of the experimentation room, one of whom acts as a master for the other hubs and tags. The four hubs are synchronised, so it is possible to calculate the arrival time differences of the tag's signal to each of them (Ubisense, 2008). The master is continuously sending a beacon, and when the tags receive it, they send a broadcast packet. When the hubs receive the broadcast packet, they are able to measure both its Angle-of-Arrival (AoA) and Time-Difference-of-Arrival (TDoA). Once they have estimated this information, they send it to the master, which will calculate the time-difference-of-arrival between the hubs and will combine it with the angle-of-arrival information to estimate the position of the tag.

Although the Ubisense system can use different kind of filters to improve the positioning of the object, during this work all them have been deactivated, so that what we get is the raw position data. This means that the system has no memory, the position is not traced and only data measured during the current time slot are used.

The system includes an automatic calibration option, which requires entering the three Cartesian coordinates plus the pitch and yaw angles of every hub. To avoid the complexity of getting all those coordinates the calibration method described in (Koskinen, 2010) has been used. It consists of calibrating the system by measuring the position of different tags whose position is known.

The update rate is 10 Hz, which means that the tag position is measured every 100 ms, corresponding with 4 time slots. In case the positions of multiple tags are measured simultaneously, all them are updated every 4 time slots; that is, increasing the number of tags does not mean reducing the update rate.

## 3 PREVIOUS WORK

Previous work done with the same experimental set-up, demonstrated that the accuracy (variance) obtained with the Ubisense modules in combination with the calibration technique presented in (Koskinen, 2010) is 15 cm. This has been measured with a set up of four hubs and a single tag at a time.

We have used these measurements to analyse the estimated position error for every dimension (x, y and z). The Gaussianity of the position error has been checked by kurtosis. For the three dimensions x, y and z the kurtosis are 4.01, 3.45 and 3.35, respectively. As the kurtosis for a Gaussian distribution is equal to 3, we could consider that the error of one tag measurement with respect to the real position follows approximately a Gaussian distribution (Figure 1, 2, 3). Therefore, the error resulting from combining multiple measurements will also follow a quasi Gaussian distribution.

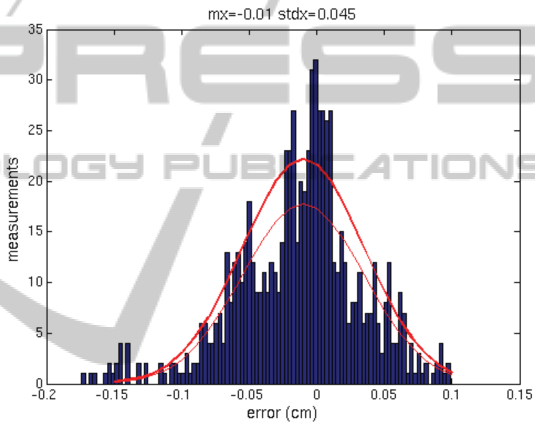


Figure 1: Histogram of the position error of the x coordinates for 3000 measurements.

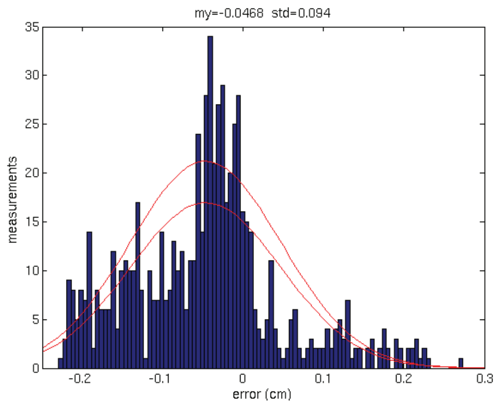


Figure 2: Histogram of the position error of the y coordinates for 3000 measurements.

As a result, with our approach we will try to improve the accuracy combining position data from multiple tags, measured all them during the same time frame.

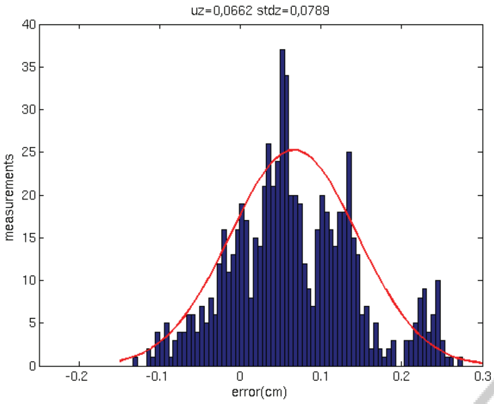


Figure 3: Histogram of the position error of the z coordinates for 3000 measurements.

# 4 PROPOSED ACCURACY IMPROVING ALGORITHM

To estimate the attitude of an object, 6 dimensions are needed: the position, with its three coordinates in the Cartesian coordinate system (x, y and z) and the rotation around the three axes, pitch, yaw and roll. To estimate all of them, it is necessary to measure the position of, at least, three tags, which should be placed on the object at a certain distance from each other. To avoid erroneously getting the same position for two tags, this distance should be equal or larger than twice the accuracy obtained when measuring the position of a single tag. Since this accuracy is known to be 15 cm, the minimum distance between two tags should be 30cm. More precisely, we will assume that the three tags are placed forming a triangle whose size and shape are perfectly known.

Consider A, B and C the three tags (Figure 4). From now on $A_{meas}$, $B_{meas}$ and $C_{meas}$ will designate the raw measured position of each tag and $A_{est}$, $B_{est}$ and $C_{est}$ the estimated position of each tag.

As shown before, the measurement errors on $A_{meas}$, $B_{meas}$ and $C_{meas}$ follow a Gaussian distribution with a given average and standard deviation $\sigma_{Ameas}$, $\sigma_{Bmeas}$ and $\sigma_{Cmeas}$ for each tag. It is assumed that for each of them the errors on the three coordinates are independent from the errors on the other tags. Next, it is possible to estimate the position of the centroid G of the triangle as the central point between the three measured positions [Equation 1, 2]. Consequently, the position error on $G_{est}$ will also follow a Gaussian distribution with standard deviation $\sigma_G$.

$$G = \frac{1}{3}(A_{meas} + B_{meas} + C_{meas}) \quad (1)$$

$$\sigma_G = \frac{1}{3}\sqrt{\sigma_{Ameas}{}^2 + \sigma_{Bmeas}{}^2 + \sigma_{Cmeas}{}^2} \quad (2)$$

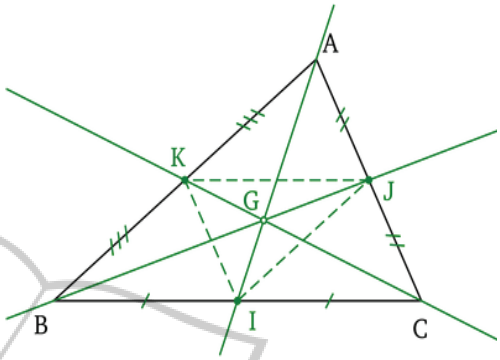


Figure 4: Triangle formed by the three tags, which are the vertices A, B and C, with its centroid G and its three medians.

As the three tags are placed on the object, also the point G can be located as a real point on the same object. This means that the position of G indicates the position of the object itself. We can see, then, that the position accuracy of the object is already improved; in the theoretical case in which $\sigma_{Ameas} = \sigma_{Bmeas} = \sigma_{Cmeas}$ it will be $\sqrt{3}$ times better than the measured accuracy.

To get the attitude, however, this one point is not enough. Instead, A, B and C should be estimated while keeping this accuracy improvement. If we split all four points in the three dimensions, $A_{est} = [A_x\ A_y\ A_z]$, $B_{est}=[B_x\ B_y\ B_z]$, $C_{est}=[C_x\ C_y\ C_z]$ and $G_{est}=[G_x\ G_y\ G_z]$, then it is possible to express the estimated tag positions as a function of $G_{est}$ and other geometrical parameters [Equation 3, 4, 5]

$$\begin{aligned} A_x &= G_x + \frac{2}{3} d_A \cos\gamma \cos\beta_a \\ A_y &= G_y + \frac{2}{3} d_A \sin\gamma \cos\beta_a \\ A_z &= G_z + \frac{2}{3} d_A \sin\beta_a \end{aligned} \quad (3)$$

$$\begin{aligned} B_x &= G_x + \frac{2}{3} d_B \cos(\gamma + \alpha) \cos\beta_b \\ B_y &= G_y + \frac{2}{3} d_B \sin(\gamma + \alpha) \cos\beta_b \\ B_z &= G_z + \frac{2}{3} d_B \sin\beta_b \end{aligned} \quad (4)$$

$$C_x = G_x + \frac{2}{3} d_C \cos(\gamma + \theta) \cos\beta_c$$
$$C_y = G_y + \frac{2}{3} d_C \sin(\gamma + \theta) \cos\beta_c \quad (5)$$
$$C_z = G_z + \frac{2}{3} d_C \sin\beta_c$$

The length of the medians passing by A, B and C respectively are denoted as $d_A$, $d_B$ and $d_C$. As the size and shape of the triangle is known also these parameters are known. Also the angles α and θ are known; these are the angles formed by two medians and which vertex is the point G (Figure 5). The remaining parameters, γ, $\beta_a$, $\beta_b$ and $\beta_c$, must be estimated from the measurements. γ is defined as the average of three angles that can be seen on the projection of the triangle on the XY plane (Equation 6). A new Cartesian coordinate system is set with its origin at the point G, then $\gamma_a$ is the angle formed by the line GI and the axis x, is the angle for by GJ and the axis x and by the line GK and the same axis. Then γ is the average of the three angles.

$$\gamma = \frac{1}{3}\left(\gamma_j + (\gamma_k - \alpha) + (\gamma_i - \theta)\right) \quad (6)$$

The angles $\beta_a$, $\beta_b$ and $\beta_c$ are the inclination angles of each tag A, B and C measured from the z coordinate (zenith direction) in the same coordinate system used to estimate γ.

$$\gamma_j = \arctan\frac{G_x - J_x}{G_y - J_y} \qquad \sigma_\gamma = \frac{1}{\sqrt{3}}\sigma_{\gamma j} \quad (7)$$

$$\sigma_{\gamma j} = \frac{\sigma_f}{1+f^2} = \frac{\sqrt{2}}{3}\frac{f}{1+f^2}\sigma_G \quad \text{where} \quad f = \frac{G_x - J_x}{G_y - J_y}$$

$$\sigma_{\gamma k} \approx \sigma_{\gamma i} \approx \sigma_{\gamma j}$$

The accuracy of all these angles depends on each angle itself, the bigger the angle, the better.

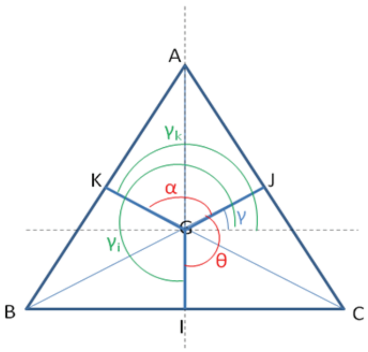


Figure 5: Projection on the plane XY of the triangle formed by the three tag A, B and C and angles formed by its medians.

Using this geometrical approach improves the locating accuracy of the object itself already three times (for that only the position of G is necessary). The accuracy of $A_{est}$, $B_{est}$ and $C_{est}$ has also improved considerably, although it will depend on the orientation of the object.

## 5 MEASUREMENT RESULTS

To test the two methods we placed three tags forming a triangle of known size and shape at different locations and positions inside the coverage area of the hubs.

The position of each tag has been estimated by using the geometrical approach. The following graphs show the histogram of the measurements errors for each of the three tags (Figure 6) and the estimations errors and the error of the estimated centroid (Figure 7) in relation to its theoretical position.

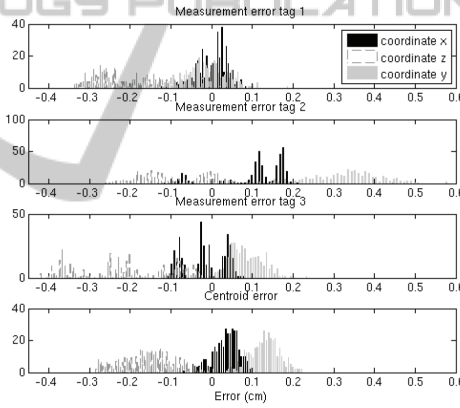


Figure 6: Position measurements' error for the three coordinates.

Theoretically, we could assume that the standard deviation of the error is the same for the three tags, and then the expected standard deviation of the centroid should be three times lower. However, in practice the deviation of measurement error can be different for each tag, so that the deviation of the centroid error can be dominated by a tag whose accuracy is much worse than the others. If we check, for example, the dimension represented in solid grey, we see the measurement for tag 1 to be better than the estimation for the centroid; the reason is that the results for tag 2 are quite poor and this affects all the estimations. If we check now the standard deviation of the estimated positions (Figure 7) we see that in the three cases it has improved at least in one dimension.

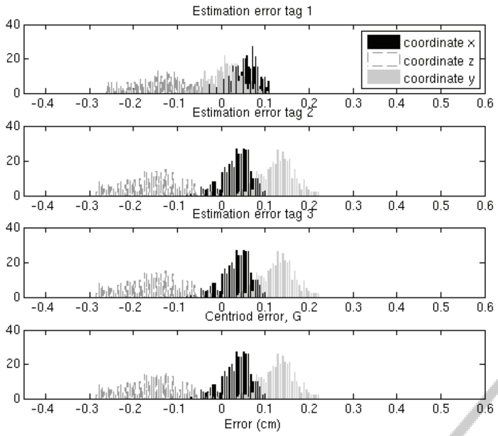


Figure 7: Position estimations' error for the three coordinates.

Notice that the error of each dimension is very similar for every tag. This is due to the fact the same values, the measured tags positions, are used to estimate each of them.

Checking the numerical values it is possible to see the deviation of the resulting estimated positions to be just what we expected:

*Tag 1:*
*Measurement error:*
*Mean (m): 0.0041 -0.1718 -0.0198*
*Std (m): 0.0359 0.1069 0.0590*
*Estimation error:*
*Mean (m): 0.0512 -0.1344 0.0096*
*Std (m): 0.0332 0.0654 0.0359*
*Tag 2:*
*Measurement error:*
*Mean (m): 0.1151 -0.0833 0.3270*
*Std (m): 0.0779 0.1001 0.0863*
*Estimation error:*
*Mean (m): 0.0348 -0.1562 0.1296*
*Std (m): 0.0332 0.0654 0.0359*
*Tag 3:*
*Measurement error:*
*Mean (m): -0.0148 -0.2136 0.081*
*Std (m): 0.0348 -0.1562 0.1296*
*Estimation error:*
*Mean (m): 0.0348 -0.1562 0.1296*
*Std (m): 0.0332 0.0654 0.0359*

*Theoretical standard deviation of the estimations (metres): 0.0332 0.0654 0.0359*

From these data we can see that the standard deviation improves after applying the geometrical approach. The object position can be known just by estimating the centroid of the triangle formed by the three tags; this means that the accuracy of the positioning is improved. However, when checking tag by tag, it can always happen that the measurements' accuracy on one of the tags is considerably worse than the measurement on the other two. In that case, as the three tags are used to estimate the others, the accuracy of some of the tags can be a bit worse than for the measurement. In any case, the average of the three tag's accuracy will be better for the estimations than for the measurements.

## 6 CONCLUSIONS

In this paper, we have presented a novel approach to improve the object location accuracy and to make a better estimation of its attitude. Placing three tags on the object we are able of obtaining its real time position in the space with an accuracy that is three times better.

The algorithm has been designed to be independent of the location technology used and the processing methods previously applied to the data. The experimentation has been carried out using raw data, so it is still possible to apply different kind of filters to improve the accuracy even more or to trace the trajectory of the object.

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