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

Additional information

Location-awareness

- Location model: data structure that organizes locations
- Location-based routing
  - symbolic location model
  - geometric location model
  - hybrid location model

Examples
- symbolic location model: address hierarchy
  - DH.Floor2.2105
- geometric location model: GPS coordinate
  - (12.3456°N, 123.456°E)
- hybrid location model: combination of address and coordinate
  - 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

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

Only pairs of precision and accuracy make sense

Precision vs. Accuracy

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<th>Accurate</th>
<th>Inaccurate (systematic error)</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 with three stations]

http://gpsworld.com/innovation-where-are-we/
Angulation

Angulation is a method for determining the position of an object by measuring distances from known points. The distances can be measured from three known positions $(x_i, y_i)$ and an unknown position $(x_u, y_u)$.

Yields three equations:

$$(x_i - x_u)^2 + (y_i - y_u)^2 = r_i^2$$

Linear equations by subtracting the $3^{rd}$ from the $1^{st}$ and $2^{nd}$:

$$2(x_3 - x_1)x_u + 2(y_3 - y_1)y_u = (r_1^2 - r_3^2) - (x_1^2 - x_3^2) - (y_1^2 - y_3^2)$$

In 3D:

Positioning with imprecise information:

- Add redundancy: over determined solution
- Least squares estimates

Mathematical Background

• Computing positions between three known positions $(x_i, y_i)$ and an unknown position $(x_u, y_u)$ given distances $r_i$ between $(x_i, y_i)$ 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 the $3^{rd}$ from the $1^{st}$ and $2^{nd}$; quadratic terms $x_u^2$ and $y_u^2$ disappear.

- In 3D: yields two points

Positioning with imprecise information:

- Add redundancy: over determined solution
- Least squares estimates

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

• Has been improved over time

• Series of 24 (now 32) 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

• 24 satellites are needed to guarantee that 4 are always visible everywhere

• Extra satellites provide redundancy

  - Deal with maintenance, replacement, …
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 are used
  - The 4th satellite used to calculate drift of clock in GPS receivers relative to that of the satellites
  - Yields much better accuracy and provides 3D fix

Satellite Positions

- Each satellite has an atomic clock that keeps time very accurately
  - Satellites synchronize their clocks
  - Also periodically synchronize with the true time maintained on earth
- Satellites also know their location very accurately

Determining Range

- Each satellite periodically generates a pseudo random code
  - Receivers also locally generate the codes in synchronized fashion
- Receivers measure Time of Arrival (TOA) of codes
- Transmission includes Time of Transmission (TOT) of code and the location of the satellite at that time
  - Allows receiver to calculate Time of Flight and distance
    - Measure time difference between the same part of code
      - From satellite: Series of ones and zeroes repeating every 1023 bits. So complicated alternation of bits that pattern looks random thus called “pseudorandom code”.
Signal Structure

- Each satellite transmits its own unique code
- Use CDMA spread spectrum
- 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
  » 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

- Required in the equation to solve the 4 unknowns is the actual location of the satellite.
  » 3 coordinates for location, plus clock drift of receiver relative to the satellite clocks
- 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
  - Satellite 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: \( c = \sim 300 \text{m/s} \)
  - WLAN clock 44MHz
  - Resolution:
    - \( 300/(2^{14}) = 3.4 \text{m} \)
  - Distance
    - \( d = c(t_{\text{MacIdle}} + t_{\text{SIFS}} + t_{\text{FD}})/2 \)
  - Distance = \( \frac{1}{2} \) time from end of data to beginning of ACK
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 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 ($t_{FD}$)

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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

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

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 finger printing based techniques
- Especially useful if finger printing provides accurate location in specific points
  » When entering a store, escalator, elevators
  » Can use the other sensors starting with these well-known locations
Literature