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Iterative approach for anchor configuration of positioning systems☆

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Abstract

With anchor positions and measurements of distances between an object and anchors, positioning algorithms calculate the position of an object, e.g. via lateration. Positioning systems require calibration and configuration prior to operation. In the past, approaches employed reference nodes with GPS or other reference location systems to determine anchor positions. In this article, we propose an approach to determine anchor positions without prior knowledge. We evaluate our approach with simulations and real data based on the Decawave DW1000 radio and show that the error is proportional to the mean error of the distance estimation.

Keywords: Positioning; Anchor configuration; Iterative algorithm; Approach

1. Introduction

Positioning systems based on distances for industrial and mobile robot applications require the position of anchors in advance. With known anchor positions, a tag or device (e.g. a mobile robot or smartphone) can determine its position based on distance measurement with respect to anchors. This method is called lateration. Recent advances in Ultra Wide Band radios allow precise ranging in the region of several centimeters, see Irahhauten et al. in [1]. However, configuration of positioning systems is considered a barrier for a further spreading of location systems as stated by de Moraes [2]. For instance, it is costly to deploy positioning systems and to manually configure them, therefore we aim to solve the configuration problem. The contributions of this work are (1) a novel approach to determine the position of anchors without prior knowledge and (2) an evaluation of the approach using both simulation and real data. We define a *position* as a quantitative representation of an object in a given coordinate system, whereas a *location* is a position enriched with additional information e.g. context according to Filjar et al. [3].

The rest of the article is structured as follows: In Section 2 we present related work and Section 3 discusses our proposal: approach and algorithm. In Section 4 we evaluate the approach with simulation data as well as real data. Last, we summarize our work in Section 5.

2. Related work

Localization and positioning of nodes in wireless sensor networks has been investigated in the past. Mao et al. in [4] provide an overview of the underlying methods and technologies that have been proposed for positioning in wireless sensor networks (WSNs), e.g. distance measurements. In [5] Savvides et al. investigate positioning algorithms from a WSN perspective. The authors suggest an iterative approach using RSSI and ultra-sonic range measurements to determine the position of nodes in a wireless sensor network and achieve an accuracy of several centimeters. Niculescu et al. present the ad hoc positioning system (APS) in [6]. The system determines location of anchor nodes based on angle measurements. Angle measurements require antenna arrays which might be prohibitive in size and power consumption as Niculescu states. A more suitable approach using angle measurements was suggested by Lee in [7]. However, approaches from Niculescu, Savvides and Lee require that *some* nodes (more than one) have access to a reference system, e.g. GPS, to determine their

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orientation and location. Such references via GPS are expensive and may be not available in all scenarios, e.g. parking garages.

Our approach does not require GPS data or prior knowledge to determine anchor positions.

3. Approach

In this section we explain our approach and describe the lateration algorithm and algorithm to determine anchor position. For the discussion we assume that distance measurement between anchors is available, e.g. with Double Sided Two-Way Ranging (DS-TWR), cf. Kim et al. in [8].

Lateration determines position of nodes based on distance measurements.

$$F(\mathbf{r}) = \sqrt{(x - x_i)^2 + (y - y_i)^2} - d_i = 0. \tag{1}$$

In Eq. (1) $\mathbf{r}_i = [x_i, y_i]^T$ and d_i is a distance measurement between unknown coordinate $\mathbf{r}$ and reference coordinate $\mathbf{r}_i$ with i measurements. Here we describe a two dimensional problem. The approach can be extended to the third dimension z in a straight-forward way. In general, x, y are sufficient for mobile robot or pedestrian applications. Eq. (1) is solved using multidimensional Newton Method and linearization with a Taylor Series around an initial guess $\mathbf{r_0}$. This leads to

$$\Delta\mathbf{r} = -J_F(\mathbf{r})^{-1} F(\mathbf{r}). \tag{2}$$

$J_F(\mathbf{r})$ in Eq. (2) is the Jacobian of $F(\mathbf{r})$ with $\Delta\mathbf{r} = \mathbf{r}_{n+1} - \mathbf{r}_n$. The solution of this equation is calculated with least squares and allows a recursive calculation of $\mathbf{r}$ based on an initial guess for $\mathbf{r_0}$ until a desired accuracy $F(\mathbf{r}) - d_i, \forall i$ is achieved. However, there are two prerequisites: The anchor positions $\mathbf{r}_i$ need to be known and the algorithm requires an initial guess $\mathbf{r}_0$.

To calculate anchor positions we select an arbitrary anchor as the origin of the coordinate system, which is $\mathbf{r}_a = \mathbf{0}$. For the second anchor position $\mathbf{r}_b$ we assume that the first two anchors are along one axis u_l and distance between both anchors is measured as $d_{a,b}$. With these two coordinates we determine the position of a third anchor $\mathbf{r}_c$ with distances $d_{a,b}$, $d_{a,c}$ and $d_{c,b}$ as shown in Fig. 1. All nodes are located in a two dimensional plane. We assume that the boundaries of a positioning system are known in advance, therefore an initial guess of $\mathbf{r}_0$ is any position inside the cell of the positioning system.

Listing 1 shows pseudocode of the approach to determine the anchor positions from distance measurements. A vector of distances d and an initial anchor matrix $\mathcal{A}$ with a total of N anchors is the input to the algorithm. The distances between the u and the v anchor define the coordinate system. For the remaining anchors, an initial guess of their positions is generated according to a uniform distribution $\mathcal{U}(\mathbf{a}, \mathbf{b})$ in the positioning system with $\mathbf{a}$ and $\mathbf{b}$ as vectors of the problem space. Then, iteratively, the remaining anchor positions are calculated. The $\mathcal{A}$ is continuously updated with every new determined anchor position.

In each iteration a random anchor with unknown coordinates is chosen. For this anchor, a random coordinate is selected from the area of the positioning system. This coordinate is inserted as an initial value into the positioning equation $F(\mathbf{r})$ as seen in (1). (1) is the Euclidean norm $\|\cdot\|_2$ between guess r_0 and the ith anchor coordinate. Furthermore, the Jacobian matrix of $F(\mathbf{r})$ is evaluated to find a better approximation of r_0. This calculation is repeated until the residual error $\left|F_{\mathbf{r}_0} - d\right|$ is below a threshold TH. Reasonable thresholds are in the order of magnitude of the distance estimation error cf. [9]. This approach is called the Newton's method to solve the position equation.

The algorithm iterates for all anchors in the positioning system. In the last step, a Mean Squared Error (MSE) is determined between measured distance $d_{i,l}$ and Euclidean distance between anchor a_i and anchor $a_{l|l \neq i}$. The MSE is compared with a threshold which depends on the standard deviation of the distance estimation. If the MSE exceeds the MSE_THRESHOLD, the algorithm discards the solution and starts the process again. The algorithm might not always converge or reach a solution with MSE below the threshold, so in practice additional exit conditions need to be considered, e.g. number of iterations. This part is not shown in the pseudocode. The decision of random anchors instead following a logical order (e.g. ascending from an id) and random initial guess results in a Monte Carlo analysis. Also, ambiguity flip (cf. [10]) can result in poor anchor positions and therefore increases the MSE, see Fig. 1. In our approach these poor anchor configurations are discarded.

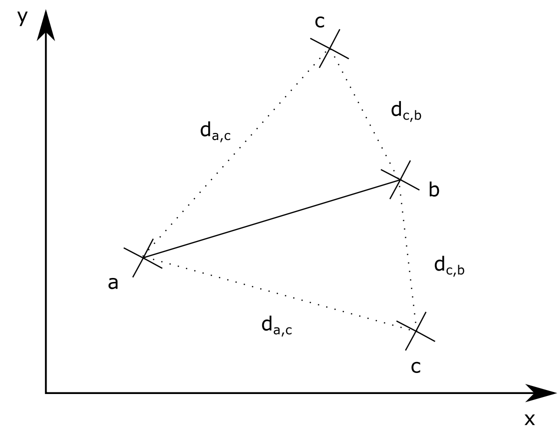

Fig. 1. Anchor positioning with respect to axis x and y. We also shows the ambiguity flip problem, as anchor c can be at both positions. The line between a and b is called mirror line.

Listing 1: Iterative algorithm to determine the anchor position.

$\mathbf{d} = [d_{1,1}, \ldots, d_{1,j}; \ldots; d_{i,1}, \ldots, d_{N,N}]$
mse = $+\infty$
while mse > MSE_THRESHOLD
    $\mathcal{A} = [0, 0; 0, d_{u,v}]$ // initialize anchor matrix
    for $i = 0, 1 \ldots N-3$
        $\mathbf{r}_0 \in P$ with $P \sim \mathcal{U}(\mathbf{a}, \mathbf{b})$
        while $|F(\mathbf{r}_0) - \mathbf{d}| >$ TH
            $F(\mathbf{r}_0) = \|\mathcal{A} - \mathbf{r}_0\|_2 + \mathbf{d}$
            $\Delta r = -J_F^{-1} F(\mathbf{r}_0)$
            $\mathbf{r}_0 = \Delta r + \mathbf{r}_0$
        end
        $\mathcal{A}(i+2) = \mathbf{r}_0$ // use $\mathbf{r}_0$ as new position
    end
    mse = $\frac{1}{N} \sum_{i,j} \left(\|\mathcal{A}(i) - \mathcal{A}(j)\|_2 - d_{i,j}\right)^2$
end

In Fig. 1 two possible solutions are shown for the position of anchor c, this is referred to as ambiguity flip cf. Moravek et al. [10]. In the next section we evaluate the approach.

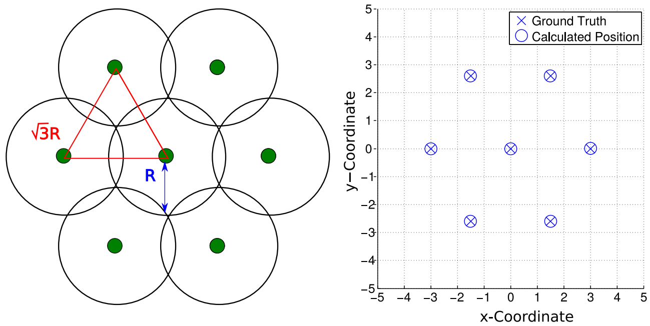

Fig. 2. Left Part: Triangular lattice pattern as suggested by [11]. The seven green anchors shape a cell of a positioning system. Right Part: Simulation results for seven anchors. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

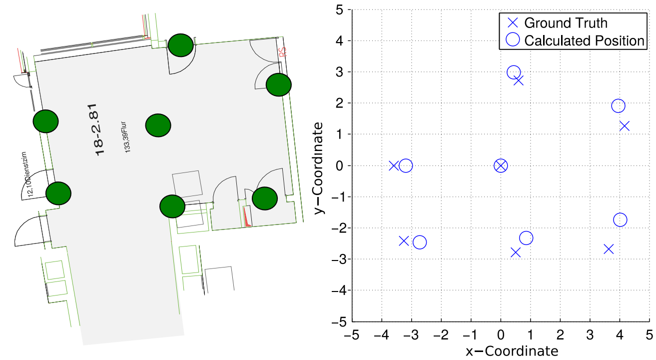

Fig. 3. Anchor placement on the floor and outcome of the algorithm with MSE = 0.39 m^2.

4. Evaluation

Our evaluation is twofold. First, we simulate ranging data to validate the correctness of the approach and in a second step, we evaluate the approach with real data obtained from UWB radios, based on Decawave DW1000 anchor nodes. In free field conditions the UWB distance estimation has a precision of $\sigma = 0.05$ m and zero mean $\mu = 0$ and achieves a maximum range of $r = 100$ m with calibrated range bias. In real environments, precision and accuracy is decreased, e.g. due to non-line of sight effects.

For the first part, seven anchors are placed in a triangular lattice pattern, shown in Fig. 2, as described by Lasla in [11]. This is an optimal pattern to achieve best accuracy with the least amount of anchors for positioning systems. In Fig. 2 seven anchors create a hexagonal pattern which is the cell of the positioning system.

The distance between two adjacent anchors is $r = 3$ m. This setup allows comparison of simulation results with real measurements. We evaluate the error between ground truth and determined position with Mean Squared Error (MSE). The mean Euclidean positioning error is the square root of the MSE and it provides a measure of how far the anchors are away from the ground truth. For the first simulation no environmental effects are in place ($\sigma = 0$ and $\mu = 0$), to simulate lab conditions. The results of the simulation are shown in Fig. 2. Blue circles represent calculated position and the crosses indicate ground truth. With circles and crosses being at the same position the proposed approach determines anchor positions precisely with MSE being nearly zero. However, if distance measurements become flawed, e.g. due to multipath effects, the outcome of the algorithm becomes worse. To simulate such effects, noise is added to the data. We assume Gaussian noise with zero mean and standard deviation σ. For each σ the simulation runs $n = 500$ times and in every iteration the simulated distance estimations are superimposed with noise. At the end of each iteration the MSE between ground truth and calculated position is determined. For the simulation we choose `MSE_THRESHOLD` $= \sigma/2$ as stated in Listing 1. The results are listed in Table 1. As expected, with increasing σ the outcome of the algorithm becomes worse. However, the algorithm still determines the position of the anchor and the accuracy of the position roughly following the standard deviation σ of the distance measurements.

Table 1
Simulation results for values of σ with $n = 500$ runs.

σ in m	0.0	0.1	0.2	0.3	0.4
MSE in m^2	0	0.08	0.21	0.35	0.62
Error in m	0	0.28	0.45	0.59	0.79

In the final step, we evaluate our approach with distance measurements from a UWB radio device (Decawave DW1000) in a real environment. Anchors are distributed along the edge of walls and distances between anchors are measured with Double Sided Two-Way Ranging (DS-TWR), cf. [8], see left part of Fig. 3. The floor plan requires adjustment of the optimal anchor deployment pattern. The overall shape of the triangular lattice pattern varies slightly due to constraints of the room layout. The ground truth is determined with a reference laser meter with accuracy ± 2 mm and manual calibration of anchor positions. For distance measurements, many ($n > 500$) measurements were taken and averaged to reduce effects of noise. However, the experiments show a range bias which decreases accuracy of the ranging to $\mu = 0.24$ m depending on the position of the anchor as well as the target of the distance measurement. These inaccuracies can be attributed to multipath propagation and other channel effects. The outcome of the algorithm is shown in right part of Fig. 3. We found MSE = 0.39 m^2 for the experiment and the average Euclidean positioning error is 0.62 m. Compared to the simulation, the MSE is worse than the values the simulation predicts. At the moment we assume that the corruption is caused by multipath and other channel effects.

Our approach determines the position of anchors based on distance measurements from anchors. The mean Euclidean positioning error is coupled to accuracy μ of the distance estimation. Compared to other methods no special nodes, e.g. equipped with GPS, are required, cf. [5–7] and Section 2.

5. Conclusion

We have proposed an iterative approach to calculate anchor positions based on distance measurements between anchor nodes. We solved the positioning problem with a Taylor expansion combined with a Monte Carlo approach to avoid ambiguity flip. Simulation shows that the approach successfully determines positions of anchors. However, accuracy of the anchor positions depends on the quality of distance measurements. We achieved a mean positioning error of 0.62 m with the Decawave DW1000 radio under real conditions. The performance of the positioning estimation is degraded as a result of erroneous distance measurements due to multipath effects which affects the outcome of the algorithm. Simulations show that with precise distance measurements the algorithm produces accurate results. In future work, we compare this method to other state of the art methods.

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