Precise Self-Calibration of Ultrasound based Indoor Localization Systems

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***Abstract*—Several ultrasound based localization systems consist of environmental anchor nodes, and mobile nodes which estimate their own position by using this infrastructure. For the location process, every anchor has to know its position. In most approaches, the location of all anchors has to be determined a priori manually. This procedure is time consuming and fault-prone. In this paper, we present Distribute & Erase, a precise self-calibration method for ultrasound based localization systems. Our approach requires no additional hardware besides ultrasound receivers or transmitters and radio transceivers which are already available for the WSN based localization system.**

***Index Terms*—Wireless sensor network, self-calibration, indoor localization, ultrasound.**

I. INTRODUCTION

Ultrasound (US) based localization systems are an important research area within the WSN domain. This is the reason why various such systems exist, like Cricket [1], AHLoS [2], or SNoW Bat [3]. But a common problem of anchor based localization systems is the determination of the anchors' positions. Our objective was to find a self-calibration method which achieves an accuracy of millimeters and requires no further hardware. Several self-calibration approaches are based on distance measurement between anchor nodes, such as the method introduced by Capkun et al. [4]: Local coordinate systems are generated for each anchor and then are joined together to a global coordinate system. As the distances in our real world localization system are measured by TDoA (time difference of arrival) between ultrasound and radio signals emitted by a mobile node and received by an anchor, a distance measurement between two anchors is not feasible without adaption of our hardware.

A GPS-based method was provided by Sichitiu and Ramadurai [5]: Instead of equipping each node with an expensive GPS-receiver, just one mobile node with GPS was used. The positions of the static anchors were determined using the distances between the anchors and the mobile node. However, GPS-based methods are not suitable for indoor localization because of the unreliable reception of GPS signals inside buildings. The achievable localization accuracy of 1-2 m is insufficient for us, too.

A higher accuracy was achieved by Moses et al. [6] through the use of sensors measuring both the direction-of-arrival (DOA) and the time-of-arrival (TOA). But the sensor nodes used in our localization system can not measure the DOA without expensive hardware modification.

Menegatti et al. investigated the capability of WSNs and AMRs (autonomous mobile robots) for calibration [7]: They introduced a self-calibration method with an AMR that determines its position through odometers attached to the driving wheels. Since this method presupposes a special mobile vehicle it is also prone to slippage of the tires.

In contrast to the mentioned approaches, we present a precise self-calibration method for ultrasound based sensor networks which just requires small, cheap, and energy-efficient sensor nodes.

II. REQUIREMENTS

To apply our Distribute & Erase (D&E) algorithm only few pre-conditions must be fulfilled. Not a single pre-calibrated anchor is required if relative positions are sufficient for the underlying localization system. If absolute position estimations are required, two (for 2D calibration) or three (for 3D calibration) pre-calibrated anchors at fixed positions are needed. The pre-calibration corresponds to the specification of the origin and orientation of the local coordinate system within the global coordinate system.

Distribute & Erase calibrates the anchors through the gradual improvement of the estimated positions. The anchors' estimated initial positions can be chosen randomly. However, as trilateration is used for all localizations, the positions used for a localization must not be collinear. The mobile nodes can take arbitrary positions for distance measurement, too, as long as each anchor measures a sufficient number of distances.

The required time for a localization step depends strongly on the time of the data aggregation. To achieve a high localization frequency, the data must be packed tightly. To ensure a minimal and predictable transfer time and to avoid mutual interference, the TDMA (time division multiple access) communication protocol HashSlot [8] is used. HashSlot assigns an exclusive transmission slot to each anchor. HashSlot requires that the anchors are arranged roughly along a grid because the slot number relies on each anchor's known cell, and is calculated by each anchor autonomously. In the case of uncalibrated anchors, the anchors' cells must be determined. But as an anchor cell is usually few square meters in size, the effort is not high and no special equipment like a laser distance measurement system is required.

So, if HashSlot is used to control the transmission of the radio packets, every anchor just has to know its anchor cell. D&E employs this precondition for successive calibration of all anchors. While D&E can also be used with other MAC protocols, like CSMA-CA, this reduces the calibration speed remarkably.

III. Distribute & Erase

This section introduces our self-calibration algorithm Distribute & Erase, which can replace the manual calibration process. For the rest of this paper, $p_{i,real}$ denotes the real position of an anchor a_i with $i \in \{1, \ldots, n\}$, and $p_{i,est}$ denotes the estimated position of anchor a_i. Anchor a_i's grid cell is herein referred to as A_i. In order to simplify, we assume just one single mobile node m with real position $p_{m,real}$, and estimated position $p_{m,est}$ respectively.

A localization is initiated by the mobile node by sending a radio signal followed by an US signal. Every anchor that has received both signals returns the calculated distance and its own position $p_{i,est}$ to the mobile node. This radio packet is called DV (distance vector).

A. Procedure

Initially, the estimated position $p_{i,est}$ of each anchor a_i is placed at the middle of the corresponding anchor cell, but every other position in the anchor cell would be possible, too. The mobile node takes a new position and locates itself using the received DVs from the anchors. The mobile node sends the newly estimated position back to the anchors, which in turn buffer this position for their own positioning.

```
while(true) {
  take new position;    //change p_{m,real}
  measure distances;    //using TDoA method
  calculate p_{m,est};  //using trilateration (III-B)
  broadcast p_{m,est};
}
```

If an anchor a_i has collected at least three non-collinear position estimations of the mobile node, it is able to update its own estimated position $p_{i,est}$ which offers a smaller position error on average.

```
while(true) {
  [localization dependent parts]
  if(new position p_{m,est} received) {
    store DV;   //p_{m,est} and measured distance to m
  }
  if(enough DVs stored) {
    update p_{i,est}; //using trilateration (III-B)
  }
}
```

A DV contains an estimated position $p_{m,est}$ or $p_{i,est}$ and the measured distance between m and the anchor a_i. Through the repeating localization of m and the anchors a_i, after a few (depending on the number of anchors) calibration steps, a *consistent* anchor arrangement will be achieved (see section III-C). One step corresponds to a positional change of m. An anchor arrangement is called *consistent*, if the re-localization of all anchors with perfect distances only confirms the already estimated positions.

B. Localization algorithm

The D&E algorithm requires a localization algorithm which tolerates inaccurate anchor positions, but still provides precise position estimations with accurate anchors. In several tests, an *adapted trilateration* fulfills these requirements. The *adapted trilateration* for a node $k \in \{m, a_i, \ldots, a_n\}$ looks as follows:

```
generate j triplets;
generate j position estimations;
if(position estimations ∈ A_k ≥ 4) {
  p_{k,final} = coordinate-wise median of all
        estimations ∈ A_k;
}
```

The *adapted trilateration* builds j triplets from the q received DVs. If $j < \binom{q}{3}$, the triplets that span the largest triangles are selected. Throughout our tests we found that $j = \frac{1}{2}\binom{q}{3}$ results in a good trade-off between run-time and accuracy. With each of the j triplets a position is estimated using a regular trilateration. Only position estimations located in the area A_k will be considered. By discarding all estimations $\notin A_k$ the average accuracy can be improved. The final position estimation $p_{k,final}$ is calculated using the coordinate-wise median of all considered position estimations. To achieve position estimations that are as accurate as possible, the *adapted trilateration* requires at least four positions $\in A_k$.

C. Illustration and match operation

Fig. 1 shows the calibration process for a small anchor plane with 3×3 anchors and a grid-length of $\approx 1.3\,\mathrm{m}$[1]. The estimated position of each anchor is located in the middle of the corresponding cell and the real position is randomly placed anywhere within the cell. It is obvious that there is still after 800 steps a significant deviation between $p_{i,est}$ and $p_{i,real}$ (Fig. 1b). According to the plotted path in Fig. 1b it seems that the distance between two estimated positions for an anchor a_i was small in the recent steps. The reason for the small distances is an almost *consistent* anchor arrangement. To match the real and the estimated positions two anchors a_{fix_1} and a_{fix_2} with known real positions are required. But the match operation is only necessary if absolute coordinates are desired. With a_{fix_1} the translation values δ_x and δ_y can be calculated:

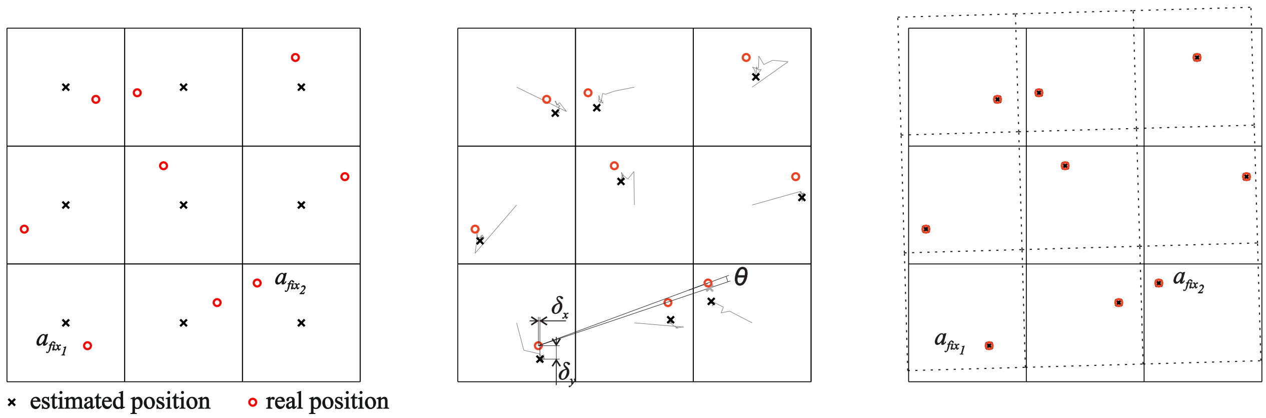
$$\delta_x = p_{fix_1,real}.x - p_{fix_1,est}.x$$

$$\delta_y = p_{fix_1,real}.y - p_{fix_1,est}.y$$

with $p_{i,real} = (p_{i,real}.x, p_{i,real}.y)$, and $p_{i,est}$ respectively. Three-dimensional coordinates can be translated with the translation matrix

$$A_{trans} = \begin{pmatrix} 1 & 0 & \delta_x \\ 0 & 1 & \delta_y \\ 0 & 0 & 1 \end{pmatrix}.$$

[1]The grid-length was automatically calculated depending on the height of the room, the US emission angle, and the necessary number of anchors within the cone.



(a) initial anchor arrangement

(b) anchor arrangement after 800 steps

(c) anchor arrangement after transformation

Fig. 1. Anchor plane during calibration

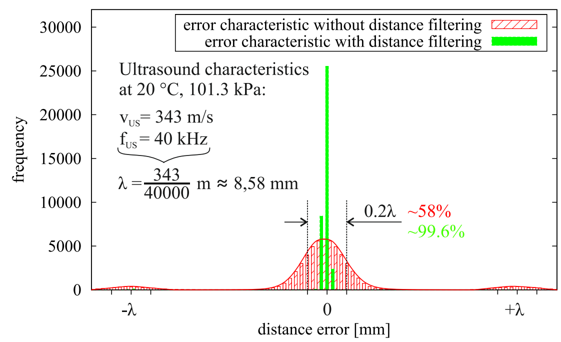


Fig. 2. Frequency density of the error characteristic of the distance measurement

Afterwards, the translated coordinates must be rotated around the chosen point of origin $p_{fix_1,real} = (x_0, y_0)$. The rotation angle θ is the angle between the straight connection of $p_{fix_1,real}$ and $p_{fix_2,real}$, and the straight connection of $p_{fix_1,real}$ and the translated coordinate $p_{fix_2,est}$. The rotation is realized using the transformation matrix

$$A_{rot} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) & x_\theta - x_\theta \cdot \cos(\theta) + y_\theta \cdot \sin(\theta) \\ \sin(\theta) & \cos(\theta) & y_\theta - x_\theta \cdot \sin(\theta) - y_\theta \cdot \cos(\theta) \\ 0 & 0 & 1 \end{pmatrix}.$$

The affine transformation A_{at} to match all anchors is

$$A_{at} = A_{rot} \times A_{trans}.$$

Fig. 1c shows the matched anchor plane, now offering an average error of just 0.7 mm.

For three-dimensional calibrations a further rotation around the axis joining a_{fix_1} and a_{fix_2} is necessary. The corresponding rotation angle can be calculated with a third static anchor a_{fix_3} with known position $p_{fix_3,real}$.

D. Improvements

The achievable calibration accuracy depends strongly on the error characteristic of the distance measurement. Therefore, it can be necessary to improve the accuracy by distance filtering. Instead of using the first distance measured, the median of 100 distance measurements is used if the variance of the distance sequence is ≤ 1.0. If the variance is > 1.0, the complete sequence is discarded. The error probability measured in our real world localization system could be improved significantly (see Fig. 2). Note that the error characteristic was measured under stable environmental conditions.

During development, the accuracy of the calibration can be determined by the average position error of all anchors

$$f_a = \sum_{i=1}^{n} |p_{i,est} - p_{i,real}|.$$

As the real positions are unknown, a self-calibration algorithm can not compute f_a. Thus, for the localization of node k the $agreement_k$ is defined, which depends on the size of the *adapted trilateration*'s scatter plot:

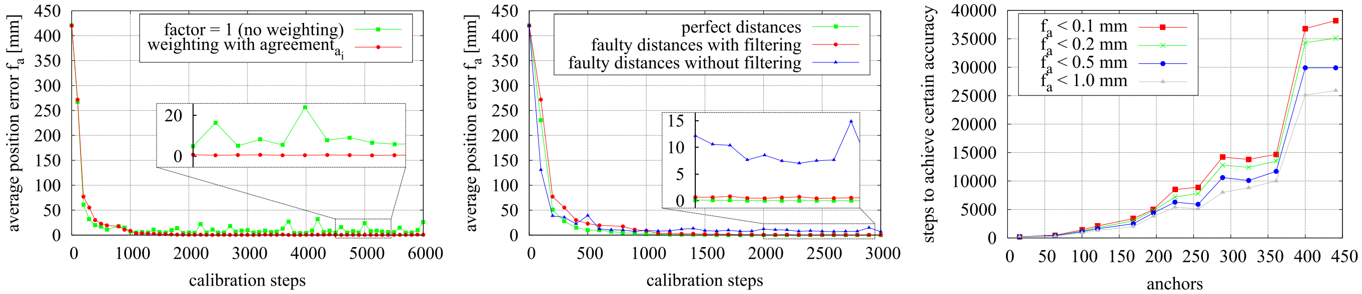
$$agreement_k := \frac{1}{c} \sum_{j=1}^{c} |p_{k,final} - p_j|$$

where $p_j,\ j \in \{1, \ldots, c\}$ are the position estimations $\in A_k$ and $p_{k,final}$ is the final position estimation. If the resulting scatter plot is large, the likelihood for an imprecise position estimation is high, too. In contrast, a small scatter plot is an indication for a more precise position estimation.

The localization of a node k can also degrade the accuracy, since the localization is possibly based on faulty position estimations. To shorten the calibration time, an $agreement_k$ dependent adjustment was implemented. If a new position $p_{i,est}$ is estimated for an anchor a_i, the adjustment vector $\binom{x_{t-1}-x_t}{y_{t-1}-y_t}$ from the past estimated position (x_{t-1}, y_{t-1}) to the new estimated position (x_t, y_t) is calculated. Instead of accepting the new position estimation, a weighted adjustment is performed with $\alpha \in (0, 1)$:

$$p_{i,est} = (x_{t-1}, y_{t-1}) + \binom{x_{t-1}-x_t}{y_{t-1}-y_t} \cdot \alpha^{agreement_i}.$$

A sufficient value of α at system start is 0.9. But as f_a decreases with time, after some calibration steps, a smaller α



(a) Run of f_a with and without weighting

(b) Run of f_a for different distance errors

(c) Necessary steps to achieve a certain accuracy for a given number of anchors

Fig. 3. Simulated results of the calibration

value should be chosen. This is the reason, why α is calculated using the average of the last 100 $agreement_m$ values of the mobile node m.

IV. Experimental results

Fig. 3a shows the run of f_a for a calibration of 11×11 anchors using distance filtering with and without weighted adjustment. The advantage of the weighted adjustment becomes even more obvious for longer calibrations, where unique distance errors recurrently increasing the average position error if no weighting is used.

As mentioned in section III-D, the achievable calibration accuracy depends strongly on the accuracy of the distance measurement. Fig. 3b shows the average error during calibration of 11×11 anchors. With perfect distances, 1200 calibration steps are required to achieve an average error $f_a < 1\ \mathrm{mm}$, and 3000 steps for $f_a \approx 0.0\ \mathrm{mm}$. Even with faulty distances an accuracy $< 1\ \mathrm{mm}$ can be achieved after 1800 steps using distance filtering. Without distance filtering, large distance errors can increase the average error f_a, e.g. the average error is still $> 5\ \mathrm{mm}$ even after 3000 steps.

The time to achieve a calibration of a certain accuracy depends also on the number of anchors to be calibrated. Fig. 3c shows the required steps to calibrate various numbers of anchors using exact distance measurements.

The most time consuming parts of the calibration are the movement of m and the data aggregation. Assuming a localization frequency of $5\ \mathrm{Hz}$, 100 distance measurements per step for distance filtering, a duration of 10 seconds per movement of m, and 1800 calibration steps (Fig. 3b), the calibration of an anchor plane with 11×11 anchors takes:

$$t_{due} = 1800 \times (10\ \mathrm{s} + \frac{100}{5\ \mathrm{Hz}}) = 15\ \mathrm{h}$$

This time can be reduced if several mobile nodes are used, or if a reduced accuracy is acceptable. As D&E is a progressive calibration method, the last calibration steps could also be gained during operation of the localization system.

As distance errors are unavoidable, and can cause position errors, a high fault-tolerance is of particular importance for self-calibration methods. Distribute & Erase purges such position errors as the position error of an anchor is distributed to its neighboring nodes and is then erased through a match operation.

V. Conclusion

In this paper we introduced Distribute & Erase, a precise self-calibration approach for US based localization systems. Some improvements were developed to enhance the accuracy and speed of the calibration. We showed that the achievable accuracy highly depends on the accuracy of the distance measurement system. With the error characteristics measured in our real world localization system an average position error $f_a < 1\ \mathrm{mm}$ is reachable. Distribute & Erase can replace the hard, time-consuming and fault-prone manual calibration, and operates distributed, autonomously and without further hardware or special a priori knowledge. Therefore, D&E is suitable for the fast, cheap and easy calibration of localization systems during deployment. As D&E calibrates progressively, it is also suitable for recalibration, especially after changes of the infrastructure.

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