Indoor Positioning Technologies and Systems
From Theory to Practice

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Introduction

Outdoor Positioning

Indoor Positioning

Airplace Platform

Conclusion
Motivation for Positioning

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Outdoor Positioning
- Satellites
- Cellular Networks

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- Technologies
- WiFi Positioning

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- System Architecture
- Airplace Components

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Target tracking
UAV missions
Missile flight

Network: 100m (cep67), 300m (cep95)
Mobile: 50m (cep67), 150m (cep95)

Navigation
Guidance
POI locator

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Navigation
Guidance
POI locator
Applications of Positioning Systems

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Applications of Indoor Positioning Systems
Overview

Rainer Mautz, 2011
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Technologies for Positioning

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Facts

► GPS started in 1973 and became fully operational in 1994 (originally 6 constellations with 4 satellites, 31 as of 2008)

► Position determined by precisely timing the satellite signals (4 satellites required for 3D position, 3-5m accuracy)

► Russian GLONASS, European Galileo (planned 2014), Chinese COMPASS (planned 2020), India and Japan follow
Objective
Augment satellite coverage in severely shadowed environments (e.g. mining pits, planetary rover navigation, urban canyons)

Features
- Requires ground-based transceivers and achieves submeter level accuracy
- Synchronization, multipath, near-far problem and legal issues
Cellular Networks (GSM, UMTS, ...)

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Objective

▶ GPS is battery hungry, has high start-up time, low availability in urban areas

▶ Use signalling in cellular networks for positioning, as a GPS back-up solution or to enhance GPS (A-GPS)
Cell IDentity (CID)

Measurements
Unique cell identifier

Advantages
- Low Cost: No modifications to handset or network
- Usable with existing equipment
- Fast response: No calculations needed

Disadvantages
- Low accuracy ranging from 50m (urban) to 30km (rural)
- Serving cell is not always the nearest cell

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Angle of Arrival (AOA)

Measurements
Signal arrival angle

Advantages

- Requires only 2 base stations
- No modifications to the mobile devices

Disadvantages

- LOS conditions
- Low accuracy
- Additional equipment (antenna arrays, directional antennas)

Source: cisco.com
Source: e-cartouche.ch

KIOS Tuesday Seminar Series 24 July 2012
Time of Arrival (TOA)

Measurements
Signal propagation time between the transmitter and the receiver

Advantages
▶ No modifications to the devices

Disadvantages
▶ Knowledge of the exact transmission times
▶ Precisely synchronized clocks (e.g. 100 nanoseconds can result in 30 meters distance error)
▶ Requires additional equipment (Measuring Units)

\[ \tau_i = \frac{d_i}{c} \]

Source: Stuber G.L., 1999
**Time Difference of Arrival (TDOA)**

**Measurements**
Time differences of the signal arriving at multiple base stations

**Advantages**
- Exact time of signal transmission is not required
- Good accuracy, 60m (rural) 200m (urban)

**Disadvantages**
- Requires additional equipment (Measuring Units) at the base stations
- Synchronization is still required

\[ \rho_{i,j} = \frac{d_i - d_j}{c} \]

Stuber G.L., 1999
Received Signal Strength (RSS)

**Measurements**
Signal strength of the transmitted signal

**Advantages**
- Already monitored as part of the standard network functionality
- No modifications to the devices
- Low deployment cost

**Disadvantages**
- Moderate accuracy in rural and urban areas
- Requires calibration of the signal propagation model

\[ \text{rss}_i[\text{dBm}] = K - 10n \log d_i \]
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- People spend most of their time indoors, e.g. shopping malls, airports, university campuses

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- Massive availability of mobile devices with wireless connectivity
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- Indoor location-aware applications, e.g. in-building guidance, asset tracking, event detection
Target Indoor Environments

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Source: google images
Inside the Human Body

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Capsule Endoscopy
Positioning of medicine capsules inside the human body using RF signals (K. Pahlavan, CWINS Group)
Infrared (IR)

Measurements
Custom IR cameras

Advantages
- Firefly delivers 3mm accuracy
- Tags are small and light-weight
- Simple system architecture, low installation and maintenance cost

Disadvantages
- Interference from florescent light and sunlight
- Expensive hardware (e.g. Firefly: 1 camera array + 1 tag controller + 32 tags = $27500, 2009)
Ultrasound

Measurements
TOA, TDOA

Advantages

▶ Inexpensive and easy to install
▶ Centimeter level accuracy

Disadvantages

▶ Temperature dependency, affected by noise sources (e.g. jangling metal objects)
▶ Suffer from reflected ultrasound signals (multipath, Doppler shift)
Ultra Wide Band (UWB)

Measurements
AOA, TOA, TDOA, signal reflection

Advantages

▶ No LOS requirement, no multipath distortion, less interference, high penetration
▶ Easily wearable and light tags
▶ Very accurate (e.g. Ubisense has 15cm accuracy in 3D)

Disadvantages

▶ Short range and computational cost
▶ Expensive equipment (Ubisense costs ∼$17000, 2009)
Radio Frequency IDentification (RFID)

**Measurements**
Cell of Origin, Signal Strength

**Advantages**
- Penetration, unobtrusive installation
- Low power system, light and easy to carry tags

**Disadvantages**
- Numerous components installed and maintained
- Short range, close proximity

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PENETRATION, UNOBSERVABLE INSTALLATION

LOW POWER SYSTEM, LIGHT AND EASY TO CARRY TAGS

RFID system by RF Code

Wherenet Real Time Locating System
Magnetic Measurements
Magnetic flux density (coil or permanent magnets)

Advantages
- Centimeter level accuracy
- Magnetic sensors are small, robust and cheap
- Penetration through buildings

Disadvantages
- Complexity of magnetic field and disturbances
- Limited coverage range

Source: wikipedia

MotionStar Wireless System
Optical Systems

Measurements
images, video

Advantages
▶ High accuracy
▶ No user carried equipment

Disadvantages
▶ Invasive installation, difficult to scale, high processing power
▶ Unreliable in dynamic environments (LOS required, light conditions, bad weather, fires)
Inertial Measurement Units (IMU)

Measurements
3D acceleration, 3D gyroscope, digital compass, dead reckoning

Advantages
▶ No infrastructure is required, sensor integrated into smartphones
▶ Light-weight, low power

Disadvantages
▶ Relative positioning system: requires initial location and frequent updates
▶ Drift introduces error
Why WiFi?

- Installation of dedicated equipment vs Ubiquitous deployment of WiFi infrastructure (APs)
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Why RSS measurements?

➤ AOA/TOA/TDOA measurements require additional hardware at the base stations or the mobile device
Why RSS measurements?

- AOA/TOA/TDOA measurements require additional hardware at the base stations or the mobile device.
- RSS values are constantly monitored as part of the standard functionality for network operating reasons and can be easily collected through OS APIs.
Indoor Signal Propagation

- Complex propagation conditions (multipath, shadowing) due to walls and ceilings
Indoor Signal Propagation

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- RSS value fluctuates over time at a given location
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- RSS value fluctuates over time at a given location
- Variable number of detected WiFi APs
- Unpredictable factors (people moving, doors, humidity)
- **Offline phase:** Build RSS radio map
  - $n$ APs deployed in the area
  - Fingerprints $r_i = [r_{i1}, \ldots, r_{in}]^T$
  - Averaging $\bar{r}_i = \frac{1}{M} \sum_{m=1}^{M} r_i(m)$

- **Online phase:** Positioning
  - Fingerprint $s = [s_1, \ldots, s_n]^T$ is observed
  - Obtain an estimate $\hat{\ell}$ using the radio map
Fingerprint-based Positioning

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**Deterministic Approach**

### Deterministic positioning methods

Location is estimated as a convex combination of the reference locations $\ell_i$ by using the $K$ locations with the shortest distances between $\bar{r}_i$ and $s$.

$$\hat{\ell} = \sum_{i=1}^{K} \frac{w_i}{\sum_{j=1}^{K} w_j} \ell'_i$$

(1)

where $\{\ell'_1, \ldots, \ell'_l\}$ denotes the ordering of reference locations with respect to increasing distance $\|\bar{r}_i - s\|$.

**K-Nearest Neighbor (KNN) variants**

- **NN**: $K = 1$
- **KNN**: $K \neq 1$, $w_i = \frac{1}{K}$
- **Weighted KNN**: $K \neq 1$, $w_i = \frac{1}{\|\bar{r}_i - s\|}$
Probabilistic Approach

Probabilistic positioning methods
Location $\ell$ is treated as a random vector that can be estimated by calculating the conditional probabilities $p(\ell_i|s)$ (posterior) given $s$.

\[
p(\ell_i|s) = \frac{p(s|\ell_i)p(\ell_i)}{p(s)} = \frac{p(s|\ell_i)p(\ell_i)}{\sum_{i=1}^{l} p(s|\ell_i)p(\ell_i)} \quad (2)
\]

\[
p(s|\ell_i) = \prod_{j=1}^{n} p(s_j|\ell_i) \quad (3)
\]

$p(s|\ell_i)$ is the likelihood, $p(\ell_i)$ is the prior and $p(s)$ is a constant.

Positioning variants

- Maximum Likelihood: $\hat{\ell} = \arg \max_{\ell_i} p(s|\ell_i)$
- Maximum A Posteriori: $\hat{\ell} = \arg \max_{\ell_i} p(s|\ell_i)p(\ell_i)$
- Minimum Mean Square Error: $\hat{\ell} = E[\ell|s] = \sum_{i=1}^{l} \ell_i p(\ell_i|s)$
Radial Basis Function Networks

\[
\ell(s) = \sum_{i=1}^{C} w_i u(s, c_i)
\]

\[
u(s, c_i) = \frac{\varphi(\|s - c_i\|)}{\sum_{j=1}^{C} \varphi(\|s - c_j\|)}
\]

- \(C\): number of centers
- \(c_i\): \(n\)-dimensional center
- \(\varphi(\|s - c\|) = \exp\left(-\frac{1}{2}\|s - c\|^2\right)\)
- \(w_i\): 2-dimensional weights
A Taxonomy for Radio Location Fingerprinting

Locations [16, 18, 21]. However, a location outputted as either of the two types can be mapped to the other type given a suitable location model.

Measurements are the types of measured network characteristics. The following network characteristics have been used in existing systems: Base Station Identifiers (BSI), Received Signal Strength (RSS), Signal-to-Noise Ratio (SNR), Link Quality Indicator (LQI), power level, and Response Rate (RR). BSI is a unique name assigned to a base station. RSS, SNR, and LQI are signal propagation metrics collected by radios for handling and optimizing communication. The power level is information from the signal sender about current sending power. The response rate is the frequency of received measurements over time from a specific base station. Many LF systems are based on BSI and RSS [11, 14, 18, 25]; other systems have used RR in addition to RSS [15, 17, 24]. BSI and SNR have also been used [16] and the combination BSI, LQI, RSS, and Power level [9, 26].

Roles denote the division of responsibilities between wireless clients, base stations, and servers. How roles are assigned impact both how systems are realized, but also important non-functional properties like privacy and scalability.

The two main categories for roles are infrastructure-based and infrastructure-less. Infrastructure-based systems depend on a pre-installed powered infrastructure of base stations. Infrastructure-less systems consist of ad-hoc-installed battery-powered wireless clients where some of them act as "base stations". Infrastructure-based systems are following Küpfer [1], being further divided into terminal-based, terminal-assisted, and network-based systems. The infrastructure-less systems are divided into terminal-based and collaborative systems. The different types of systems differ in who sends out beacons, who makes measurements from the beacons and who stores the radio map and runs LF estimation, as shown in Figure 2. Most LF systems have been built as terminal-based, terminal-assisted, or network-based. The collaborative systems are divided into terminal-based and collaborative systems. The different types of systems differ in who sends out beacons, who makes measurements from the beacons and who stores the radio map and runs LF estimation, as shown in Figure 2. Most LF systems have been built as terminal-based, terminal-assisted, or network-based.
Airplace System

Terminal-based Infrastructure-assisted Architecture

- **Low Communication Overhead**: Avoids uploading the observed RSS fingerprint to the positioning server

- **User Privacy & Security**: Location is estimated by the user

http://www2.ucy.ac.cy/~laoudias/pages/platform.html
RSS Logger Application

Facilitates collection and storage of the RSS data on the device.

- Developed around the Android RSS API for scanning and recording data samples in specific locations
- User-defined number of samples
- Users can contribute their data to Airplace for constructing and updating the radiomap through crowdsourcing
Distribution Server

Constructs the RSS radiomap and disseminates it to the requesting clients.

- Listens for connections from clients, that either contribute their RSS data or request the radiomap for positioning
- Parses all available RSS log files and merges them in a single compact radiomap file
- Fine tunes algorithm-specific parameters and stores them in a configuration file which is distributed with the radiomap
Find Me Application

Implements the positioning client running on the users device.

- Connects to the server for downloading the radiomap and algorithm-specific parameters
- Algorithm bank with several algorithms (KNN, MMSE, etc.)
- Dual Operation Mode: **Online** (real-time positioning) or **Offline** (evaluation of algorithms)
Airplace Video Demonstration

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- Moving from Google Maps to Google Floors!!
Thank you for your attention
Questions?


