CMPE58C: Sp. Tp. Mobile Location Tracking & Motion Sensing

Technology Overview

Can Tunca

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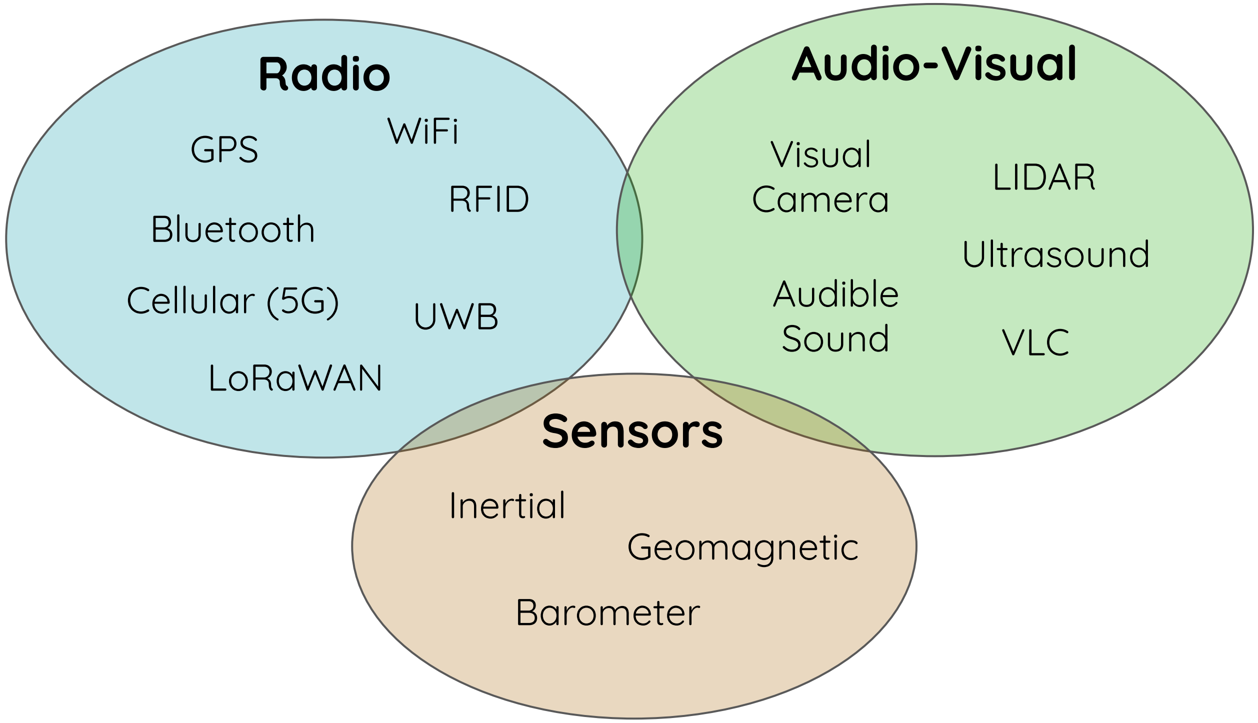
There are so many alternatives…

- GPS is the standard solution for outdoors, no question
- No such standard solution <u>yet</u> for where GPS fails
- No widely adopted solution for indoors
- As mobile devices got more sophisticated, alternatives emerged
  - Technologies dedicated to positioning
  - Technologies that are used beyond their original purpose for positioning
- Combination of different technologies might be the answer
- We will go over many, but the list can be extended…

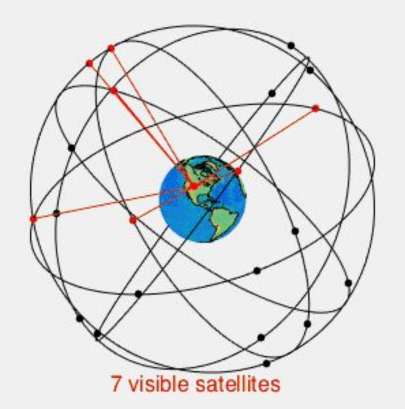
Some considerations first…

- **Cost:** Can be the deal breaker…
- **Scalability:** Low cost does not always mean scalable, should be easy to deploy/maintain
- **Good performance/accuracy:** Important, but depends on the use case…
- **Reliability:** Maintaining a baseline accuracy, very important for some use cases (e.g. navigation for visually impaired people)
- **Ecosystem:** Existing devices/technology is important, technology is sticky…
- **Ease of implementation:** Important for scalability, algorithms could be sophisticated, but means of access should be provided (e.g. developer APIs)
- **User experience (UX):** Considering use cases involving humans, accurate solutions does not always have the best UX (e.g., responsiveness, update rate, orientation)

A Rough Categorization of Location Tech



GPS



- Global Positioning System
- Wider term: Global Navigation Satellite Systems (GNSS)
- ~31 satellites at Medium Earth Orbit (MEO)
- Time-of-flight based
- Similar constellations: GLONASS (Russia), BeiDou (China), Galileo (EU)
- Commercial apps actually use A-GPS (Assisted-GPS): GPS + cellular...

✅ Strengths

- Good accuracy (typically < 5 meters)
- Works anywhere on Earth
- No infrastructure required to extend coverage
- Widespread usage and device availability
- Free to use

❌ Weaknesses

- Does not work indoors
- Does not work well with limited line-of-sight (LOS)

  i.e. Buildings, even trees may disrupt performance
- More energy-consuming than some alternatives

Bluetooth (BLE)

- Actually a comms tech, not designed for positioning
- Bluetooth Low Energy (BLE) aka Bluetooth 4.0
- Popularized for positioning after iBeacon protocol by Apple
- Common methods: signal strength (RSSI) based + trilateration
- Common architecture: Device-based - measuring multiple stationary beacons

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✅ Strengths

- Low cost
- Very widespread, difficult to find a commercial device without BLE capability (even lighting fixtures have it nowadays!
- Low energy
- BLE 5.1 offers methods such as angle-of-arrival (subject to new hardware)

❌ Weaknesses

- Susceptible to signal effects (e.g. fading, shadowing, multi-path)
- Works in ISM band, susceptible to interference
- Requires infrastructure (even if it is low cost)
- Short range

WiFi

- Similarly, positioning is not its main purpose
- Very similar to BLE in terms of signal characteristics, methods, architectures
- Access Points (AP)
- Possibility of both device- and infrastructure-based approaches
- An upcoming tech: Fine Time Measurement (FTM) - measuring round-trip-time (RTT)

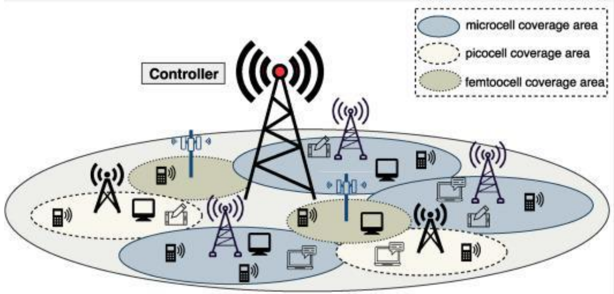
✅ Strengths

- Very widespread
- Infrastructure already in place
- APs allow inventive infrastructure based approaches

❌ Weaknesses

- Susceptible to signal effects (e.g. fading, shadowing, multi-path)
- Works in ISM band, susceptible to interference
- Mobile phones: iOS does not provide a developer API for WiFi

Cellular (focusing on 5G)



- Cellular networks have to know users' locations to improve service quality
- Infrastructure-based
- Angle-of-arrival + beamforming
- Base stations at micro scale: picocells, femtocells (imagine base stations like APs)
- Focus on Internet-of-Things (IOT)
- 5G physical layer is very diverse: sub-6GHz vs. mmWave (where the fun is!)

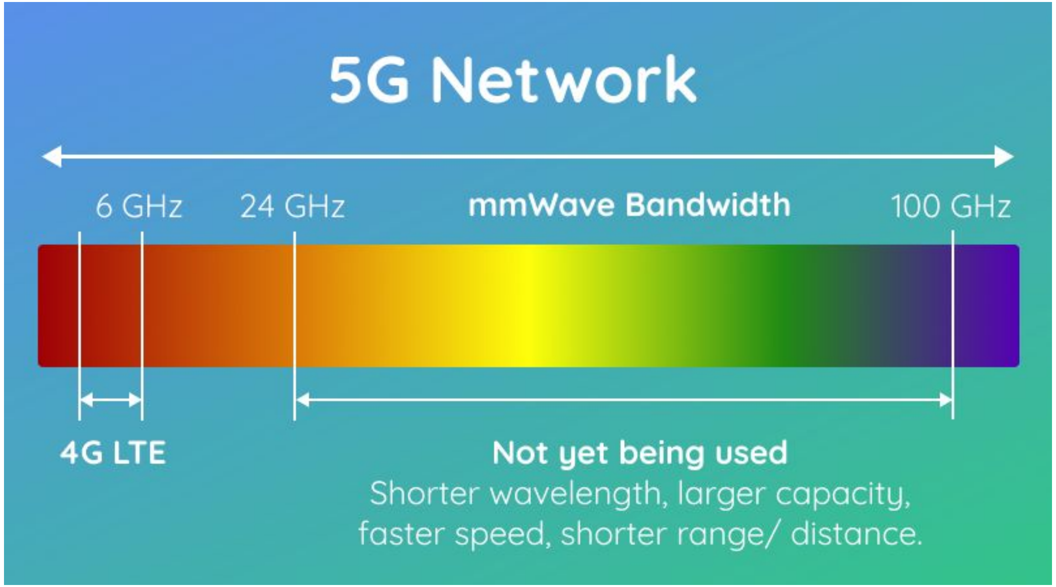
✅ Strengths

- High potential to become the standard (everybody needs cellular access!)
- Exciting tech in the form of angle-of-arrival, potentially sub-1m accuracy
- Good location is a prerequisite for higher data rates (the incentive is greater compared to other tech)

❌ Weaknesses

- Angle-of-arrival is only possible reliably at the picocell/femtocell level: Need for infrastructure
- The advertised 5G advantages mostly concern mmWave band - the hardware is still not there
- New infrastructure is costly
- Only a fraction of smartphones support 5G today (even fewer support mmWave!)

5G + mmWave



5G Network
6 GHz
24 GHz
mmWave Bandwidth
100 GHz
4G LTE
Not yet being used
Shorter wavelength, larger capacity,
faster speed, shorter range/ distance.

RFID

- Standard solution for access management, identity/proximity based apps
- Very widely used for asset tracking: Rather than tracking assets in real-time, refresh assets locations via periodic or reactive scans
- Passive architecture, tags are powered via signals from outside

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✅ Strengths

- Very low cost
- Low power (passive)

❌ Weaknesses

- Very short range (a few meters at best)
- Requires a dense infrastructure for scale
- Not available on most smartphones (iOS devices don't have it)
- RFID tags/cards are not capable of sophisticated computation/algorithms

UWB (Ultra-wideband)

- A relatively new technology
- Communicate via short pulses on a very wide frequency band
  (It becomes easier to measure time aspects of a signal as band widens)
- Both time-of-flight (ToF) and angle-of-arrival (AoA) capabilities
- A two-way communication protocol (as opposed to BLE beacons)

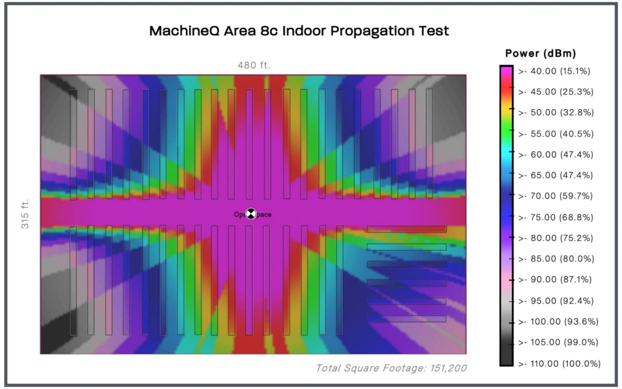
✅ Strengths

- Low energy (although in practice more energy-consuming than BLE)
- High accuracy (sub-1m possible in theory)
- Wideband characteristics also allow high data rates (more incentive to be popularized)

❌ Weaknesses

- Susceptible to signal effects (e.g. fading, shadowing, multi-path), even more so than BLE
- Requires dense infrastructure
- Not so common - Some smartphones have it, but limited developer APIs as of today
- Medium-high cost, may get cheaper in the future

LoRaWAN



- Designed primarily for IoT and connectivity
- Extremely long range (kilometers!)
- Much better signal penetration compared to BLE, WiFi
- Relatively lower frequency band
- Other similar alternatives: NB-IoT, SigFox

✅ Strengths

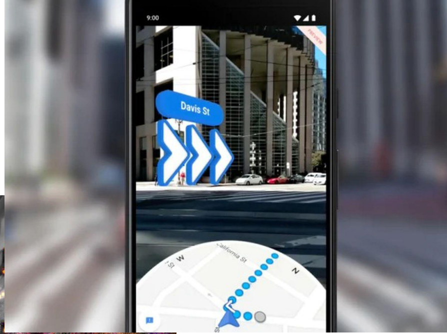
- Potentially sparser infrastructure
- Low power

❌ Weaknesses

- Still susceptible to signal effects
- No real advantage in terms of distance estimation compared to BLE/WiFi

Visual Camera

- Landmark recognition for absolute positioning
- Feature recognition for relative positioning (e.g. Augmented Reality)
- Also suitable for infrastructure-based: Detecting and tracking people through stationary cameras
- Reading QR codes on floor/ceiling? (instead of landmarks)



✅ Strengths

- High accuracy (especially combined with other tech as inertial sensors)
- Widespread
- Cheap

❌ Weaknesses

- Landmark based methods require extensive training
- Privacy concerns
- Camera has to face the region of interest (e.g. does not work for a phone in the pocket)
- High energy consumption

LIDAR

- Essentially a depth camera
- Imagine a very accurate radar
- Usually augments visual camera approaches
- Started appearing in smartphones, but usually for Augmented Reality applications

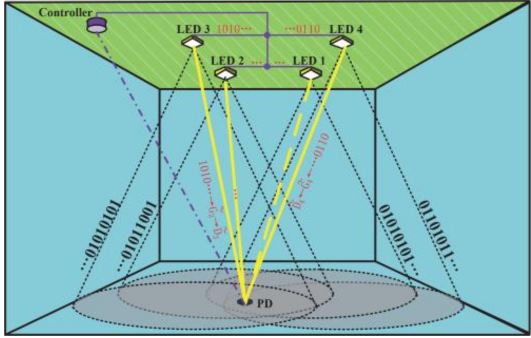
✅ Strengths

- High accuracy
- Very suitable for AR applications (context-awareness and virtual object placement)

❌ Weaknesses

- Similar weaknesses to visual camera
- High cost
- Not widespread

VLC



- Visible light communication
- Lights in a building have a unique signature that can be detected with a camera (usually indiscernible by a human)
- Can be embedded in the actual lighting of a building!
- Light intensity can be used as a received signal strength (RSS) indicator to compute distance
- Common method: trilateration, identity based positioning is also possible for dense light arrays

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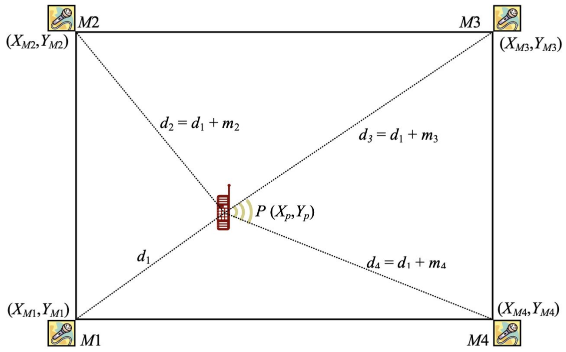
✅ Strengths

- High accuracy (sub-1m)
- Receiver is simple - only a visible camera sufficient
- Can solve both illumination and positioning use cases at the same time

❌ Weaknesses

- Requires line-of-sight between light and camera
- Privacy concerns (the camera is used after all, who knows for what)
- Sophisticated transmitter (more costly than regular lighting)

Audible Sound



- Not necessarily perceivable by humans, involves sound detectable by a regular microphone (20Hz - 20kHz)
- Suitable for ToF/TDoA approaches due to lower speed of sound waves
- Infrastructure-based approaches are more common
- Could be used in conjunction with radio tech to synchronize audio signals
- Amplitude based distance estimation also possible, but error prone

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✅ Strengths

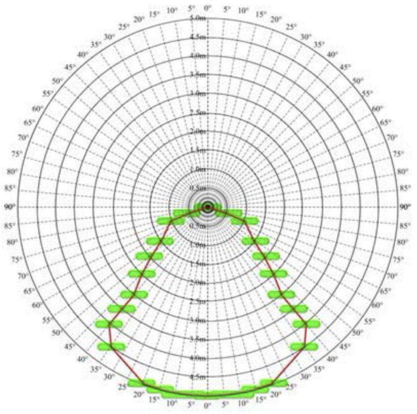
- Cheap (only regular microphones)
- Widespread
- Good accuracy, especially with many transmitters/receivers (sub-1m possible)

❌ Weaknesses

- Requires a dense infrastructure
- Privacy concerns
- Poor obstacle penetration characteristics (requires line-of-sight for optimal performance)
- Very dependent on microphone/speaker orientation

Ultrasound

- > 20kHz, allows more fine-grained time measurements
- Methods similar to audible sound: ToF/TDoA
- Ultrasonic signals can carry more information, so transmitters can embed identity information (makes device-based architectures more likely)
- More directional, allows topologies with less leakage
- Some state-of-the-art indoor positioning systems are based on Ultrasound (e.g., Active Bat, MIT Cricket)



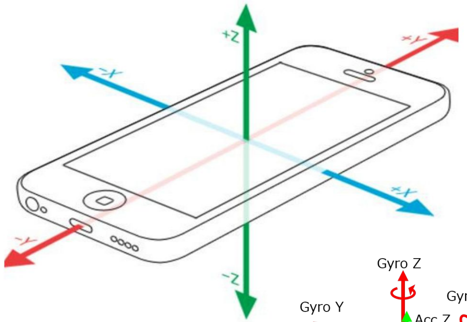
✅ Strengths

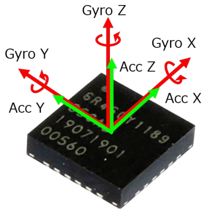
- Very high accuracy (a few centimeters!)
- No privacy concerns as opposed to audible sound

❌ Weaknesses

- Short range (even shorter than audible)
- High cost
- Requires special hardware
- Requires line-of-sight for optimal performance
- Requires a dense infrastructure

Inertial Sensors





- Accelerometer: Measures acceleration (user acceleration + gravity)
- Gyroscope: Measures rotation rate
- Both sensors are 3-dimensional
- Units containing these sensors are called IMUs (Inertial Measurement Unit)
- Data is usually fused in some way (an example: 3D orientation detection)
- Usually used in conjunction with another method (since they can do only relative)

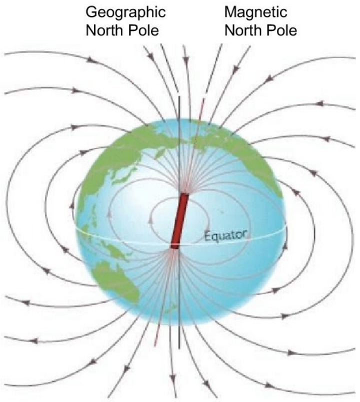
✅ Strengths

- Very responsive
- Widespread (almost every smartphone has them)
- Low cost
- Independent of outside factors
- Small size (only a few millimeters, no antenna)
- Low energy?

❌ Weaknesses

- It is very difficult to compute displacement in contrary to theory (bias, noise, drift)
- High quality sensors with low bias/noise are very costly
- Can compute only relative motion, not anchored on a floorplan or the World

Magnetometer



- aka Compass
- IMUs also contain this sensor, but not really a motion sensor
- Measures Earth's geomagnetic field + environmental effects
- Can measure <u>absolute</u> heading (as opposed to other inertial sensors)
- Environmental effects include metallic objects, devices generating electromagnetic fields...
- Environmental effects/imperfections lead to interesting fingerprinting opportunities...

✅ Strengths

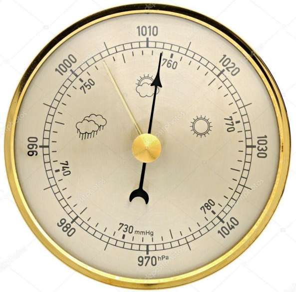
- Widespread
- Low cost
- Readings are in the absolute coordinate system
- Low energy
- The imperfections can be turned to an advantage with interesting fingerprinting approaches

❌ Weaknesses

- Very susceptible to environmental effects
- Notoriously unreliable indoors (see next slide)
- Requires frequent calibration to be usable

Magnetometer, indoors...

Barometer



- More like a weather sensor, measures atmospheric pressure...
- Can measure relative altitude changes very well
- Not really good long term, absolute pressure values depend on weather!
- Good for detecting floor changes
- Can be coupled with stations measuring atmospheric pressure at a known position

✅ Strengths

- Not as widespread as other sensors, but getting there...
- Good for measuring altitude changes short term
- There are only a few alternatives specifically exploring vertical positioning

❌ Weaknesses

- Not good long term, cannot trust absolute value unless coupled with measurement stations
- Affected by weather and even temperature changes within the same floor

A worthy mention...

Metropolitan Beacon Systems (MBS)

- What if GPS-like signals can be broadcast terrestrially
- Base stations like cellular network, higher signal strength with more penetration
- Yet to see a widespread, successful application
- Example: NextNav

  (there was a huge hype a few years back, didn't pay off yet)