Outline

• Properties of localization procedures
• Approaches
  » Proximity
  » Trilateration and triangulation (GPS)
  » Finger printing (RADAR)
  » Hybrid systems

Properties of localization procedures

• Physical position vs data types
• Reference systems
• Processing: localized vs centralized
• Data quality
  » Accuracy and precision
  » Scale
• Deployment aspects
  » Limitations
  » Cost
  ➞ Very diverse systems – lots of research

Data types

• Many ways to measure location, e.g.
  » GPS location of a mobile phone
  » Area where an access point has sufficient reception
• Corresponding data types
  » point locations in terms of coordinates: physical or geometric locations
  » extended region locations given by names: symbolic locations
Spatial Information

• Sources of location information
  » Location of a device can be measured using positioning methods
  » Additional spatial information can be retrieved from a spatial information system

• Additional information
  » Geometric information
    – coordinate system and unit transformations
    – precision and accuracy of measurement
  » Region information
    – location hierarchies

Location-awareness

• Location model: data structure that organizes locations
  » symbolic location model: address hierarchy
    DH.Floor2.2105
  » geometric location model: GPS coordinate
    (12.3456°N, 123.456°E)
  » hybrid location model
    DH.Floor2.2105.Seat(0,4)

Quality of Position Information

Positioning accuracy:
largest distance between an estimated position and the true position

Precision:
the ratio with which a given accuracy is reached, averaged over many repeated attempts

Example:
average error of less than 20cm in 95% of cases

Precision vs. Accuracy

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<th>Inaccurate</th>
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Approaches

- **Proximity**
  - estimate distance between two nodes
- **Trilateration and triangulation**
  - using elementary trigonometric properties: a triangle is completely determined,
    - if two angles and a side length are known
    - if the lengths of all three sides are known
  - infer a 3d position from information about two triangles
- **Fingerprinting (scene analysis)**
  - using radio characteristics of a location as fingerprint to identify it
- **Hybrid methods**: combine multiple sources of information

Proximity and Distance

- **Binary nearness**: using finite range of wireless communication and/or threshold
  - within range of a beacon signal from a source with known position
  - yields region locations, e.g.: cell in cellular network
- **Distance measurement** (ranging)
  - Received signal strength
  - Time of flight (time of arrival)
  - Time difference of arrival

Measuring Location: Trigonometry Basics

- **Triangles in a plane**
  - Lateration: distance measurement to known reference points
    - a triangle is fully determined by the length of its sides
    - Time of Flight (e.g. GPS, Active Bat)
    - Attenuation (e.g. RSSI)
  - Angulation: measuring the angle with respect to two known reference points and a reference direction or a third point
    - a triangle is fully determined by two angles and one side as shown
    - Phased antenna arrays
    - aircraft navigation (VOR)

Trilateration

[Diagram of trilateration]
Angulation

• Computing positions between three known positions \((x_i, y_i)\) and an unknown position \((x_u, y_u)\) given distances \(r_i\) btw \((x_i, y_i)\) and \((x_u, y_u)\)
• Yields three equations \((x_i - x_u)^2 + (y_i - y_u)^2 = r_i^2\)
• Linear equations by subtracting 3rd from 1st and 2nd: quadratic terms \(x_u^2\) and \(y_u^2\) disappear
  \[2(x_3 - x_2)x_u + 2(y_3 - y_2)y_u = (r_2^2 - r_3^2) - (x_2^2 - x_3^2) - (y_2^2 - y_3^2)\]
  \[2(x_3 - x_1)x_u + 2(y_3 - y_1)y_u = (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)\]
• In 3D: yields two points
• Positioning with imprecise information:
  » Add redundancy: over determined solution
  » Least squares estimates

Mathematical Background

GPS

• Radio-based navigation system developed by DoD
  » Initial operation in 1993
  » Fully operational in 1995
• System is called NAVSTAR
  » NAVigation with Satellite Timing And Ranging
  » Referred to as GPS
• Series of 24 satellites, in 6 orbital planes
• Works anywhere in the world, 24 hours a day, in all weather conditions and provides:
  » Location or positional fix
  » Velocity, direction of travel
  » Accurate time

GPS Constellation
GPS involves 5 Basic Steps

- Satellite Ranging
  » Determining distance from satellite
- Trilateration
  » Intersection of spheres
- Timing
  » Why consistent, accurate clocks are required
- Positioning
  » Knowing where satellite is in space
- Correction of errors
  » Correcting for ionospheric and tropospheric delays

How GPS works?

- Range from each satellite calculated
  \[ \text{range} = \text{time delay} \times \text{speed of light} \]
- Technique called trilateration is used to determine your position or "fix"
  » Intersection of spheres
- At least 3 satellites required for 2D fix
- However, 4 satellites should always be used
  » The 4th satellite used to compensate for inaccurate clock in GPS receivers
  » Yields much better accuracy and provides 3D fix

Determining Range

- Receiver and satellite use same code
- Synchronized code generation
- Compare incoming code with receiver generated code

Measure time difference between the same part of code

Signal Structure

- Each satellite transmits its own unique code
- Two frequencies used
  » L1 Carrier 1575.42 MHz
  » L2 Carrier 1227.60 MHz
  » L5 Carrier 1176.45 MHz
- Codes
  » CA Code uses L1 (civilian code)
  » P(Y) Code uses L1 & L2 (military code)
  » M Code uses L1 & L2 (military code)
Three Satellite Ranges Known

20,000 Km radius

22,000 Km radius

21,000 Km radius

Located at one of these 2 points. However, one point can easily be eliminated because it is either not on earth or moving at impossible rate of speed.

Accurate Timing is the Key

- Satellites have very accurate atomic clocks
- Receivers have less accurate clocks
- Measurements made in nanoseconds
  - 1 nanosecond = 1 billionth of a second
  - Speed of light (c) ~ 1 ft/nanosecond
- 1/100th of a second error could introduce error of 1,860 miles
- Discrepancy between satellite and receiver clocks must be resolved
- Fourth satellite is used to solve the 4 unknowns (X, Y, Z and receiver clock error)

Satellite Positioning

- Also required in the equation to solve the 4 unknowns is the actual location of the satellite.
- Satellites are in relatively stable orbits and constantly monitored on the ground
- Satellite’s position is broadcast in the “ephemeris” data streamed down to receiver
  - Downloading complete set of almanac data requires 12.5 minutes (transmitted at 50 bps)

Sources of Errors

- Largest source is due to the atmosphere
  - Atmospheric refraction
    - Charged particles
    - Water vapor
- Other sources:
  - Geometry of satellite positions
  - Multi-path errors
  - Satellite clock errors
  - SV position or “ephemeris” errors
  - Quality of GPS receiver
How about Indoors?

- We can use received WiFi signal strength (RSS) to measure distance to APs with known location!
- Does not work in practice: too many factors affects RSS: objects, people, …
  » Triangulation based on RSS tends to results tend to give large, unpredictable errors
- How about using time of arrival?
  » E.g., based on sound, radar-like techniques, …
  » Works better, but it is still hard
  » Can work well but often requires special infrastructure
  » Reflections can also create inaccuracies: longer path!

CAESAR: Carrier Sense-based Ranging

- Question: can we use time of flight ranging using commodity WiFi hardware?
- Yes, but it gets a bit messy
  » Need to include SNR measurement
- Local station determines location of (mobile) remote stations
- Design criteria
  » Exploit standard 802.11 protocol implementations
  » Real time results
  » Low cost (low network usage, no additional hardware, minimal calibration)

CAESAR: Key Idea

- Time of flight from ACKs
- Speed of light: $c \approx 300\text{m/s}$
- WLAN clock 44MHz
  » Resolution: $300/(2\times44) = 3.4\text{m}$
  » Distance $d = c \times (t_{\text{MacIdle}} - t_{\text{SIFS}} - t_{\text{FD}})/2$

CAESAR: Adjustment to Noise

- Method depends on correct estimation of response time, which depends on the SNR
- Automatic gain control is used if
  » Preferred region (PR): no AGC
  » Strong signal detected (SSD): e.g. subtract 30dB from signal
  » Weak signal detected (WSD): may need adjust signal to to bring it into PR (or signal is not detected)
- Proposed solution:
  » Detect states SSD, WSD, and preferred range
  » Use different values for Time for Frame Detection ($t_{\text{FD}}$)
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Angle of Arrival (AoA)

- A measures the direction of the incoming signal using a radio array.
- By using 2 anchors, A can determine its position
- Alternatively: the anchor measure the angle of A’s signal and coordinate

Angle of Arrival Techniques

- Antenna arrays are increasingly popular
- They are usually used to steer the signal, but can be used to identify the angle at which it arrives
- Difference in arrival time can be used to measure angle

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**Location Fingerprinting**

- **Fingerprint Methods for Recognizing Locations**
  - Examples
    - Visual identification of places from photos
    - Recognition of horizon shapes
    - Measurement of signal strengths of nearby networks (e.g. RADAR)
  - Method: computing the difference between a feature set extracted measurements with a feature database
  - Advantages: passive observation only (protect privacy, prevent communication overhead)
  - Disadvantage: access to feature database needed

**RADAR: Key Idea**

- RSS from multiple APs tends to be unique to a location

**RADAR Approach**

- Scenario: floor layout with three base stations (in the hallways)
- Empirical method
  - offline phase: database is constructed
    - collect signal strength measurements from all three base stations at 70 distinct locations
    - store each of the 70 measurement triples together with the spatial location and orientation in a database
  - online phase: position can be determined
    - measure the current signal strength from all three base stations
    - find the most similar triple(s) in the database
  - Resolution 2.94m (50th percentile)

**Model-Based Radio Map**

- Model set-up phase has high cost
- Alternative use radio propagation model and floor plan (instead of measurements)
  - Considered models
    - Rayleigh fading model: small-scale rapid amplitude fluctuation to model multi-path fading
    - Rician distribution model: like Rayleigh but with additional LoS component
    - Floor Attenuation Factor propagation model: large scale path loss with building models
    - Wall Attenuation Factor model: considers effects from walls between transmitter and receiver
  - Resolution 4.3m (50th percentile)
**Effects of applying correction**

- Signal strength as a function of distance
- with correction for walls

**Localization**

- Find nearest neighbor in single space (NNSS)
  - Default metric is Euclidean distance
- Physical coordinates of NNSS -> estimated user location
- Refinement: k-NNSS
  - Average the coordinates of k nearest neighbors

- N1, N2, N3: neighbors
- T: true location of user
- G: Guess based on averaging

**Limits of Localization Using Signal Strength**

- Measuring distance based on signal strength is an attractive idea for wireless sensor networks:
  - RSS does not require additional hardware
  - RSS declines with distance
  - Many different promising methods proposed
- Experimental study:
  - 802.11 technology with a range of methods and environments tested
  - Median localization error of 10ft and 97th percentile of 30ft
- Fundamental limitations that require
  - more complex environment models
  - additional infrastructure

**Results**

- Median error distance is 2.13 meters when averaging is done over 3 neighbors
- Diminishing as the number of physical points (training values) mapped increased
Hybrid Technologies

- Cell phones: have many other sensors
  » Accelerometer, compass, ...
- Can be used to estimate the user’s walking speed, direction, ...
- This information can be combined with fingerprinting based techniques
- Especially useful if fingerprinting provides accurate location in specific points
  » When entering a store, escalator, elevators
  » Can use the other sensors starting with these well-known locations

Study

- Three area-based algorithms:
  » Simple Point Matching
  » Area Based Probability
  » Bayesian Network
- Yield a region instead of a point
  » allows representation of uncertainty
  » can trade accuracy for precision
    - accuracy: likelihood that point is in region
    - precision: size of region
- Comparison: eight point-based alg.s
  » Bayesian Point
  » Averaged Bayesian
  » RADAR
  » Averaged RADAR
  » Gridded RADAR
  » Highest Probability
  » Averaged Highest Probability
  » Gridded Highest Probability

Literature


Area-based Algorithms

- Simple Point Matching
- Area Based Probability
- Bayesian Network
Two Office Environments

I: industrial office environment

C: campus office environment

Results

C, size 35

C, size 115

I, size 215

Uncertainty

x - PDF

y - PDF

Other Direct Methods

- Active Badge: infrared beacons in rooms
- Active Office: location of specific device
  - arrays of ultrasound receivers
  - central controller sending radio signal
  - time difference of arrival (95%, 8cm)
- Cricket
  - device queries anchors
  - anchors provide ultrasound and radio signal for TDoA
- Overlapping connectivity
- Approximate point in triangle
- Angle of arrival: narrow, rotating beams
### Multi-hop Environments

- Given position of some anchor nodes, estimate positions of other nodes in network
- Connectivity-based methods (based on topology)
  - Model as a type of linear program optimization
  - Multi-dimensional scaling improving estimates from an all-pair shortest path algorithm
- Multi-hop range estimation: estimate distance between node and anchor
  - Hop-count distance
  - Using lateration, Euclidean distance estimate
- Iterative multi-lateration: estimate position relative to neighbors
- Probabilistic positioning description based on RSSI