An Efficient Configuration Method for Real Time Locating Systems

Robert Grimm
University of Erlangen-Nuremberg
Erlangen, Germany
Email: robert.grimm@informatik.stud.uni-erlangen.de

Thorsten Edelhäußer
University of Erlangen-Nuremberg
Department 2 in Computer Science
Erlangen, Germany
Email: thorsten.edelhaeusser@cs.fau.de

Gabriella Kókai
Fraunhofer Institute for Integrated Circuits
RF Department
Erlangen, Germany
Email: kki@iis.fraunhofer.de

***Abstract*—We introduce a new method to estimate the position and direction of receiving elements of a Real Time Locating System (RTLS). In an Angle of Arrival (AoA) system, we are able to reconstruct the antenna configuration using measurements at only three reference points. No further prior knowledge is required, and the computations are very lightweight. The localisation procedure is presented and the results of a simulated experiment setup are shown. We discuss possible usage scenarios and advantages of our solution as well as possible extensions.**

I. Introduction

Not only in many areas of production, but also in providing services to customers at different locations, the position of an object is very valuable to know. To localise such objects, the Fraunhofer Institute for Integrated Circuits (IIS) in Erlangen, Germany is developing systems to track objects with wireless mobile transmitters [1].

This kind of localisation system makes it possible to determine the coordinates of various objects equipped with wireless transmitters, such as goods in warehouses, or to track participators and equipment in sports events. A system constructed to perform this in real-time is called a Real Time Locating System (RTLS) which allows to intervene in or monitor the observed process.

Techniques such as the Global Positioning System (GPS) or the currently built Galileo system - see [2], [3], [4] for further information - are lacking in accuracy for special purposes or are not available in some environments like indoor scenarios (e.g. in warehouses). To meet such demands, an RTLS has to rely on its own infrastructure which needs separate installation routines for each setup, especially for mobile systems that are for instance used at sports events. The arising problem is the quick and accurate measurement of the system's components, especially the pose (position and direction) of the receiving elements that is needed to initially configure and setup the RTLS.

In this paper, we present a novel approximation scheme to measure and compute the position and orientation of the receiving antenna. Our method requires no prior information. We only need three different coordinates and corresponding angles of arrival, acquired for example by an autonomous driving robot, to get a good approximation of position and orientation of the receiving element.

The rest of this paper is organised as follows: The next section outlines related work. Sections III and IV describe the techniques used for the proposed novel method. In Section V we present our results of experiments in a simulation environment. Section VI concludes and suggests further extensions and applications of our algorithm.

II. Related work

Today the investigations focus mainly on the actual localisation techniques. Only some research is done in finding initial calibration algorithms for RTLSs. Mostly the algorithms are proposed for whole RTLSs featuring multiple sensor nodes. These approaches can be divided into anchor-based and anchor-free algorithms. Anchor-based means that a-priori knowledge of the system is available, e.g. the position and orientation of a few sensors are known. However, we assume an anchor-free scenario where no sensor pose information is given at all.

Aside from fully manual methods, there are also robot-assisted calibration techniques. In [5] a mobile user drives along a constrained path, taking distance samples that allow node localisation. Kemper and Linde [6] extend this idea to calibrate an angulation based multi-sensor localisation system by giving movement instructions to a human agent. Their algorithm boils down to a non-linear equation system that is solved using a Newton-Raphson method.

Moses *et al.* [7] analyzed a self-calibration procedure for a set of sensor arrays involving measurements from at least three source points. Unlike in our proposed algorithm, not only the direction of arrival of the signals need to be given but also the time of arrival. The solution is found by minimizing a nonlinear least squares problem.

III. Background

As a premise to the presented method in Section IV we now introduce some basic elements and instruments which build the basis of our approach. Figure 1 shows the information flow between all involved components where three main components compose our method:

- one receiving element of the RTLS
- one or more autonomous robots
- the pose estimation module

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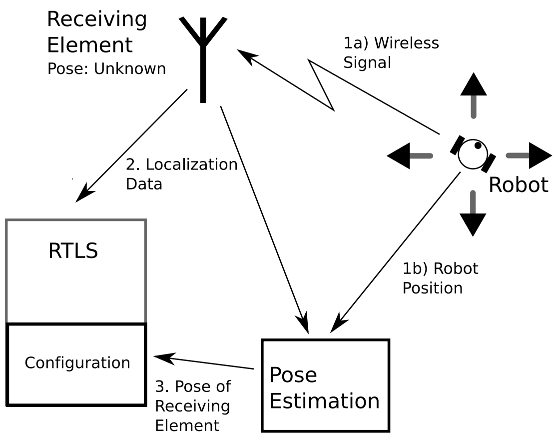


Fig. 1. Overview

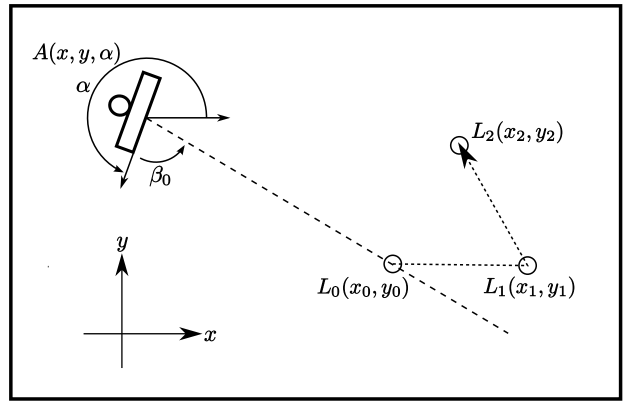


Fig. 2. Measurement procedure. A robot drives along a triangle-shaped path and triggers the recording of the relative angle with respect to the antenna at position A.

In normal operation, an RTLS consists of several antennas surrounding one or more objects to be localised. In a wireless system each object is equipped with a radio transmitter. In this work we consider an Angle of Arrival (AoA)-System where each antenna can determine the relative angle of arrival of each object's signals. Given the location and orientation of all receiving elements is known, the object's position can be computed by the RTLS using the angles and some kind of triangulation scheme [8] that shall not be discussed here. Our work rather focused on the problem of actually calibrating such a system, that is finding out the pose of the receiving antennas.

The rest of this section gives an introduction to the used techniques and describes deployed components in detail.

A. Receiving elements

The receiving elements are part of the RTLS. To localise a wireless mobile transmitter, the RTLS has to know where the antennas of each receiving element are located (position of antenna) and which orientation (direction of antenna) they have. Each receiving element delivers the relative position of the wireless transmitter expressed in the Angle of Arrival (AoA).

As shown in step two of Figure 1, the sole task of a receiving element is to send its localisation data to the RTLS and to the pose estimation module (explained in Section IV).

B. Data acquisition

While the data may be collected by different independently acting agents, it should be noted that all data must be available in the same reference coordinate system. In practice, the origin of the data as well as point geometry and order can be completely arbitrary. However, for illustration we shall assume one robot that performs an autonomous drive in order to collect AoAs on different positions. Its path should prescribe a triangle.

The robot calculates its own position via odometry [9] and delivers it to the pose estimation module. Odometry usually has the big disadvantage of decreasing accuracy over the traveled distance. Nevertheless, we decided to assume perfect odometry to be able to assess the quality of our method independently from the data-acquiring agent.

The RTLS based on AoA is able to compute the robot's location in terms of the incoming signal angle from the radio signals it periodically emits.

IV. Autonomous configuration procedure

The following section describes our autonomous configuration procedure for an RTLS and how the parameters of one of the receiving elements are determined. This method can be extended to more receiving elements by measuring the localisation data for more than one element at a time and afterwards running the pose estimation algorithm individually for each element.

The procedure of determining the configuration parameters for one receiving element of the RTLS can be divided into two phases:

1) Measuring the environment
2) Calculation of the antenna pose

The first step is independent of the following calculations. That means, the calculation can be done offline and on a different machine. However, we are confident that our computations take much less time than the actual process of acquiring the AoAs, even when performed on devices with limited compute performance. Therefore we also encourage the use in interactive systems (see also Section VI).

A. Measuring the environment

During the measurement phase, the robot collects three data points, composed of the position of the reference point $L_i(x_i, y_i)$ (point where the measurement is done) and the corresponding measured angle β_i, called Angle of Arrival (AoA), from the view of the localisation system with $i \in \{0; 1; 2\}$. This process is shown in Figure 2. The robot can emit signals for the localisation system over its Wireless Local Area Network (WLAN) device, from which the RTLS computes the angles. The localisation system sends the angle back to the robot over ethernet or WLAN.

First, the robot is manually placed at an initial point with a specified orientation. The measurement phase is started and the robot receives the first angle β_0 from the localisation system and stores it with the position $L_0(x_0, y_0)$ in the database. L_0 is the first reference point and all the others will be calculated relative to these coordinates via odometry by the robot. Thus, the origin of the robot coordinate system is point L_0 in Figure 2. Using the knowledge of the starting point in global coordinates, all positions, including the one of the antenna, can be transformed from the robot-local coordinate system to a world coordinate system after running our algorithm. Successively, the robot drives to two more points $L_i(x_i, y_i)$. Its path describes two edges of a triangle. At each point, a new measurement is done and the angle and the position of the robot are inserted into the database.

B. Calculation of the antenna pose

The main contribution of the presented method is the estimation of the antenna pose from the data of three distinct measurement points. It takes the measured localisation and position data of the robot and outputs the position and direction (pose, $A(x, y, \alpha)$ in Figure 2) of the receiving element.
It should be noted that in general this problem is not uniquely solvable using only three points, so in most cases we cannot give an exact solution but only an approximation. Considering that other algorithms fail if so few points are available, the approximation still delivers impressive accuracy.

The computation is carried out in four consecutive steps:

Algorithm 1: Pose Estimation Algorithm

Input : Three positions L_i with corresponding measured angles β_i
Output: $Position$ AntPos and $Orientation$ AntOrient of antenna

```
Lines ⟵ ComputeLines(L, β)
AntPos ⟵ IntersectLines(Lines)
AntAngZero ⟵ ReEstimateAoA(L, AntPos)
AntOrient ⟵ ComputeOrientation(AntAngZero, β)
return AntPos, AntOrient
```

*1) **Computing the line equations** :* Without loss of generality we re-label the leftmost point as seen from the receiving element, i.e. the one with the largest Angle of Arrival (AoA), to L. The rightmost one with the smallest AoA shall be R, and the middle point will be referred to as M. This setup is illustrated in Figure 3.

For each measurement point we set up a linear equation in parametric form for the line through the point and the (unknown) antenna position A:

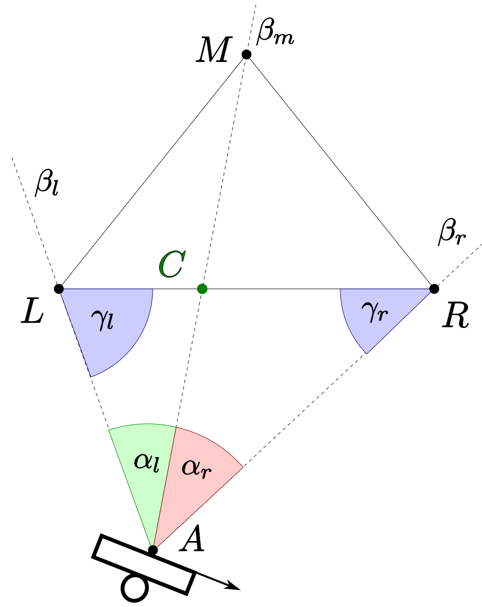


Fig. 3. General case of three mutually different AoAs. The antenna position A is located at the intersection of lines through the three measurement points L, M, and R. The line directions are computed using point C that can generally be only estimated.

$$g_l : \vec{x} = L + \lambda_l \cdot \vec{d_l},$$
$$g_m : \vec{x} = M + \lambda_m \cdot \vec{d_m}, \text{ and}$$
$$g_r : \vec{x} = R + \lambda_r \cdot \vec{d_r}.$$

We observe that the knowledge of point C which lies at the intersection of the triangle baseline and the line from M to A would allow us to compute the line directions $\vec{d_l}, \vec{d_m}$, and $\vec{d_r}$: $\vec{d_m}$ is found trivially. We rotate the direction of $R - L$ clockwise around point L by the angle γ_l that is computed using simple geometry and trigonometry in the triangle ΔLAC to get $\vec{d_l}$. We find $\vec{d_r}$ using analogous computations by rotation of $L - R$ counterclockwise around point R by γ_r.
Unfortunately, C can only be computed exactly if both points L and R are at the same distance from A. In this case,

$$C = \frac{\alpha_r}{\alpha_l + \alpha_r} \cdot L + \frac{\alpha_l}{\alpha_l + \alpha_r} \cdot R, \tag{1}$$

with $\alpha_l = \beta_l - \beta_m$ and $\alpha_r = \beta_m - \beta_r$.

While L and R are of course not always equidistant from A, we may still rely on Equation 1 to find an approximation as we assume the difference in distances to be significantly smaller than the overall distance between the data points and A.

If two data points are collinear, i.e. the respective AoAs are equal, the points L and C or R and C fall together, resulting in two instead of three lines intersecting at A. However, no approximation is necessary in this case, and hence two equal AoAs are not necessarily a disadvantage.

*2) **Intersecting the Lines**:* The receiving element is located at the intersection of the three lines g_l, g_m, and g_r. In the general case this can be modeled as a linear system where each row corresponds to the intersection of two of the lines. The three unknowns λ_l, λ_m, and λ_r are found by solving this system. Closed-form solutions for the unknowns for efficient evaluation at runtime can be found by solving each of the three equations using a symbolic algebra system. Since the three intersections generally produce three slightly different points, we compute the receiving element position by averaging these coordinates.

3) ***Orientation Estimation*** *:* Now knowing the position $(x_A, y_A)^T$ of the receiving element, we would further like to find out its orientation, i.e. its angle with respect to the x axis in the robot-local coordinate system. The orientation corresponds to the angle α in Figure 2.

For each data point $(x_i, y_i)^T$, the AoA is re-estimated for an antenna rotation of 0°:

$$\widehat{\beta}_i = \arctan(\frac{\Delta y_i}{\Delta x_i}),$$

with the distances $\Delta x_i = |x_i - x_A|$ and $\Delta y_i = |y_i - y_A|$.

The real orientation angle is simply the difference between the estimated angles and the ones that were actually measured.

V. Experiments

In this section, we discuss the results obtained from simulating an AoA RTLS and applying our method to estimate the pose of a receiving element.

The antenna is placed at the centre of a square area 3000 units wide and 3000 units high. This assures that the results are generally valid and not only apply to a certain constellation of angles or distances. For each point within the area, we calculated the pose estimation error, each time assuming that the robot follows a path that resembles an equilateral triangle. The first edge is aligned to the global coordinate system x axis; however, using a slightly distorted or rotated measurement path does not seem to have a strong impact on the results.

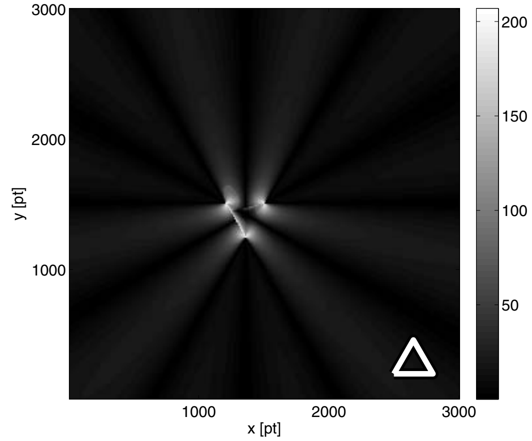
The antenna rotation was randomly chosen to 283 degrees. This value has only a minor influence on the approximation error, since we observed that different positions all around the antenna produce approximately equally good results.

As an objective function we took the distance between the antenna's estimated position (x_e, y_e, α_e) and its real position (x_r, y_r, α_r) according to Equation 2.

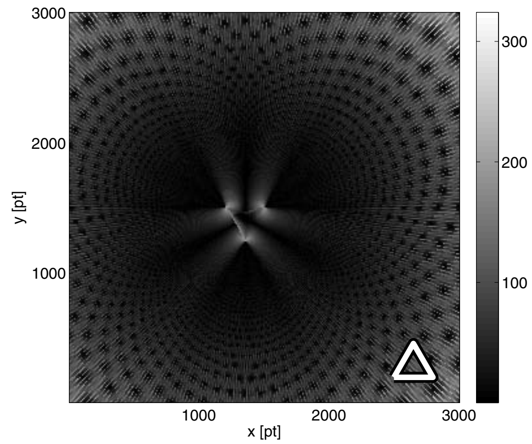
$$D = \sqrt{(x_e - x_r)^2 + (y_e - y_r)^2 + (10 \cdot [\alpha_e - \alpha_r])^2} \quad (2)$$

We added the difference of the angle, weighted by a factor of 10, to the distance in order to give a numerical representation of the result's quality. A value of 10 is chosen to approximate the angle error in the same dimension as x and y. To differ the result from a real Euclidian distance we sign the error distance D to the unit pt. In the accompanying figures, the triangle in the bottom right corner resembles the actual size and shape of the measurement paths.

In Figure 4(a) we assumed precise AoA computation and perfect knowledge of the measurement positions. The edge length of the measurement triangle was set to 10 % of the



(a) Ideal conditions.



(b) Angles rounded to next integer value.

Fig. 4. Approximation error depending on the starting position. The antenna is located at position $(1500, 1500)^T$. The measurement triangle size is visualized in the bottom right.

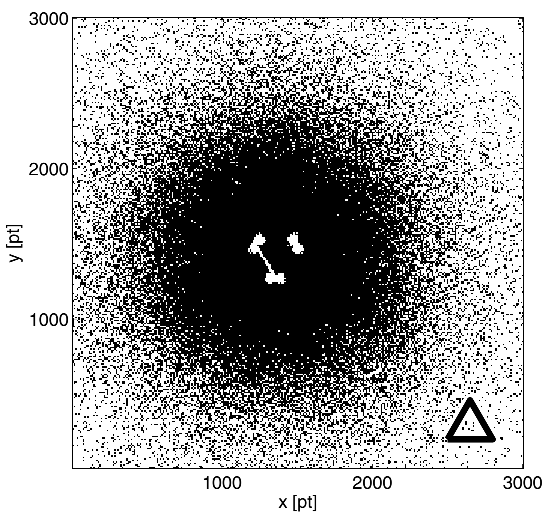
field height, i.e. 300 units. For the largest part of the square, the measurements produce results with an error of less than 30pt. Only as the measurements come close to the receiving element the error increases to values of 40-120pt. These errors are probably due to the approximation of point C (see Eq. (1)). The median error is about 12pt.

To take measurement errors into account, we then rounded the AoAs to the nearest integer values. As can be seen in Figure 4(b), this immediately leads to a significant loss of accuracy. While measurements within a distance of 1000 units from the antenna are still mostly below 50pt, the error increases, the further away the measurements are. The median error is now about 36pt.

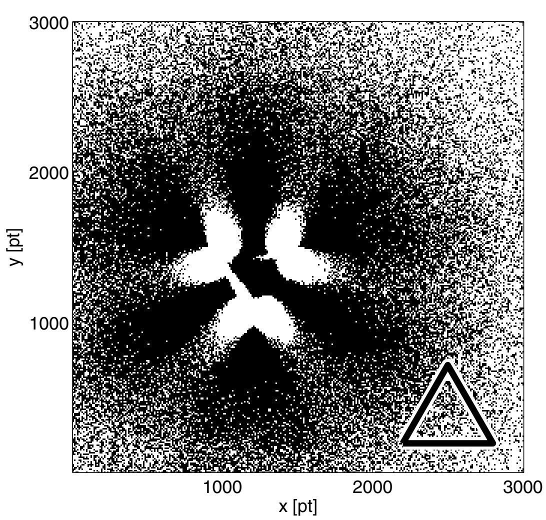
Finally, in Figure 5(a) we simulated inaccuracy in the AoA computations by adding normally distributed random noise with a variance of one degree and rounding the resulting angle to the next integer value. In this case, the median error is about 112pt, with maximum error values of more than 2500pt. For better visual perception now only starting points were plotted that resulted in an pose estimation error of less or equal than 112pt.

The sensitivity regarding noise becomes very reasonable when looking at the AoA values. At a distance of 1000 units from the receiving element, the AoAs at the distinct measurement points often differ merely by one or two degrees. The problem becomes highly ill-conditioned: small changes in the measurement angles cause large deviations in the distant point where the lines intersect.

Nevertheless, appropriate scaling may help to obliterate measurement errors. The bigger the measurement triangle, the more different we expect the angles to be, and thus the less prone to errors the pose estimation becomes. Doubling the size of the triangle to 20% of the field height, the median error of the last experiment (random noise and rounded AoAs) was reduced to 82pt. The points that resulted in an approximation error of less or equal than 112pt are displayed in Figure 5(b)



(a) Noisy data: the accuracy decays fast if the antenna is far away.



(b) Using a larger triangle increases robustness at longer distances. However, positions close to the antenna should be avoided.

Fig. 5. Suitable starting positions when AoAs are perturbed by noise. Black points indicate an accuracy of 112pt or better.

To conclude, generally the triangle size should be selected as large as possible in order to improve numeric stability. On the other hand, Angle of Arrival locating systems often rely on receiving elements that perform best if the object lies in a certain field of view, e.g. between 60 and 120 degrees from the antenna. Also, the measurement robot's odometry is not perfect, its accuracy may decrease with a longer path. Furthermore, as clearly visible in Figure 5(b), big triangles may increase the approximation error for positions close to the antenna. Therefore, in practical applications an optimal balance between AoA accuracy and triangle size will have to be determined experimentally.

The results of our simulation in Figure 5(a) indicate that the method works for initially configuring an RTLS with a satisfactory accuracy of 112pt, if we permit some noise and rounding errors. To illustrate these dimensions with real-world units, we consider the edge length of the measurement triangle (300pt) corresponding to 300mm. According to the distance function (Equation 2), we can therefore estimate the antenna position with an accuracy of 112mm or better if it is within a range of about 1000mm. Also, due to the weighting factor of 10, the estimated rotation of the receiving element differs by at most 12 degrees from the real rotation. By iteratively combining several independent estimation cycles, even better results may be achieved.

This result is certainly good enough for some applications where high accuracy is not so important, but to satisfy systems with higher precision such as described in [10], some post processing has to be applied. This could be done e.g. by online calibration algorithms where redundancy of the RTLS is used to recalculate the positions of the antennas. For these kinds of systems our results provide a good initialisation. Methods like [11] require a manual setting of starting antenna positions where our method could be applied.

VI. Conclusion

In this final section, we briefly summarise our contribution and suggest further directions of research.

We presented a non-iterative estimation scheme to compute an antenna pose from only three measurement points and corresponding Angles of Arrival in an RTLS. We propose the measurements be collected using an autonomous robot driving along a triangle-shaped path. However, our algorithm is able to perform the computations using any three data points. The necessary computations are very lightweight and involve only few calls to trigonometric functions, so they can be implemented easily and deliver results in real-time even on mobile agents. We recommend the incorporation of prior knowledge if available. Increasing the distance between the points as much as possible ensures better error tolerance.

As described in this article, our algorithm is rather sensitive to noise. The precision of the measurement point coordinates, i.e. of the robot odometry, and its influence on our method still need to be examined.

The ideal triangle size and shape also remains to be investigated. While our choice of an equilateral triangle intuitively seems to be most robust due to its rotational invariance and symmetry, in some cases a different shape, such as a right triangle or even one that is degenerated to three collinear points, may yield better results.

This is especially interesting in the context of an interactive environment, where the pose estimation system does not observe the measurements passively but where it may directly influence the coordinates at which the measurements are taken. Depending on previous data, the system could for instance suggest future measurement locations that are especially suitable to deliver accurate results.

On the other hand, our method may also be used for offline calibration. In this case, several data points are given, and the open question is how to select the ones that produce the most accurate result.

We will also try to find further ways to incorporate more than three measurements into the computation. These could be used not only to increase robustness and precision but also to detect measurement errors caused e.g. by multipath effects [12]. This is especially useful in environments where most AoAs are computed correctly but a few measurements show extreme deviations of for example 60 degrees. If such erroneous data is used in our scheme, the result is rendered virtually useless.

Finally, real-world experiments may reveal further sources of error, and give us better a idea of the error dimensions we have to face.

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