INTRODUCTION TO SPATIAL SENSING AND REASONING FROM SENSOR DATA

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Module objective

Knowledge and understanding

- Understand the fundamentals of spatial reasoning from various types of sensor data

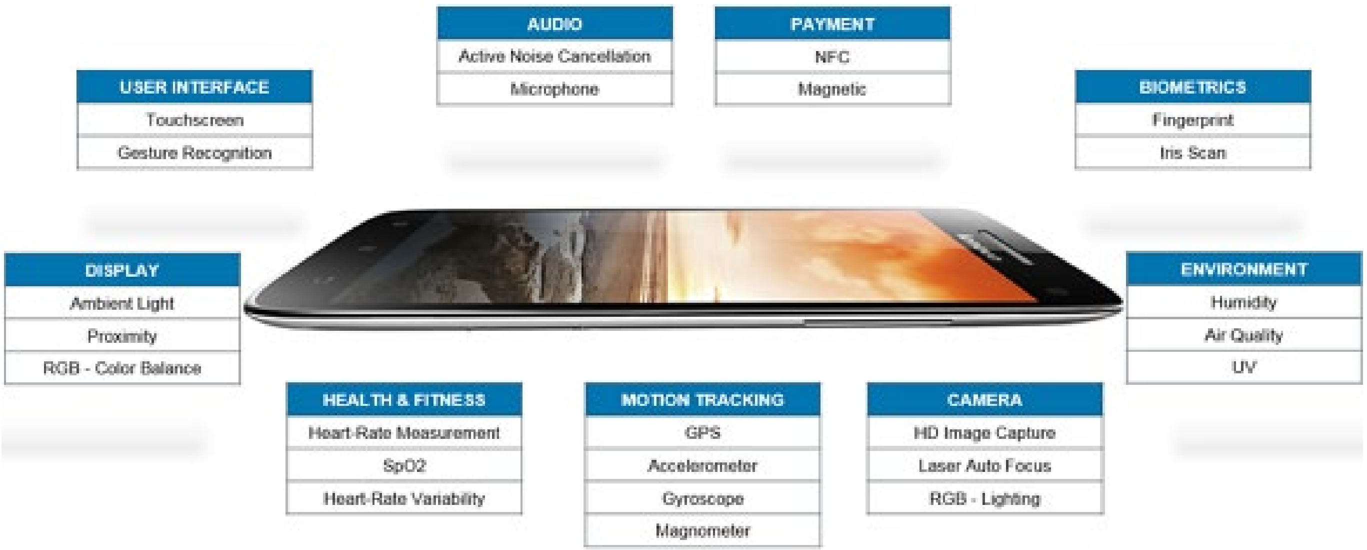
Key skills

- Design and evaluate various types of sensor data required for spatial reasoning

Spatial reasoning

- Global (absolute) position
  - Position within general global reference frame
  - Global Positioning System or GPS (longitudes, latitudes)
- Relative position
  - Based on arbitrary coordinate systems and reference frames
  - Distances between sensors (no relationship to global coordinates)
- Symbolic position information
  - “Interaction classroom”, “PGP canteen”

Introduction



Floor pressure

Ultrasonic time of flight

WiFi

Array microphone

Laser range-finding

Kinect 3D

Passive Infrared sensor

Reference:
- http://web.cse.ohio-state.edu/~xuan/courses/5432/5432_localization.ppt.
- https://www.sensorsmag.com/components/smartphone-sensor-evolution-rolls-rapidly-forward

Introduction

- Proprioceptive sensors *(internal)*
  - Measure values internally to the system (robot),
  - e.g. motor speed, wheel load, heading of the robot, battery status
- Exteroceptive sensors *(external)*
  - Information from the robots environment
  - Distances to objects, intensity of the ambient light, unique features.
- Passive sensors
  - Measure energy coming from the environment
- Active sensors
  - Emit their proper energy and measure the reaction, better performance, but some influence on environment
- What positioning accuracy do I really need and why?
  - How often do I need to determine an object’s location?
  - How big is the area I need to cover?

Reference: https://www.eliko.ee/choose-right-indoor-positioning-system/

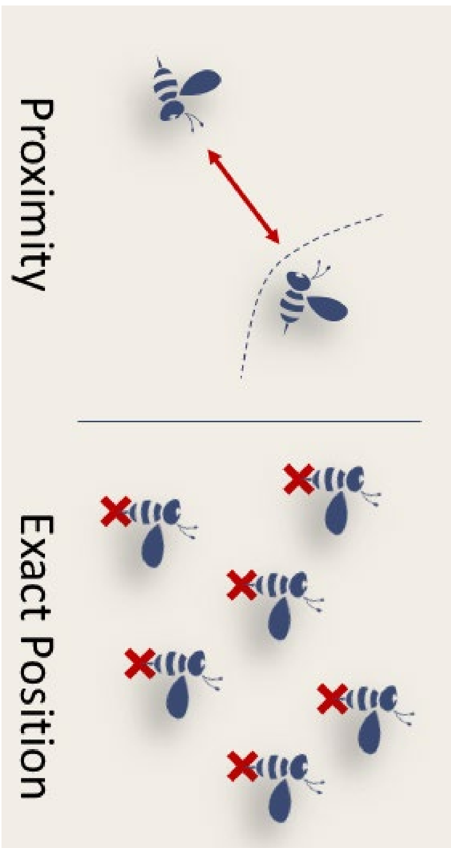
Spatial reasoning

- Positioning system consists of Navigation sources (at known locations) and Users (their locations need to be determined)

Information from location sensors	Positioning principle
Binary information if communication is possible or not	Proximity
Quality of communication link • Received signal strength (RSS) • Bit error rate (BER) • (RFID) read success rate	Fingerprinting
Time of arrival (TOA)	Trilateration
Time difference of arrival (TDOA)	Multilateration
Angle of arrival (AOA)	Angulation

Spatial reasoning: Proximity

- Proximity: User's position = position of closest navigation source



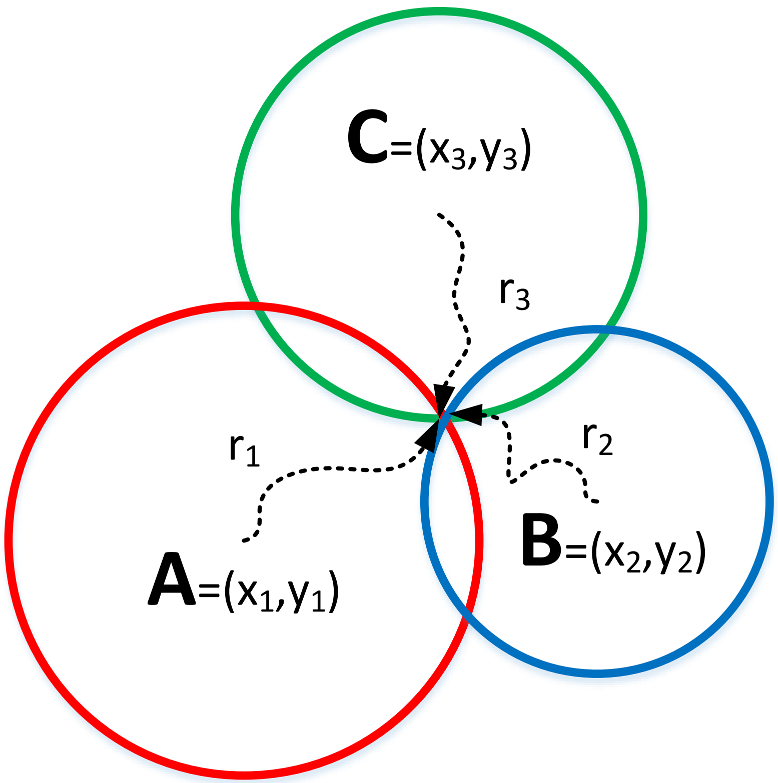
	BEACONS	GPS	WI-FI	NFC
Recommended for	In/near-store and micro-location use-cases	Macro-location and out of store use-cases	In-store use-cases	Close proximity, secure interaction
Some potential uses	In-aisle notifications and offers, in-store navigation, hands-free payment	Near-store notifications and offers, pre-arrival customer 'check-in'	In-aisle notifications and offers, in-store navigation, hands-free payment	Payments, product tagging
Ease of set up and maintenance	Medium	Medium-high	Medium	Medium
Range	Medium	Long	Medium-low	Close
Accuracy	Medium	Medium-low	Medium	High
Ease of use for consumer	Medium	Medium	Medium-high	Medium-high
Energy efficiency on consumer device	Medium-high	Medium-low	Medium-high	High

Reference:
- https://www.accenture.com/us-en/insight-beacons-location-based-technology-revolutionizing-how-retailers-business
- https://nanotron.com/EN/2017/04/19/professional-location-awareness-is-presence-proximity-and-tracking/

Spatial reasoning: Fingerprinting

- Use an n-dimensional space containing *received signal strength* (RSS) vectors $(rss_1, rss_2, \cdots, rss_n)$ of reference points; n = number of navigation sources. Reference points described as tuples $(\text{coordinates}, \text{RSS vector}) = ((x, y), (rss_1, \dots rss_n))$
- Nearest neighbour
  - Find reference point *ref* for which $d(RSS_{user}, RSS_{ref})$ is minimal
  - Decision: $POS_{user} := POS_{ref}$
- Multiple nearest neighbour
  - Find k (e.g. three) "closest" (see above) reference points
  - Decision: $POS_{user} \coloneqq center\left(POS_{ref1}, \cdots, POS_{refk}\right)$
- Interpolation
  - Find three "closest" reference points
  - Use interpolation algorithm on triangle to obtain POS_{user}.

Spatial reasoning: Trilateration



Time of Arrival (TOA)

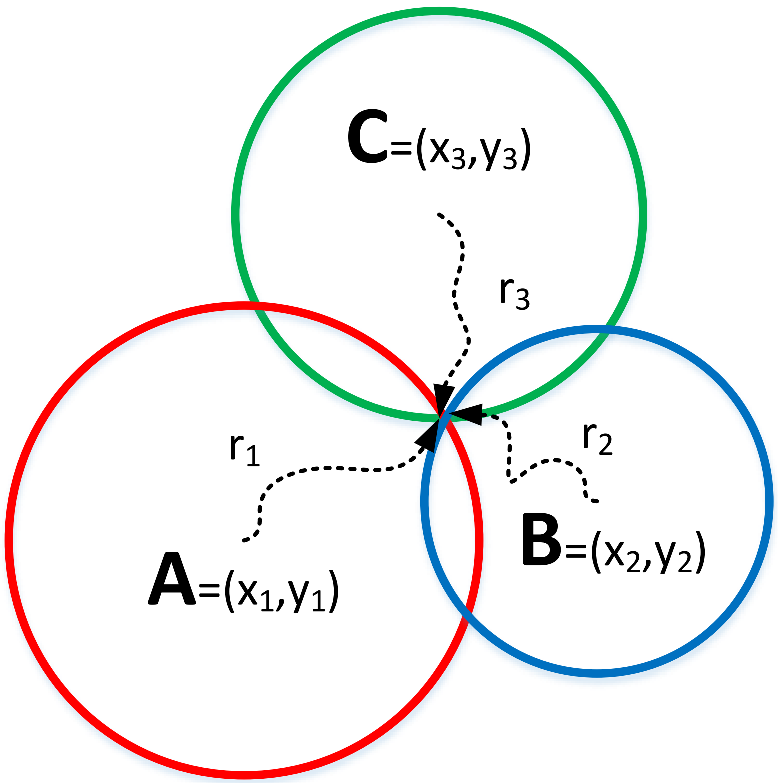
- Foghorn is sounded precisely on the minute mark
- Mariner has an exact clock and notes elapsed time
- Distance = propagation time * speed of sound (around 335 meter/second)

With three measurements, we have

$$(x - x_1)^2 + (y - y_1)^2 = r_1^2$$
$$(x - x_2)^2 + (y - y_2)^2 = r_2^2$$
$$(x - x_3)^2 + (y - y_3)^2 = r_3^2$$

<Taken 2>, Locating Dad, https://www.youtube.com/watch?v=WWeYvvN-F5s

Spatial reasoning: Trilateration



Time Difference of Arrival (TDOA)

- Uses propagation delay between mobile terminal and multiple base stations
- No global time
- Only time differences are known

The travel time of a signal from a reference station to the current position is given by the distance divided by the signal propagation speed v, we can obtain the time difference of arrival Δt_{AB} (between source A and B) and Δt_{BC} (between source B and C) as:

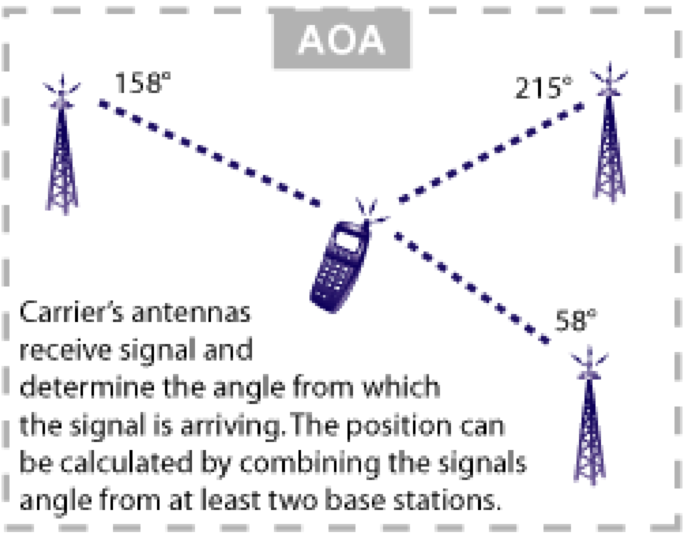
$$\Delta t_{AB} = \frac{1}{v}\sqrt{(x-x_1)^2+(y-y_1)^2} - \frac{1}{v}\sqrt{(x-x_2)^2+(y-y_2)^2}$$

$$\Delta t_{BC} = \frac{1}{v}\sqrt{(x-x_2)^2+(y-y_2)^2} - \frac{1}{v}\sqrt{(x-x_3)^2+(y-y_3)^2}$$

Spatial reasoning: Angulation

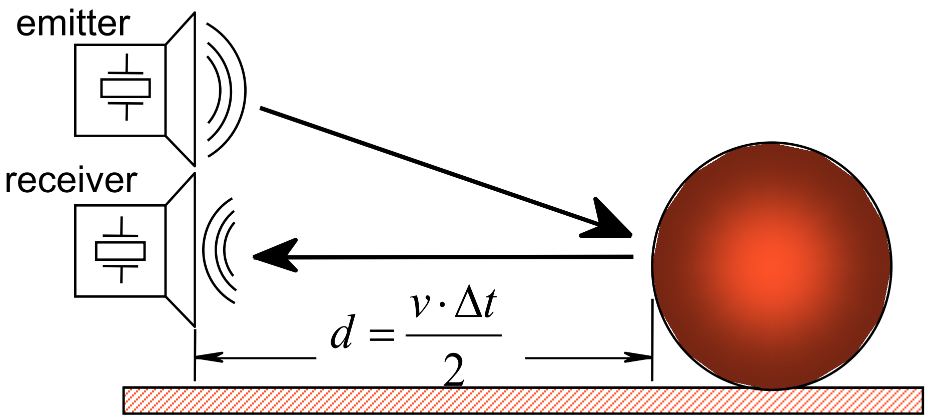
Angle of arrival (AOA)

- Base station measures angle to mobile terminal
  - Rotate antenna to the highest RSS value
  - Derive angle from RSS values of individual antennas in an antenna array.



Reference: http://www.e-cartouche.ch/content_reg/cartouche/LBStech/en/html/LBStechU2_poslabel1.html

Ultrasonic range sensor



http://www.robot-electronics.co.uk/shop/Ultrasonic_Rangers1999.htm

Operational principle

- An ultrasonic pulse is generated by a piezo-electric emitter, reflected by an object in its path, and sensed by a piezo-electric receiver. Based on the speed of sound in air and the elapsed time from emission to reception, the distance between the sensor and the object is easily calculated.

Main characteristics

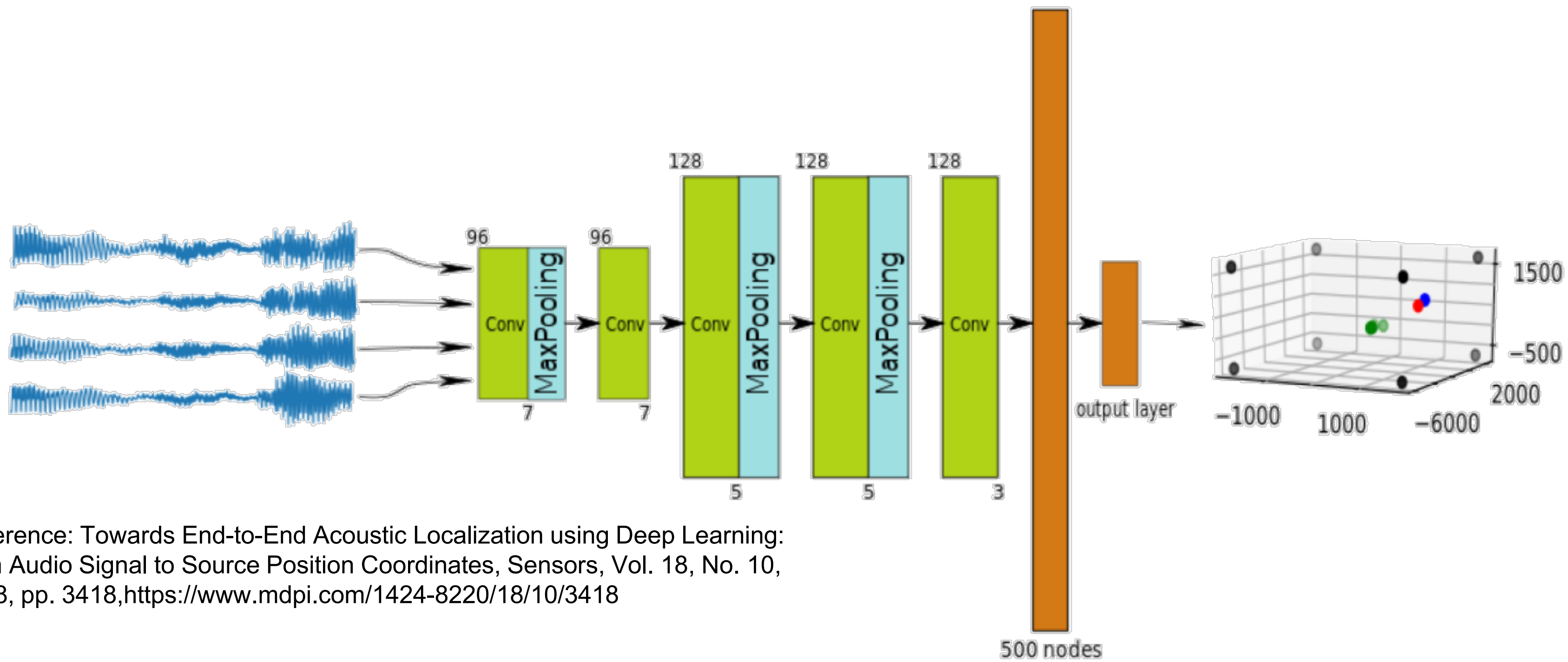
- Precision influenced by angle to object
- Useful in ranges from several cm to several meters
- Typically relatively inexpensive

Applications

- Distance measurement

Spatial reasoning: Acoustic

Our system obtains the position of an acoustic source from the audio signals recorded by an array of M microphones. Given a reference coordinate origin, the source position is defined with the 3D coordinate vector $\mathbf{s} = (s_x \;\; s_y \;\; s_z)^\top$. The microphones positions are known and they are defined with coordinate vectors $\mathbf{m}_i = (m_{i,x} \;\; m_{i,y} \;\; m_{i,z})^\top$ with $i = 1, \ldots, M$. The audio signal captured from the i^{th} microphone is denoted by $x_i(t)$. This signal is discretized with a sampling frequency f_s and is defined with $x_i[n]$. We assume for simplicity that $x_i[n]$ is of finite-length with N samples. This corresponds to a small window of audio with duration $w_s = N/f_s$, which is a design parameter in our system.



Reference: Towards End-to-End Acoustic Localization using Deep Learning: from Audio Signal to Source Position Coordinates, Sensors, Vol. 18, No. 10, 2018, pp. 3418,https://www.mdpi.com/1424-8220/18/10/3418

Spatial reasoning: Vision

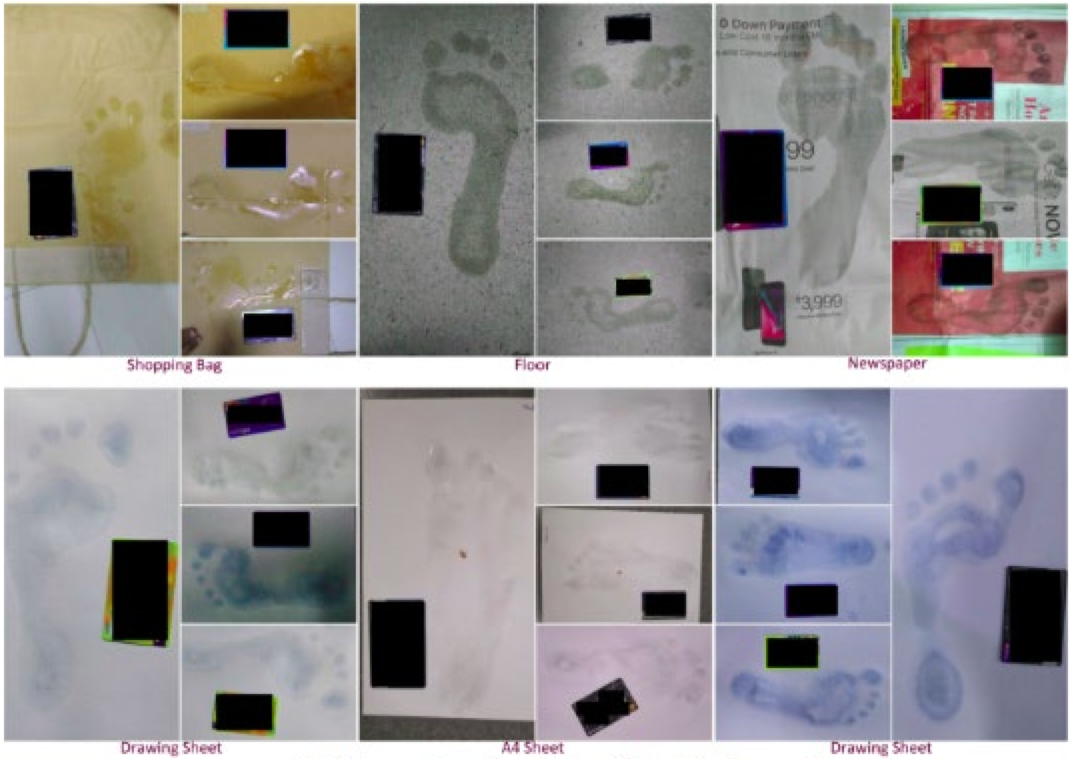
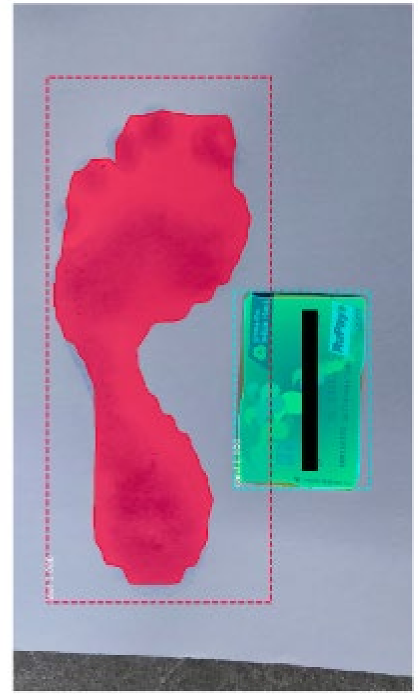


Fig-2: Impressions of wet feet on different background

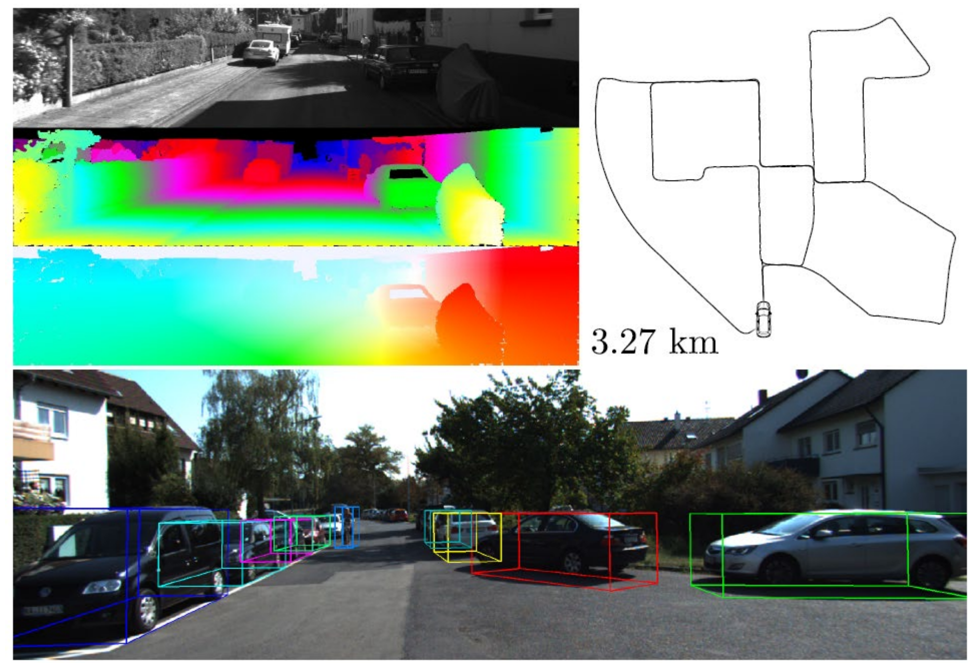


Height: 8.08 inches
Breadth: 3.41 inches
Arch type: High

Reference: https://labs.imaginea.com/post/measuring-feet-using-deep-learning/

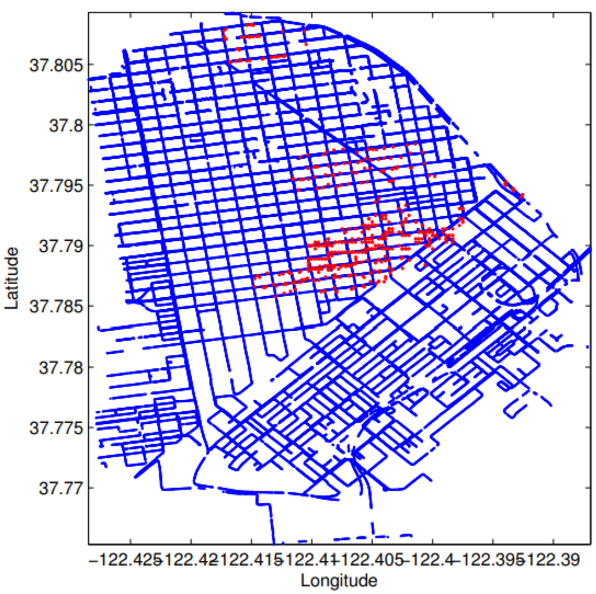
Example: KITTI dataset

- Two stereo cameras (1392×512 pixels)
- Laser scanner, GPS+IMU (inertial measurement unit)
- 6 hours at 10 frames per second.



Reference: http://www.cvlibs.net/datasets/kitti/

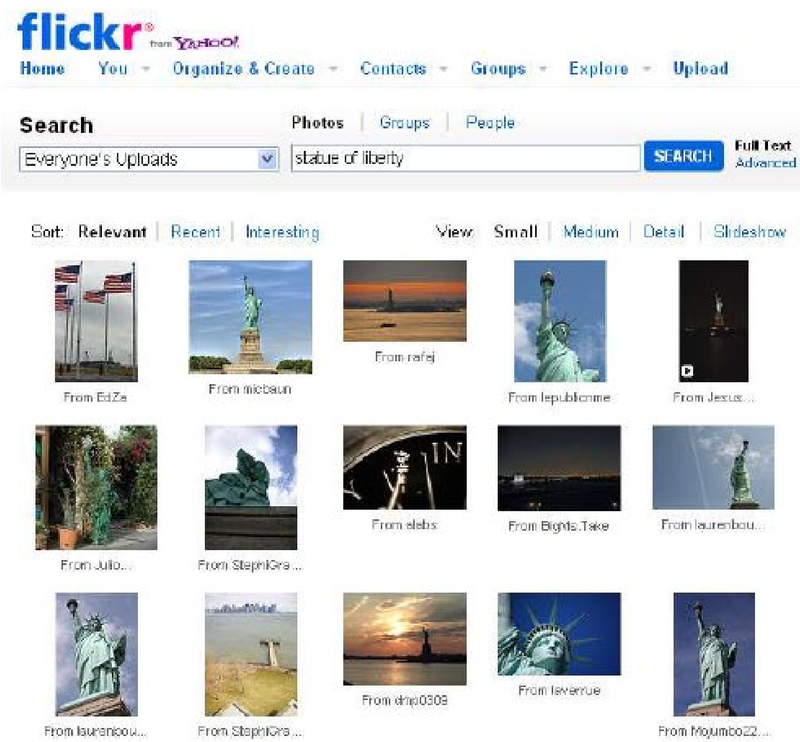
Spatial reasoning: Vision



Reference dataset (blue dots) and query set (red dots)

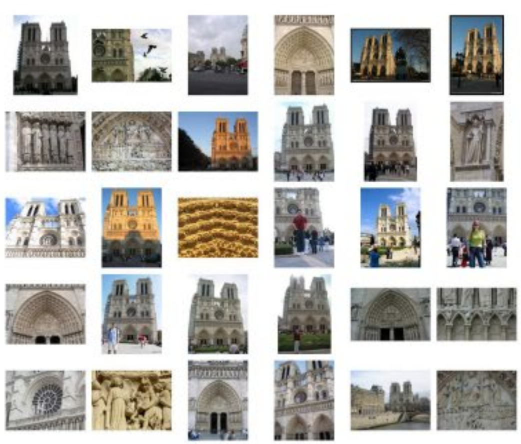
Reference: D. Chen, G. Baatz, K. Koser, S. Tsai, R. Vedantham, T. Pylvanainen, K. Roimela, X. Chen, J. Bach, and M. Pollefeys. City-scale landmark identification on mobile devices, CVPR, 2011. http://semihyagcioglu.com/projects/image-geolocalization/

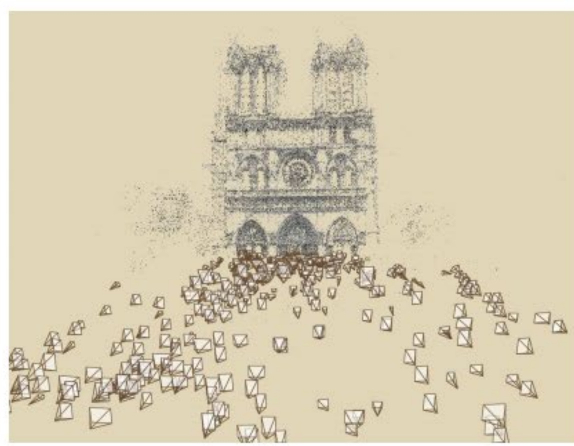
Spatial reasoning: Vision



Reference:

- M. Goesele, N. Snavely, B. Curless, H. Hoppe, S. Seitz, Multi-View Stereo for Community Photo Collections, ICCV 2007, https://grail.cs.washington.edu/projects/mvscpc/
- N.Snavely, S.Seitz, Phto Tourism: Exploring Photo Collections in 3D, SigGraph 2006. http://phototour.cs.washington.edu/





What we have learnt

- Motivation and application examples of spatial reasoning from various types of sensory data, such as
  - WiFi
  - Acoustic
  - Vision

Thank you!

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