Research Training Group Embedded Microsystems
Project D.2

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Configuration-free Ultrasound Tracking System using Time Differences of Arrival

Introduction

With increasing availability of mobile technology in industrial and recreational activity, location awareness has become an important factor. However, precise and cost-efficient indoor localization systems are still rare.

We present an approach for indoor localization using Time Differences of Arrival (TDOA) of acoustic or ultrasound signals. We have created novel algorithms to calculate both, the positions of receivers and of a moving target, without the need of given positions a priori. With this auto-calibration our system is easy to set up and scalable, as the positions of receivers do not need to be calibrated by hand. Using our system we can track a target with an error of 10 cm.

Methods

We have created two localization algorithms [1]:

- In a multi-dimensional implementation of Newton's method we calculate the positions of n receivers and m signal sources. The relation between two receivers M_i, M_k, and a signal S_j is described by the hyperbolic equation:

$$f_{i,j} = \| M_i - S_j \| - \| M_k - S_j \| - c\,(T_{i,j} - T_{k,j}) \quad \text{(w.l.o.g: } k = 1)$$

  This leads to an equation system $\mathbf{Qu} = \mathbf{b}$ of $(n-1)m$ equations and $p(n+m)$ variables (in the plane: $p = 2$). We calculate the Jacobian $\mathbf{Q}$ and the function vector $\mathbf{b}$:

$$\mathrm{Q} := \begin{bmatrix} \frac{\mathrm{d}f_{2,1}}{\mathrm{d}\mathbf{S}_{1,1}} & \cdots & \frac{\mathrm{d}f_{2,1}}{\mathrm{d}\mathbf{S}_{m,p}} & \frac{\mathrm{d}f_{2,1}}{\mathrm{d}\mathbf{M}_{1,1}} & \cdots & \frac{\mathrm{d}f_{2,1}}{\mathrm{d}\mathbf{M}_{n,p}} \\ \frac{\mathrm{d}f_{2,2}}{\mathrm{d}\mathbf{S}_{1,1}} & \cdots & \frac{\mathrm{d}f_{2,2}}{\mathrm{d}\mathbf{S}_{m,p}} & \frac{\mathrm{d}f_{2,2}}{\mathrm{d}\mathbf{M}_{1,1}} & \cdots & \frac{\mathrm{d}f_{2,2}}{\mathrm{d}\mathbf{M}_{n,p}} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\mathrm{d}f_{n,m}}{\mathrm{d}\mathbf{S}_{1,1}} & \cdots & \frac{\mathrm{d}f_{n,m}}{\mathrm{d}\mathbf{S}_{m,p}} & \frac{\mathrm{d}f_{n,m}}{\mathrm{d}\mathbf{M}_{1,1}} & \cdots & \frac{\mathrm{d}f_{n,m}}{\mathrm{d}\mathbf{M}_{n,p}} \end{bmatrix}$$

$$\mathbf{b} := (f_{2,1}, f_{2,2}, \ldots, f_{n,m})^{\mathrm{T}}$$

  Using the least squares method we solve for the unknown vector: $\mathbf{u} = (\mathbf{Q}^{\mathrm{T}}\mathbf{Q})^{-1}(\mathbf{Q}^{\mathrm{T}}\mathbf{b})$, where $\mathbf{u} := (S_{1,1}, \ldots, S_{m,p}, M_{1,1}, \ldots, M_{n,p})^{\mathrm{T}}$. The first estimate $\mathbf{u}^{(0)}$ is initialized with appropriate values. In every iteration step h we update $\mathbf{u}^{(h+1)} \leftarrow \mathbf{u}^{(h)} - \mathbf{u}$ until the abort condition $|\mathbf{u}| < \varepsilon$ is satisfied.

  To solve an hyperbolic equation system in the plane at least four receivers and at least six signals are required.

- We address the problem of local minima by a recursive approach using a tree search with refinement of an error function through the search space. In the *Recursive Partitioning* approach a node in the search tree represents an unique configuration of four receivers and at least six signals to be tested. Using the hyperbolic error function we test for validity of positions, given the TDOA data, and an error margin depending on the depth of the node in the tree (Fig. 1).

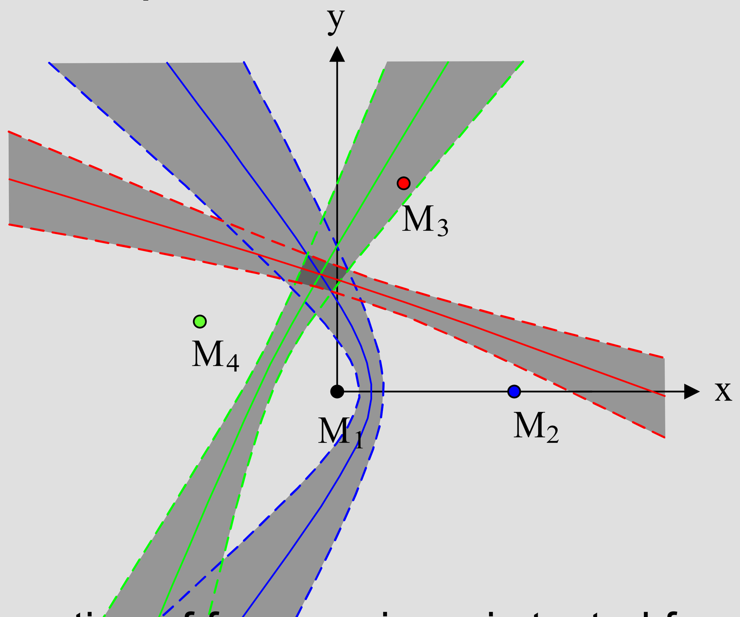


Figure 1: A configuration of four receivers is tested for a common intersection of the hyperbolic corridors, representing a possible signal source.

Ultrasound devices

In cooperation with F. Höflinger (IMTEK), we have created the *Configuration-free Ultrasound Tracking System*. It consists of a small sender unit (beacon), emitting discrete ultrasound pulses at a fixed rate (e.g. 300 ms) and receiver devices.

The receivers exist as external USB devices connected to a laptop computer (Fig. 2), or as standalone devices with a built-in Gumstix SoC running an ARM Cortex-A8 CPU.

Both types of receivers are compatible and connected via Wi-Fi to synchronize and to exchange TDOA information.

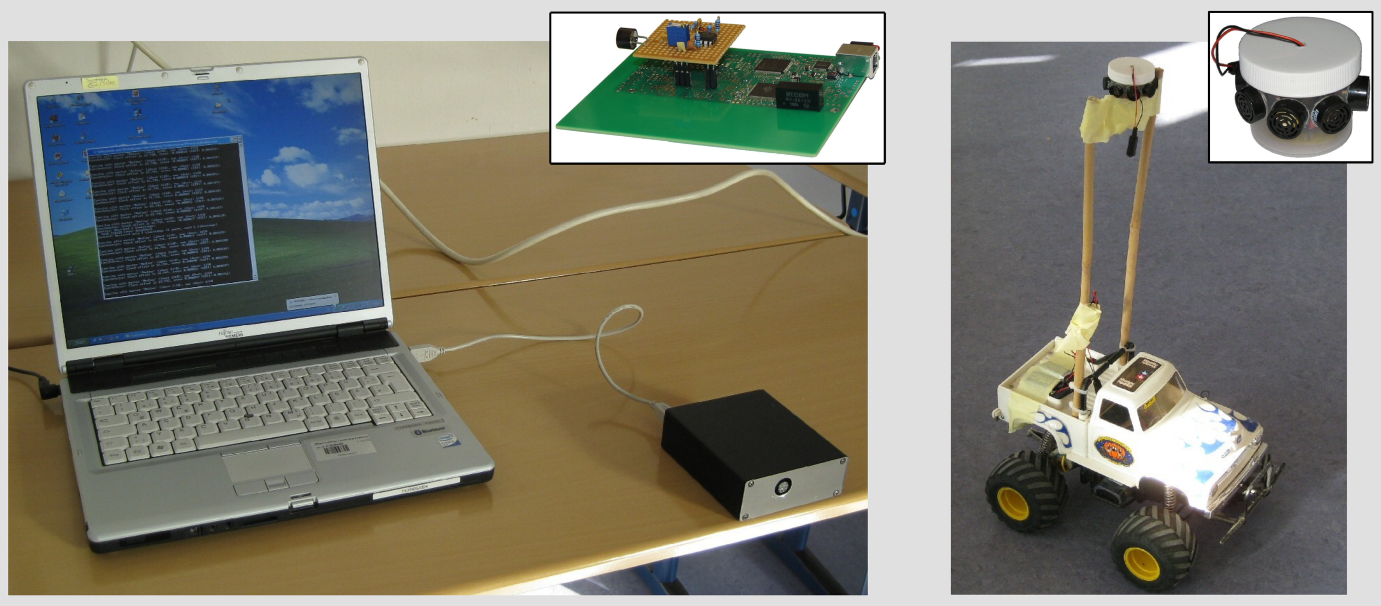
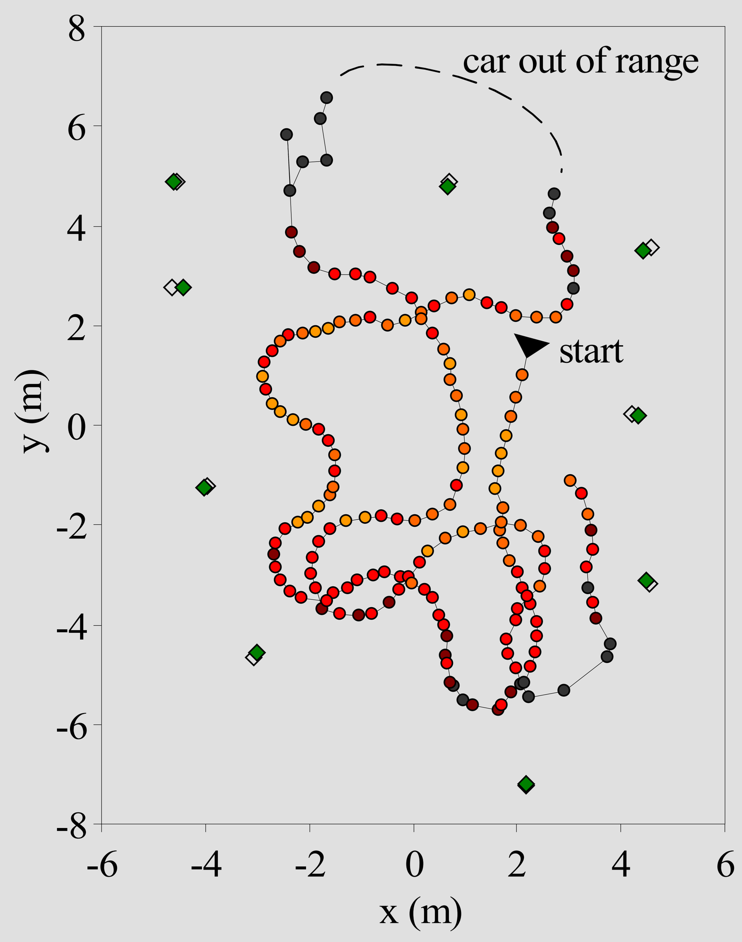


Figure 2: *Left*: USB receiver device connected to a laptop. *Right*: RC car with omnidirectional ultrasound beacon mounted.

Experiments

We have performed extensive experiments to verify the performance of the ultrasound tracking system [1]. In an indoor scenario we arranged nine receivers in an oval of 12×10 m. The ultrasound capsules were aligned towards the center.

We attached the ultrasound beacon to a model RC car and navigated on a random trajectory [2]. The positions of the receivers and the signals were calculated by our algorithm and aligned to references, which we had measured manually.



After mapping the relative positions to the ground-truth an average error of the receivers of only 10.7 cm (σ = 5.0 cm) remained.

Figure 3: Trajectory of the RC car (black, red, yellow) through the receivers (green) and the references (gray). The color indicates the number of devices a signal was received by.

Acknowledgements

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References

[1] J. Wendeberg, F. Höflinger, C. Schindelhauer, and L. Reindl. Anchor-free TDOA Self-Localization. In Proceedings of the 2011 International Conference on Indoor Positioning and Indoor Navigation (IPIN), May 2011.

[2] YouTube: http://www.youtube.com/watch?v=nKyYJy20CTc, Oct. 2011.

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