TDOA Self-Localization based on Ambient Sound Signals

Johannes Wendeberg, Christian Schindelhauer
Research Training Group Embedded Microsystems, Chair for Computer Networks and Telematics,
Department for Computer Science, University of Freiburg, Germany
wendeber@informatik.uni-freiburg.de

Abstract:
We present a localization system for mobile devices relying only on ambient sound signals from unknown positions. By evaluation of the time differences of arrival (TDOA) we can calculate both the positions of smartphones with microphones and of ambient sound signals. The localization system requires no infrastructure, except for a wireless network which is used for synchronization and the exchange of recorded time marks. In our software application we synchronize the devices and timestamp the audio stream up to an order of 0.1 ms. This results in a positioning precision in the order of 10 cm.
Our approach enables cost-efficient localization in indoor environments and when Global Navigation Satellite Systems (GNSS) are not available.

1. Introduction

Many applications on mobile devices like smartphones, PDAs, laptops, and tablet computers rely on position information, e.g. for filtering data according to the location context. Precise locality information is rarely provided by the communication network itself. A common approach is to equip the devices with additional hardware like GPS receivers which raises costs and increases the energy consumption. However, these approaches fail in shielded areas, in indoor environments and for small distances.

We present a smartphone application to localize a group of devices in a mobile environment without the need of any further infrastructure. Ambient sound signals are the only information source. Time marks are assigned to the recorded audio stream for each distinctive audio event. Then we evaluate the time differences of arrival (TDOA) between devices.

The innovation of our approach is, that we need absolutely no positional anchor points in space – neither any predefined smartphone positions nor the positions of the environmental sounds. This stands in contrast to common multilateration approaches. However, we use a WiFi connection to establish a common timebase between the devices and to exchange time marks. In this way the employment in dynamic environments with random sound events is made possible, e.g. in crowded areas like market places or concerts, or for thunderstorm tracking. Especially, the application becomes useful when established positioning systems (e.g. GPS) are too imprecise or fail, as during underwater self-localization of scuba divers.

Localization of mobile devices with additional infrastructure has been a broad and intensive research topic. Popular applications include GSM localization [1, 2] and WiFi network fingerprinting [3]. For *known* sender or receiver position information TDOA localization can be addressed in closed form [4, 5, 6] or by an iterative approach [7]. Moses et al. use TDOA with additional angle information (direction of arrival, DOA) to locate both *unknown* sender and receiver positions [8]. This requires expensive microphone arrays or directed microphones. Our approach uses only TDOA information without any further infrastructure.

2. Algorithms

We have developed two novel algorithms to address the self-localization problem of both unknown signal senders and receivers.

The *Iterative Cone Alignment* method [9] reconstructs the positions of at least four receivers in the plane and at least five receivers in three-dimensional space. The positions of the sound signals are computed as well. Fundamental is the signal propagation equation

$$\varphi \quad = \quad c\,(t_{\mathbf{M},\mathbf{S}} - t_{\mathbf{S}}) - \| \mathbf{M} - \mathbf{S} \| \qquad (1)$$

where c is the signal velocity, **S** and **M** denote the unknown positions of senders and receivers in two-dimensional space, t_{S} is the unknown signal time and $t_{\mathbf{M},\mathrm{S}}$ is the given sound signal time mark. $\| \bullet \|$ denotes the euclidean distance. Equation (1) describes a cone in (2+1)-dimensional space. If **S** resides on the surface of the cone with apex **M** then $\varphi = 0$.

The Iterative Cone Alignment relies on an energy minimization approach implemented in a physical spring-mass simulation. The energy minimization approach simulates physical particles of **S** and **M** for each signal and receiver (microphone). It attempts to restore valid positions of **S** on the cone surfaces of **M**. Except for symmetries, for a sufficient number of senders and receivers this leads to a globally unique solution of **S** with respect to every receiver.

The *Ellipsoid TDOA method* [10] calculates the positions of exactly three devices in the plane and of four devices in three dimensions under the assumption of infinitely distant sound sources. This can be written in closed form and solved rapidly. Experiments point out that the assumption of remote sound sources still holds if the distances of the sound sources are just greater than twice the distances between the devices.

3. iPhone App

We use the Apple iPhone as a platform that combines a fast ARM11 CPU with the intuitive multitouch interface making it a good choice for our interactive software [11]. The application ("App") serves both as an experimental platform for the development of our algorithms and as a nice and easy-to-use gadget for the public domain. Both localization schemes are included in our application. The Ellipsoid TDOA method requires three connected iPhones forming a triangle; at least four iPhones are necessary for the iterative method to obtain a unique solution. The algorithms rely upon discrete “timestamps”, i.e. the times when short, steep edged audio signals arrive at the devices. The signals are recorded via the built-in microphones and then analyzed by audio processing. Results of the calculations are displayed in an OpenGL visualization which can be rotated and zoomed using multitouch gestures.

4. Conclusions and Outlook

We have considered the problem of relative localization of nodes in a computer network solely based on ambient signals. There is absolutely no knowledge available about the received audio signals except that they can be distinguished from each other. There are no anchor points given in the network.

For this problem we present the *Iterative Cone Alignment*, an iterative solution based on a physical spring-mass simulation. It solves the problem if the number of receivers and sound sources is large enough. Furthermore we present an elegant closed-form solution, the *Ellipsoid TDOA method* for three receivers. It provides a solution in the plane although the underlying equation system is under-determined. We only need the assumption that the sounds originate from far away.

We have created a software platform and implemented our algorithms. We have installed the software on a modern smartphone which provides the computational power and usability for highly mobile applications at the same time. The practicality of our algorithms has been proven in real-world experiments.

The rapid Ellipsoid TDOA method can be employed to support the Iterative Cone Alignment as an initial guess of the iteration. The distance estimation might accelerate the approximation convergence and help to recover from ambiguities.

Of importance is also the question of unsynchronized localization. The use of radio signals from Wi-Fi access points, from GPS or from broadcast prevents precise synchronization among receivers due to the greater speed of light. We will extend the Ellipsoid TDOA method to unsynchronized operation.

Furthermore, we plan to include the use of non-discrete continuous signals, e.g. voices, traffic noise or analogous radio signals. By testing for correlation of audio signals it should be possible to detect time differences analogously to sharp signals. This would dramatically increase the information basis of the algorithms.

5. References

[1] Christopher Drane, Malcolm Macnaughtan, and Craig Scott. Positioning GSM Telephones. *IEEE Communications Magazine*, 36:46–54, 1998.

[2] Veljo Otsason, Alex Varshavsky, Anthony LaMarca, and Eyal de Lara. Accurate GSM Indoor Localization. In *Ubicomp*, pages 141–158, 2005.

[3] Brian Ferris, Dirk Hähnel, and Dieter Fox. Gaussian Processes for Signal Strength-Based Location Estimation. In *Proceedings of RSS*, 2006.

[4] Jean-Marc Valin, François Michaud, Jean Rouat, and Dominic Létourneau. Robust Sound Source Localization Using a Microphone Array on a Mobile Robot. In *Proceedings International Conference on Intelligent Robots and Systems (IROS)*, pages 1228–1233, 2003.

[5] Le Yang and K. C. Ho. An Approximately Efficient TDOA Localization Algorithm in Closed-Form for Locating Multiple Disjoint Sources With Erroneous Sensor Positions. *IEEE Transactions on Signal Processing*, 57:4598–4615, Dec. 2009.

[6] M.D. Gillette and H.F. Silverman. A Linear Closed-Form Algorithm for Source Localization From Time-Differences of Arrival. *Signal Processing Letters, IEEE*, 15:1–4, 2008.

[7] Dragana Carevic. Automatic Estimation of Multiple Target Positions and Velocities Using Passive TDOA Measurements of Transients. *IEEE Transactions on Signal Processing*, 55:424–436, Feb. 2007.

[8] R.L. Moses, D. Krishnamurthy, and R.M. Patterson. A Self-Localization Method for Wireless Sensor Networks. *EURASIP Journal on Advances in Signal Processing*, pages 348–358, 2003.

[9] Johannes Wendeberg. Laufzeitbasierte Schallortung mit unbekannten Sender- und Empfängerpositionen. Master’s thesis, University of Freiburg, 2009.

[10] Thomas Janson, Christian Schindelhauer, and Johannes Wendeberg. Self-Localization based on Ambient Signals. *ALGOSENSORS 2010*, to appear in LNCS, Springer, 2010.

[11] Thomas Janson, Christian Schindelhauer, and Johannes Wendeberg. Self-Localization Application for iPhone using only Ambient Sound Signals, *2010 International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, accepted, 2010.