Jigsaw: Indoor Floor Plan Reconstruction via Mobile Crowdsensing

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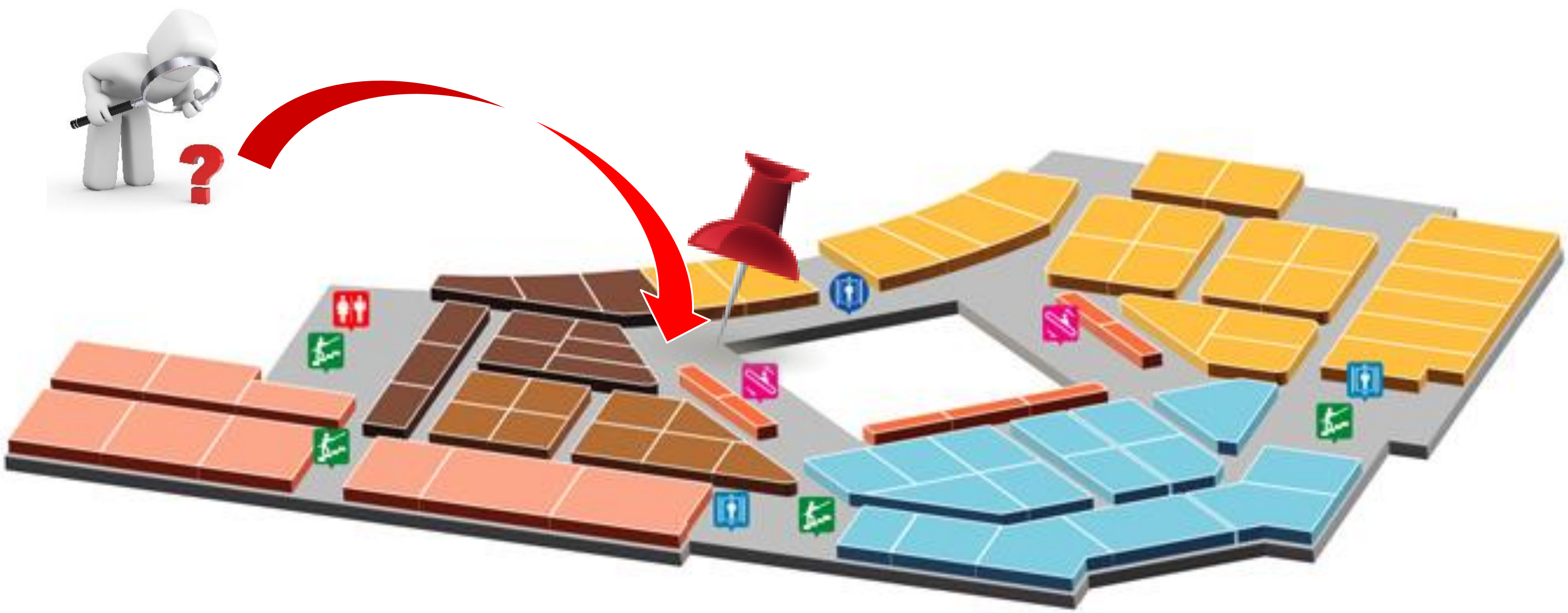
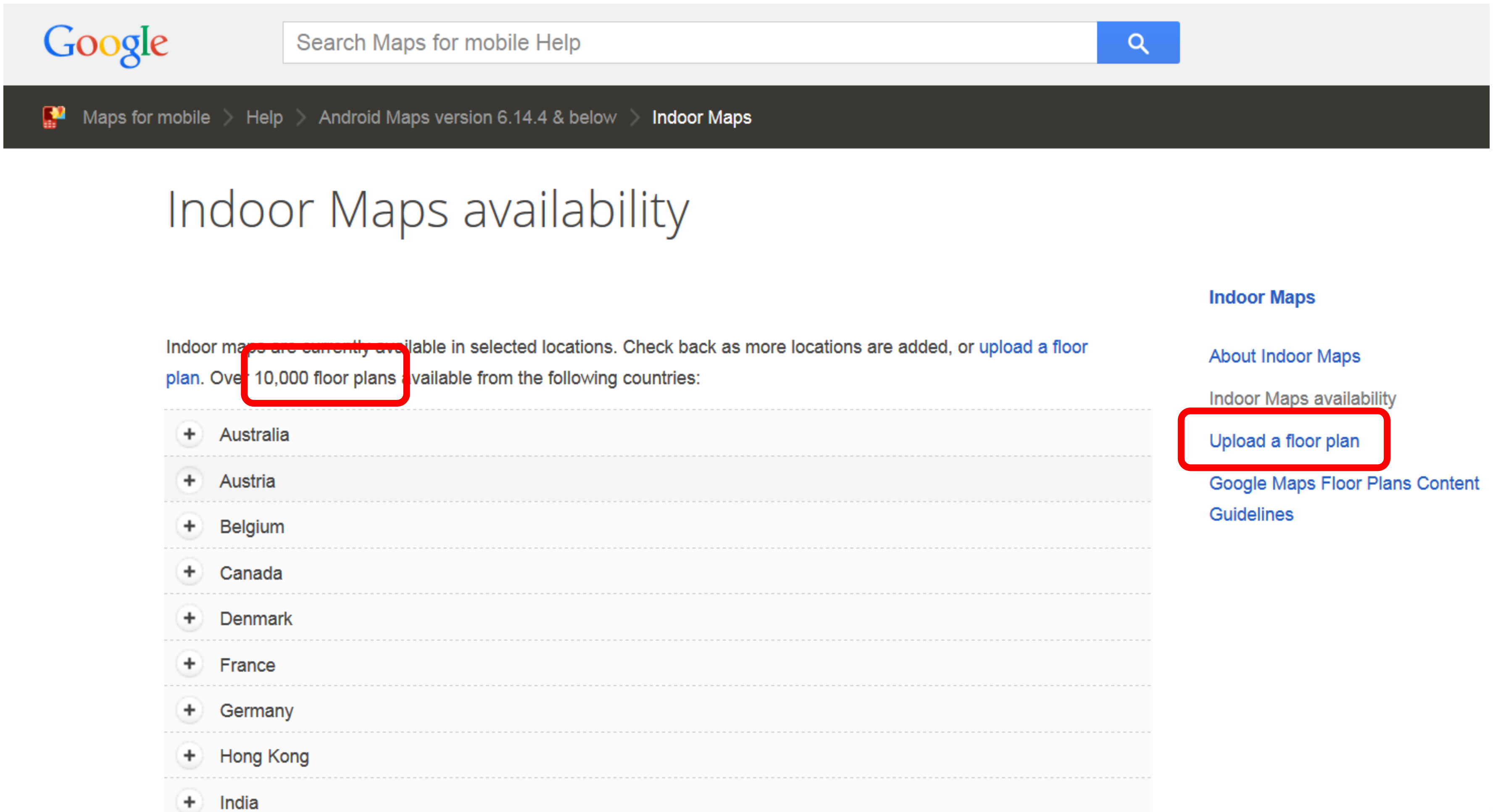
Jigsaw: Floor plan reconstruction

- **Motivation**



Jigsaw: Floor plan reconstruction

◆ Motivation



Jigsaw: Floor plan reconstruction

- **Motivation**
- **Crowdsensing based construction**
  - Gather piecewise data from individual mobile users
    - e.g., images, inertial sensor data
  - Extract floor plan information
  - Put pieces together into a complete floor plan

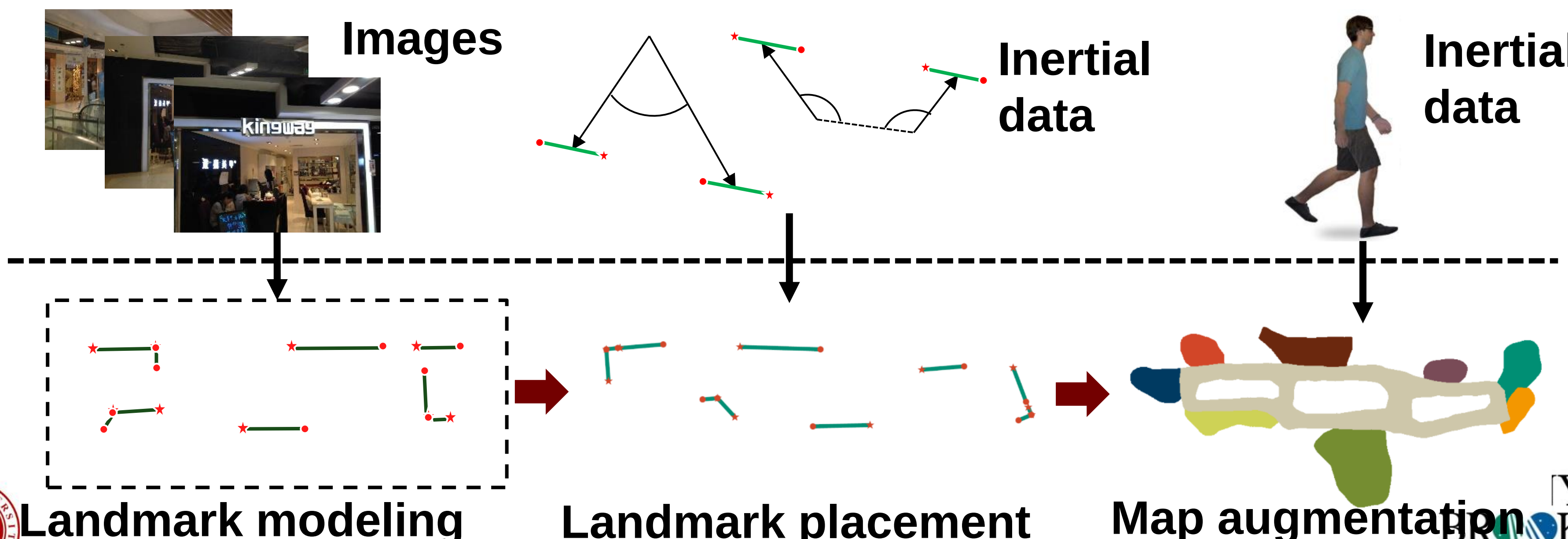
- **Benefits**
  - Service providers (e.g., Google) don't need to negotiate with building owners one by one
  - No need to hire dedicated personnel for inch-by-inch measurements either

Crowsensing to construct floor plan

- **Challenges**
  - Accurate coordinates and orientations of indoor landmarks (i.e., POIs such as store entrances)
    - Inertial data couldn't provide
  - Insufficient "anchor points"
    - Error accumulation in dead reckoning
    - Over- and under- estimation of accessible areas
- **Inspiration**
  - Complementary strengths of vision and mobile techniques
    - Vision ones to produce accurate geometric information for landmarks
    - Inertial data to obtain placement of landmarks, and less critical hallway and room shapes
  - Use optimization and probabilistic formulations
    - Robustness against errors/noises from data

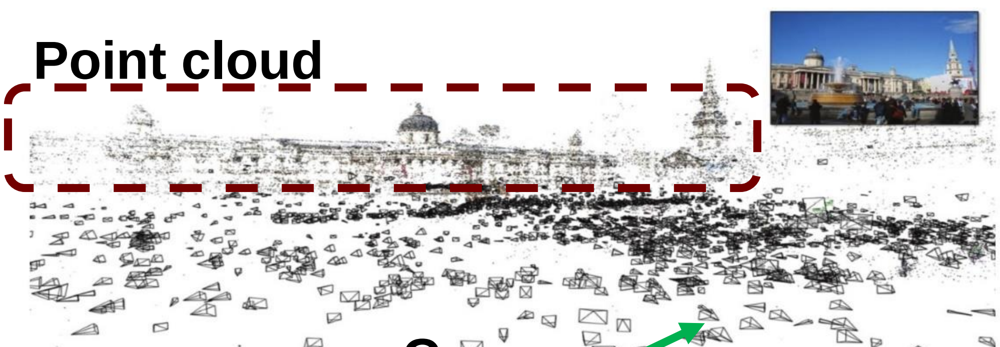
Jigsaw overview

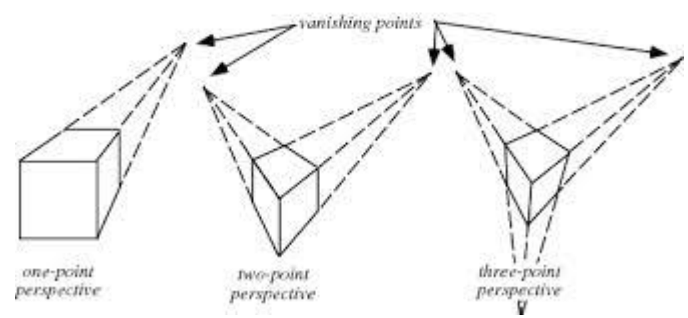
- **Three stages**
  - **Landmark modeling: extract landmark geometry from images**
  - **Landmark placement: obtain pairwise landmark spatial relation (e.g., distance, orientation) from inertial data**
  - **Map augmentation: construct hallway and room shapes from mobile traces**



Landmark modeling

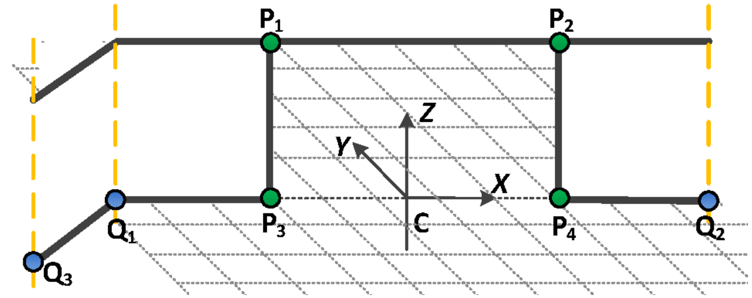
- **Goal**
  - **Extract sizes and coordinates of major geometry features (e.g., widths of entrances, lengths/orientations of walls) of landmarks**
- **Method: extend two computer vision techniques**
  - **Structure from Motion(SfM): given a set of images of the same object from different viewpoints, generate (in the LOCAL coordinate system)**
    - **1) a "cloud" of 3d points representing the exterior shape of the object;**
    - **2) the location where each image is taken**
  - **Vanishing line detection: given an image, detect orthogonal line segments of the object**



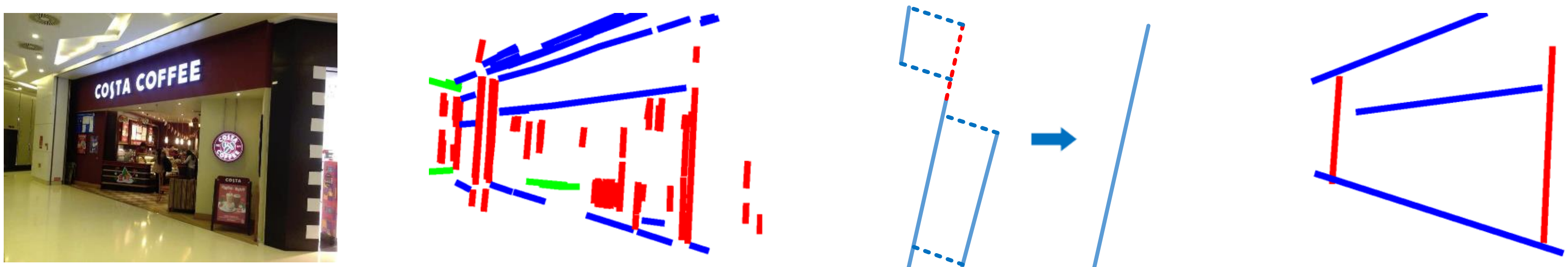


Landmark modeling process(1/2)

- **Geometric vertices**
  - P: four corners of a store entrance
  - Q: connecting points of wall segments

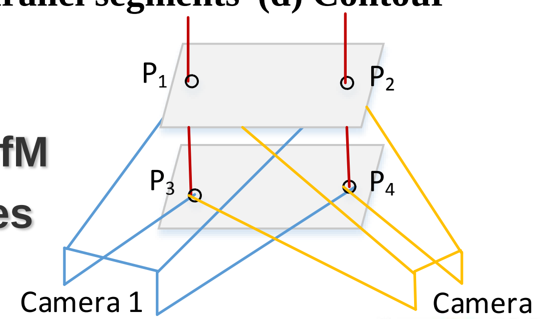


- **Extract the coordinates of geometric vertices**
  - Step 1. Extract landmark's major contour lines on each image



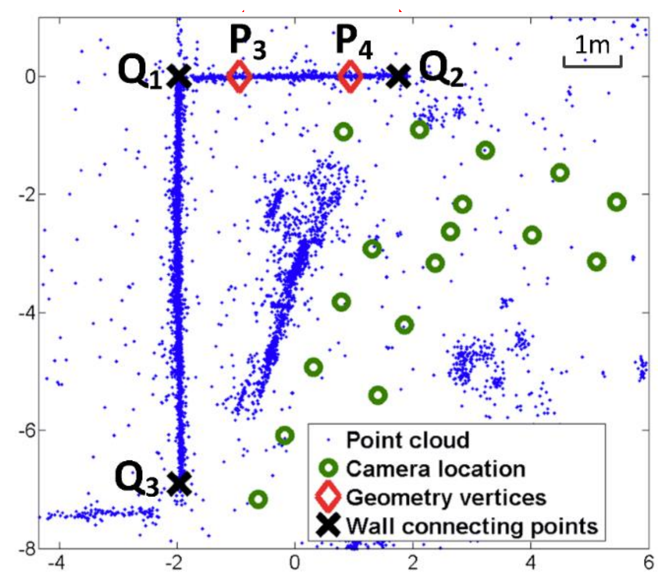
(a) Original image (b) Vanishing line detection (c) Merge co-linear and parallel segments (d) Contour

  - Step 2. Project 2D lines into 3D
    - Project 2D lines using transformation matrices by SfM
    - Use adapted k-means to cluster major geometry lines



Landmark modeling process(2/2)

- **Detect connecting points of wall segments**
  - **Project the 3d point cloud onto XY plane**
  - **Detect wall segments and their connecting points**
    - **Use entrance line (P_3P_4) from the previous step as the start**
    - **Find the two ends(Q_1Q_2)**
    - **Continue to search for more connecting point (Q_3)**

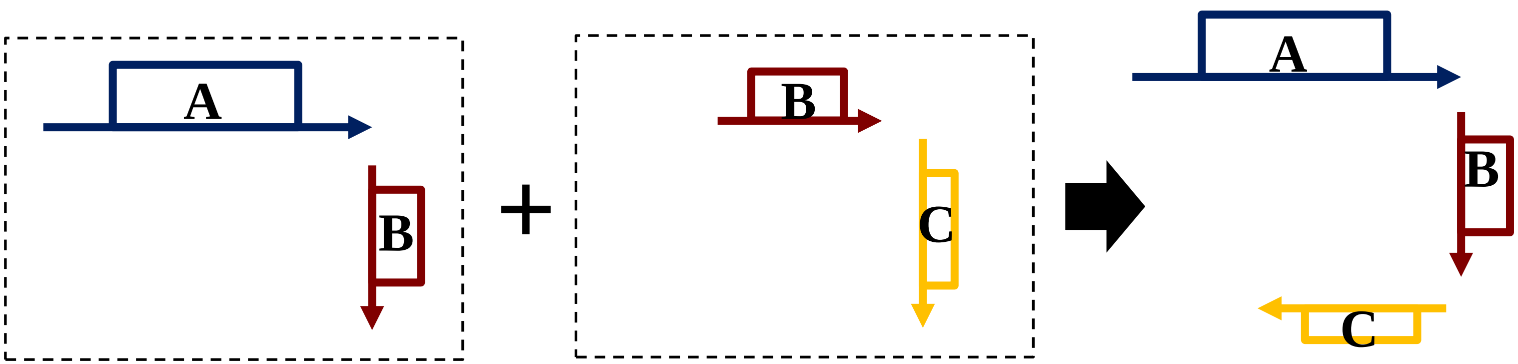


Landmark placement

- **Goal**

  - Input: landmark models in their local coordinate systems
    - Major geometry features, positions of cameras
  - Output: landmarks placed on a global coordinate system
    - Absolute coordinates and orientations

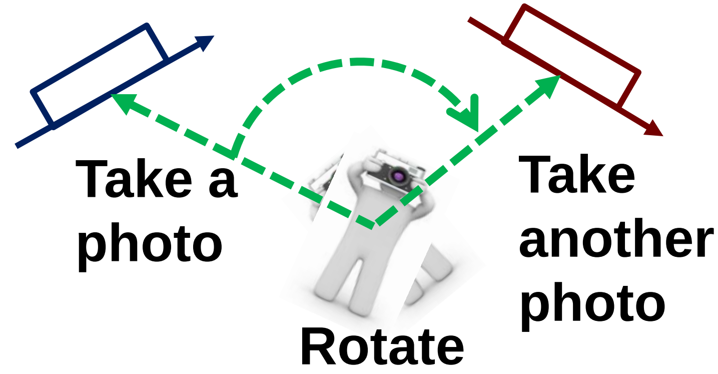
- **Method**

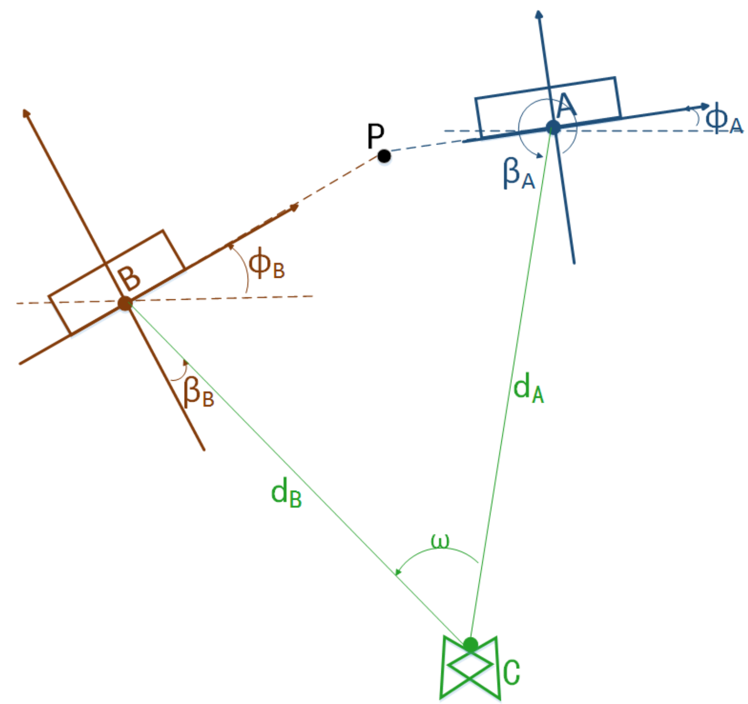


  - Step 1. Obtain pairwise spatial relationship between adjacent landmarks
  - Step 2. place adjacent landmarks on the common ground

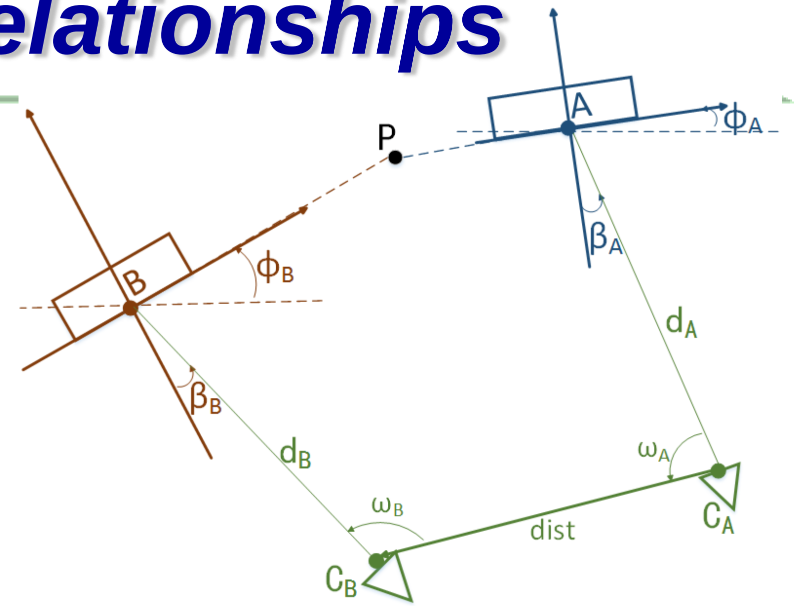
Micro-tasks for spatial relationships

- **A series of data gathering actions**
  - **Obtain pairwise distance and orientation constraints**
- **Click-Rotate-Click(CRC)**
  - $\boldsymbol{\omega}$: **rotated angles from gyroscope**
  - $(\boldsymbol{d_A}, \boldsymbol{\beta_A})$ **and** $(\boldsymbol{d_B}, \boldsymbol{\beta_B})$ **: SfM output**
  - **Relative distance and orienation between A,B uniquely determined**
- **Click-Walk-Click(CWC)**
  - $|C_AC_B|$: **step counting**
  - $\boldsymbol{\omega_A}$ ***and*** $\boldsymbol{\omega_B}$: **placement offset estimation and gyroscope readings**
  - $(\boldsymbol{d_A}, \boldsymbol{\beta_A})$ **and** $(\boldsymbol{d_B}, \boldsymbol{\beta_B})$ **: SfM output**
  - **Similar measurements calculation**





Micro-tasks for spatial relationships



- **A series of data gathering actions**
  - **Obtain pairwise distance and orientation constraints**
- **Click-Rotate-Click(CRC)**
  - **ω: rotated angles from gyroscope**
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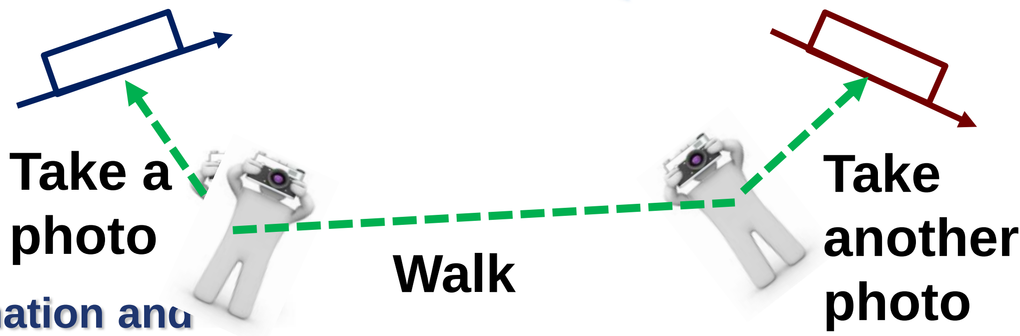
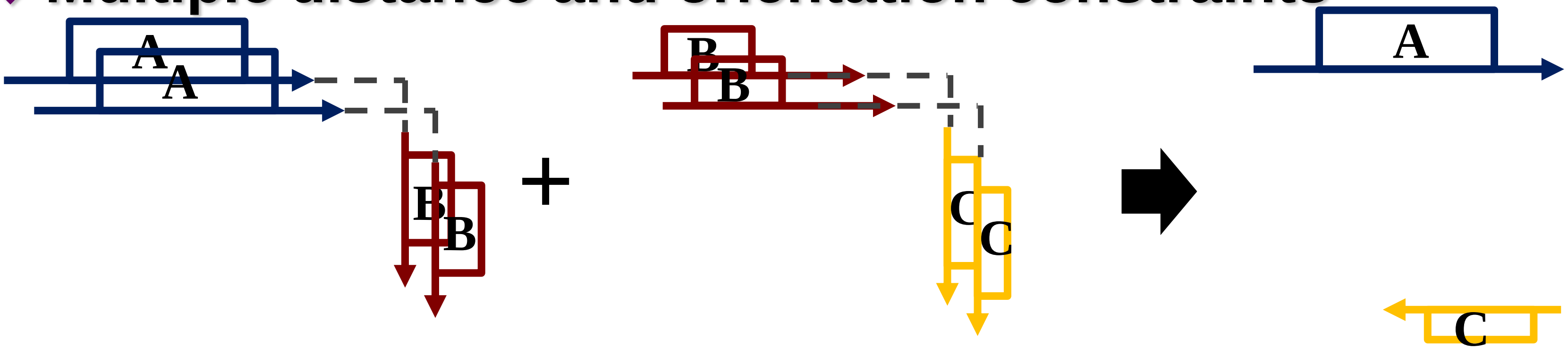


Landmark placement formulation

- Multiple distance and orientation constraints



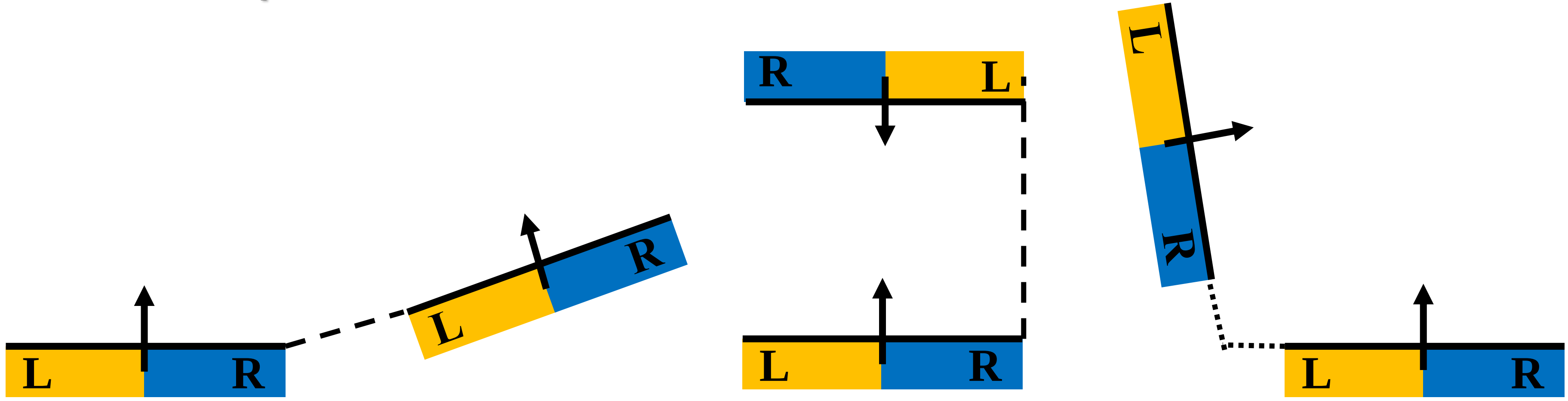
- Maximum Likelihood Estimation (MLE)
  - Θ^*: the most likely coordinates and orientations
    - Θ ={X, ϕ}: coordinates and orientations of landmarks
    - Z, O: observations of X, ϕ

$$\theta^* \quad = \quad \arg\max_{\theta} P(Z, O | X, \phi)$$

- Landmark placement results

Hallway boundary construction

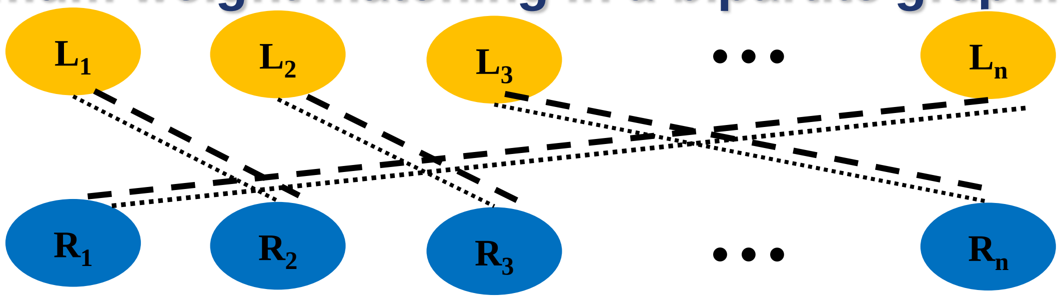
- **Two connection options**
  - Direct line between two segments
    - collinear or facing each other
  - Extend two segments to an intersection point
    - Perpendicular walls



[*] H. W. Kuhn. The hungarian method for the assignment problem. Naval research logistics quarterly, 2(1-2):83–97, 1955.

Hallway boundary construction

- **Two connection options**
  - **Direct line between two segments**
    - **collinear or facing each other**
  - **Extend two segments to an intersection point**
    - **Perpendicular walls**
- **Problem formulation**
  - **Minimum weight matching in a bipartite graph.**

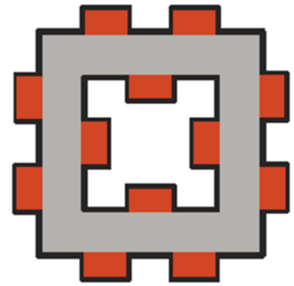


  - **Solution: Kuhn-Munkres algorithm***
    - **$O(n^3)$, n: number of landmarks**

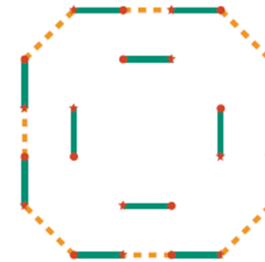
[*] H. W. Kuhn. The hungarian method for the assignment problem. Naval research logistics quarterly, 2(1-2):83–97, 1955.

Compare with alternative methods

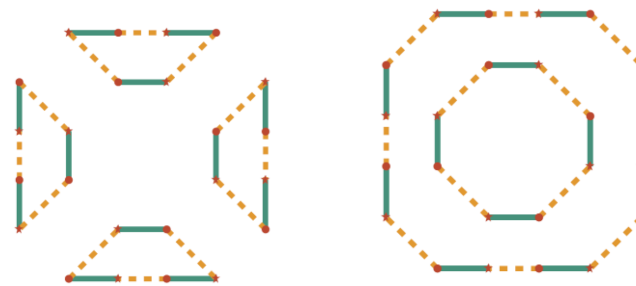
- **Naïve convex hull**
  - Miss segments inside
- **Greedy algorithms**
  - Depend on order of connecting
  - Miss 90º corners



Example scenario

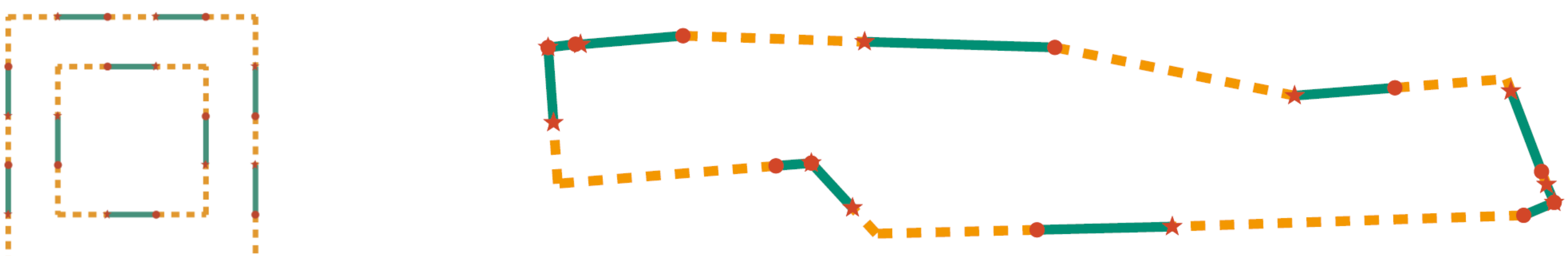


convex hull



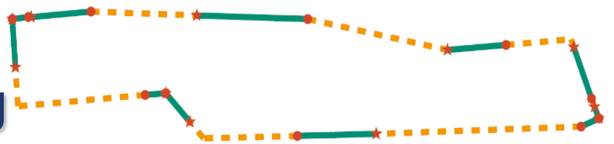
Greedy method results

- **Our results**

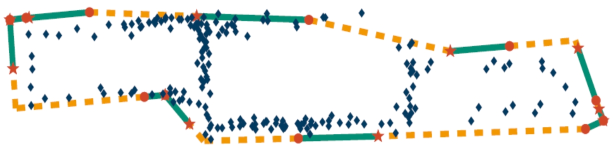


Details reconstruction: hallway shape

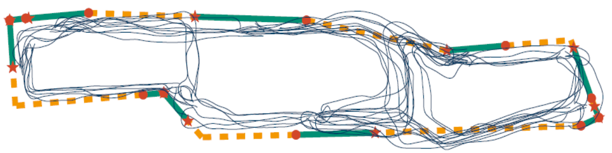
- **Step 1. build *occupancy grid map***
  - Grid cells each with a variable representing the probability it is accessible
  - a) External boundary of hallway
  - b) Camera positions
  - c) Trajectories



External boundary



+ Camera positions



+ User trajectories

Details reconstruction: hallway shape

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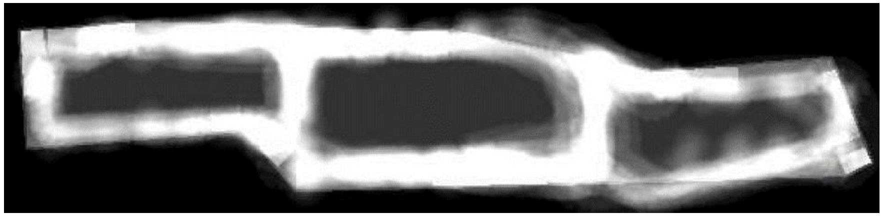
Occupancy map



- **Step 2. Binaryzation with a threshold**
- **Step 3. Smoothing**
  - Alpha-shape*

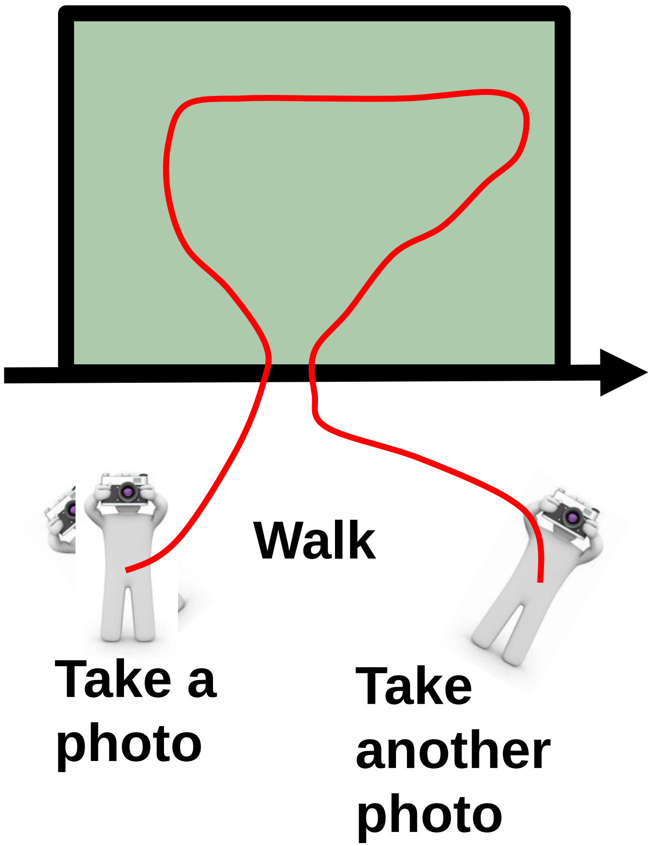
Thresholding

Smoothing

[*] H. Edelsbrunner, D. G. Kirkpatrick, and R. Seidel. On the shape of a set of points in the plane. IEEE Transactions on Information Theory, 29(4):551–558, 1983.

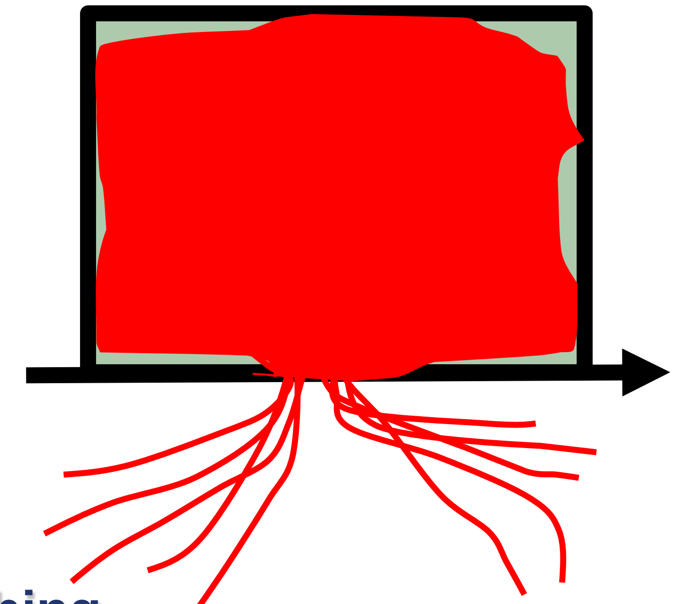
Details reconstruction: room shape

- **Room reconstruction**
  - **Data-gathering micro-task**
    - **CWC inside one room**
  - **Step 1. determine initial/final locations**
    - **Two camera locations as anchor points**



Details reconstruction: room shape

- Room reconstruction
  - Data-gathering micro-task
    - CWC inside one room
  - Step 1. determine initial/final locations
    - Two camera locations as anchor points
  - Step 2. use trajectories to build an occupancy grid map
  - Step 3. similar thresholding and smoothing



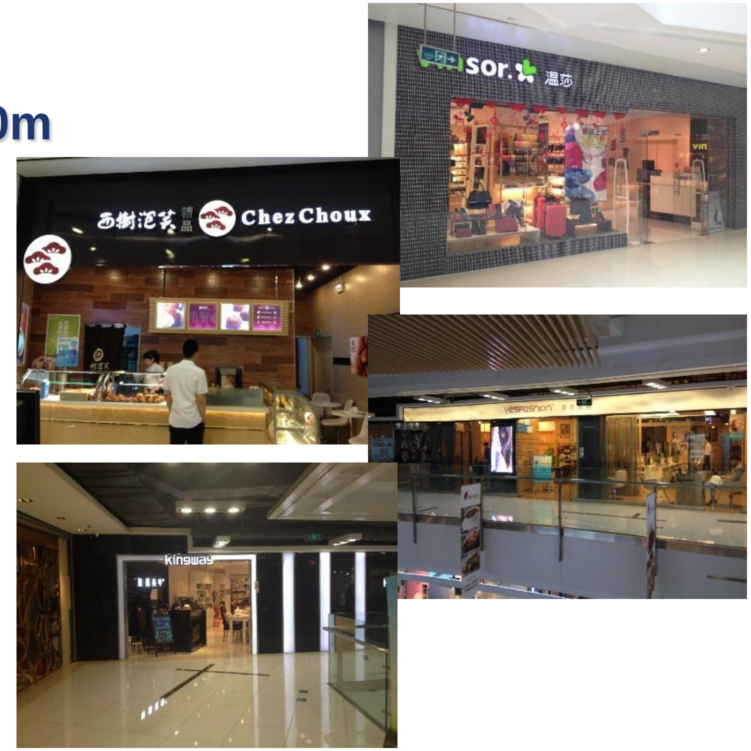
- Results

Stores

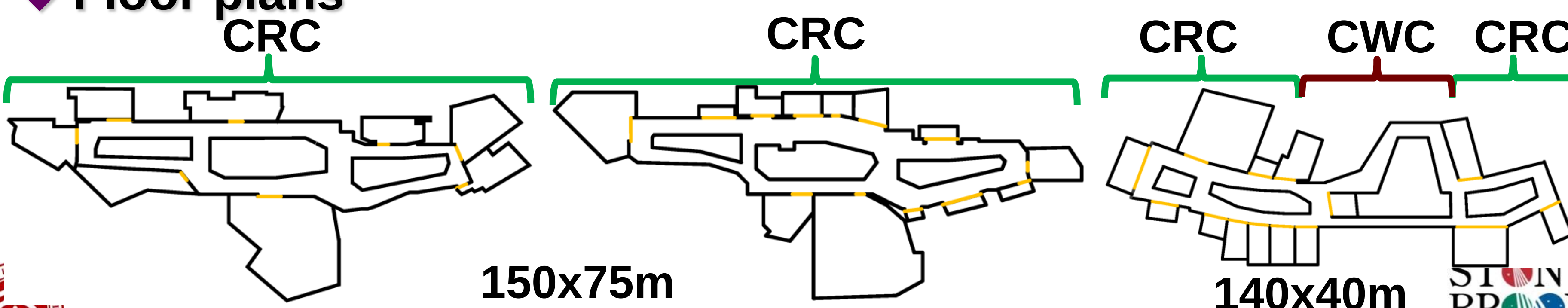
Combined hallway, stores

Evaluation

- Methodology
  - 3 stories of malls: 150x75m and 140x40m
  - 8,13,14 store entrances as landmarks
  - 150 photos for each landmark
  - 182,184,151 CRC measurements
  - 24 CWC measurements in story 3
    - Comprised of two parts
  - 96,106,73 user traces along hallway
  - ~7 traces inside each store

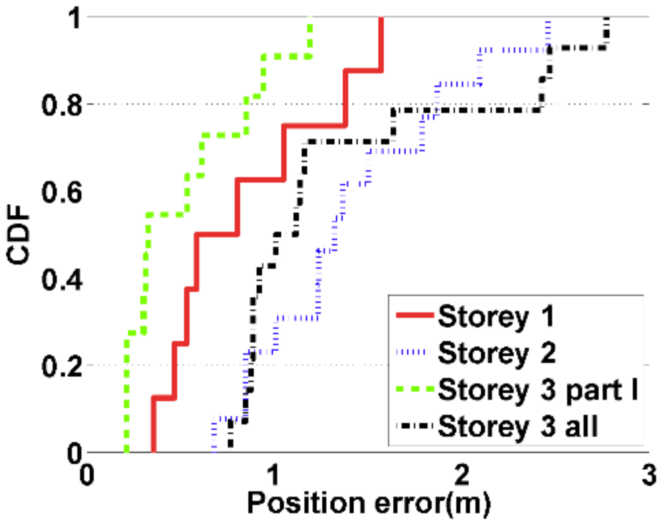


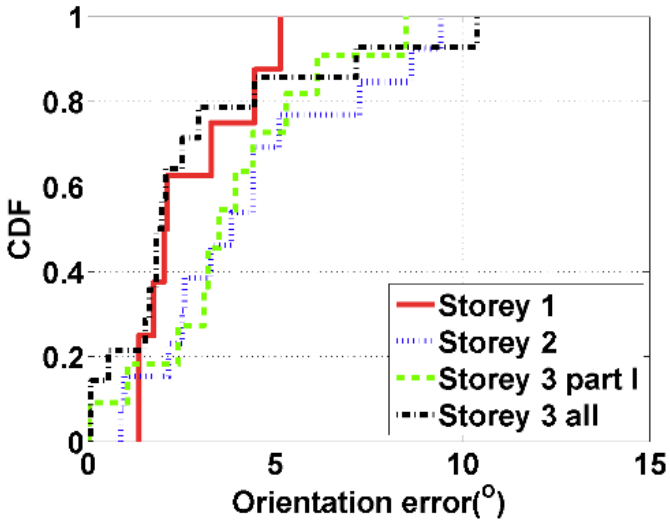
- Floor plans



Reconstructed floor plans

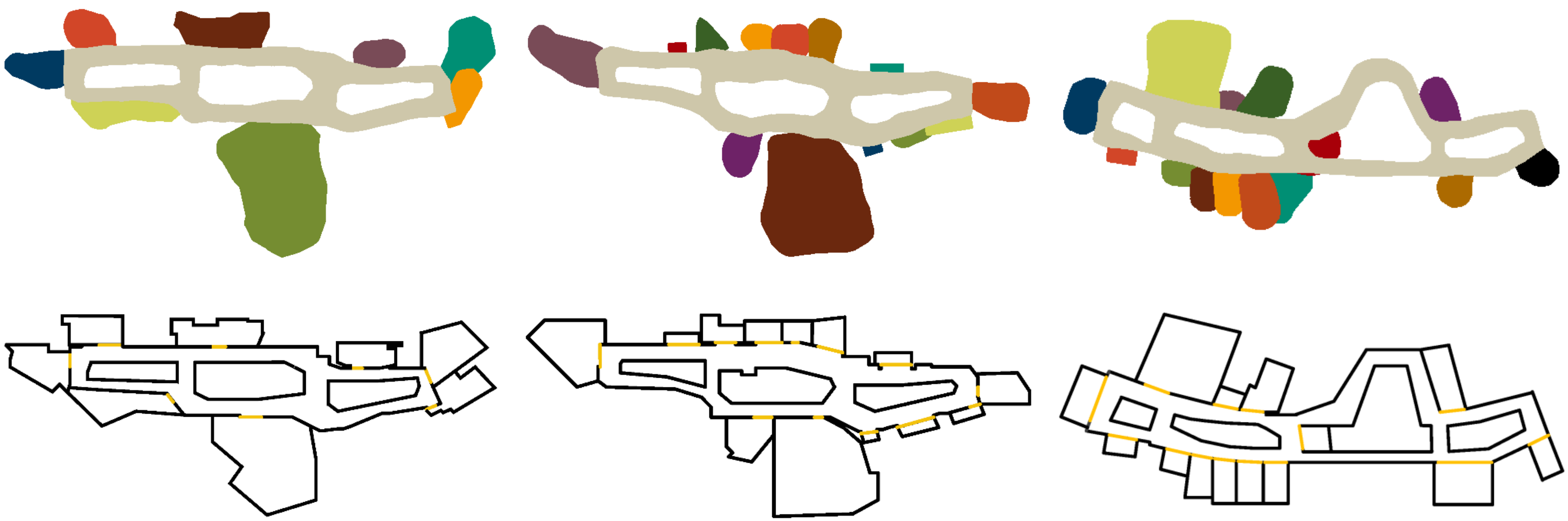
- **Landmark placement performance**
  - Store position error 1-2m
  - Store orientation error 5-9 degrees





Reconstructed floor plans

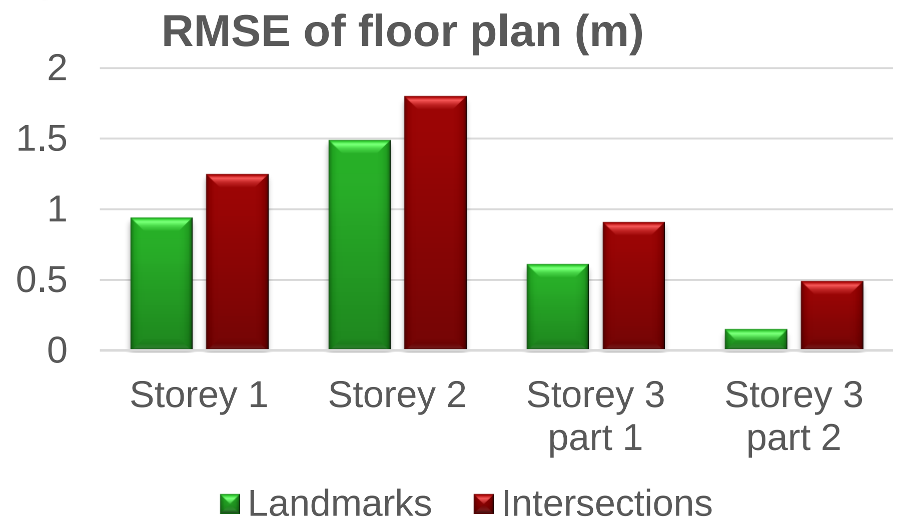
- **Landmark placement performance**
  - **Store position error 1-2m**
  - **Store orientation error 5-9 degrees**
- **Constructed floor plans**



Detailed results

- **Accuracy of floor plans**
  - **Root mean square error (RMSE)**
    - $X_i=(x_i,y_i)$: 2D coordinates
  - **Features**
    - Landmarks
    - Hallway intersections

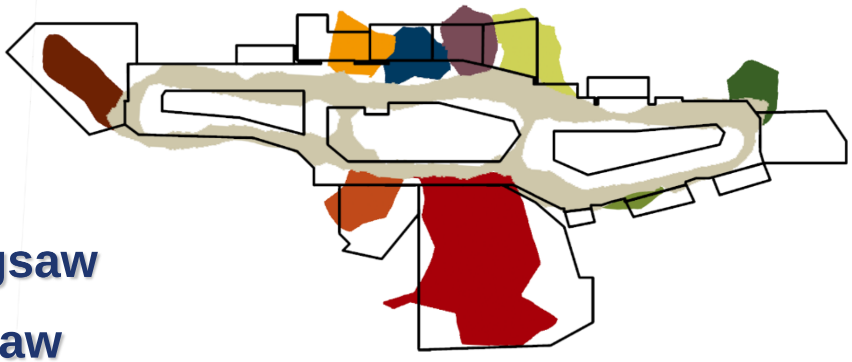
$$e_{RMS} = \sqrt{\frac{\sum_{i=1}^{n}(X_i^{map} - X_i^{test})^2}{n}}$$



- **Hallway shape**
  - **Overlay the reconstructed hallway onto its groundtruth to achieve maximum overlap**
  - **Hallway shape**
    - Presicion~80%, Recall~90%, F-score~84%

Comparison with CrowdInside++

- Several assumptions of CrowdInside*
  - Sufficient numbers of anchor points (GPS, inertial, ..)
  - Sufficient amount of traces passing through anchor points
  - Distinctive WiFi signatures in different rooms
- Artificial improvements in CrowdInside++
  - Double the number of anchor points; assume they are GPS-based
  - All traces pass through adjacent anchor points
  - Manually classify room traces
- Results of CrowdInside++
  - Miss a few small-sized stores
  - RMSE and maximum error: 4x of Jigsaw
  - Hallway shape: ~30% less than Jigsaw



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- Results of CrowdInside++

- Causes
  - Error accumulation of inertial-only approach
  - Deterministic alpha-shape instead of probabilistic occupancy map

* M. Alzantot and M. Youssef. Crowdinside: Automatic construction of indoor floorplans. In SIGSPATIAL, 2012.

Related work

- Floor plan construction: relatively new problem
  - CrowdInside, Jiang *et. al.*, Walkie-Markie, MapGenie
    - We combine vision and mobile techniques
    - We use optimization and probabilistic techniques
- SLAM
  - Noisy and piece-wise crowdsensed data
    - No high precision special sensor: laser ranges, stereo/depth cameras
  - Estimate landmark orientations
- 3D construction in vision
  - Floor plans require only 2d
- Localization with vision techniques
  - Sextant, OPS

Summary

- **Combine complementary strengths of vision and mobile techniques**
  - Vision: accurate geometric information, landmark only
  - Mobile: relative positions of landmarks, sketches of hallway/room shapes
  - Camera locations as anchor points
- **Optimization and probabilistic formulations for solid foundations and better robustness**
  - MLE: landmark placement
  - Minimum weight matching: hallway boundary construction
  - Occupancy grid map: hallway/room shapes

Thank you!

Questions?