Landmark Management in the Application of Radar SLAM

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Outline

1. Introduction
   - Motivation → Radar SLAM, Landmark management
   - Advantage → High accuracy, Low cost, Small size, Robustness in harsh weather
2. Methods
   - Framework → EKF SLAM (state augmentation)
   - Landmark management → Rule based (M/N logic)
3. Simulation Results
4. Conclusions

SLAM Using An FMCW Radar

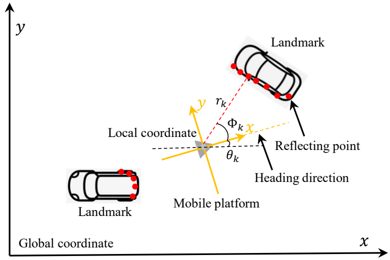
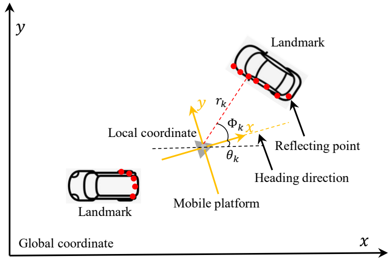


Illustration of a typical considered SLAM scene

- FMCW = frequency-modulated continuous-wave radar
- θ_k = Orientation of the mobile platform
- r_k = Range of a particular detection point from the platform
- ϕ_k = Azimuth angle of a particular detection point

- Low cost
- High accuracy
- Better suited to extreme weather conditions, such as rain, fog, smoke

SLAM Using An FMCW Radar



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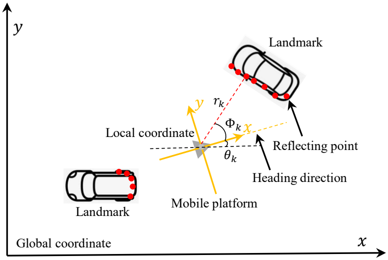
State of the art approaches:

- EKF SLAM, Fast SLAM etc.
- Assume each landmark can return at most one detection
- Assume landmarks remain static

SLAM Using An FMCW Radar



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What we need:

- Varying number of radar detections for each landmark
- Vehicles may arrive or leave the scene (slow dynamic)

EKF SLAM: Problem Formulation

$$\mathbf{x}_k^a = \Big[\underbrace{x_k,\ y_k,\ \theta_k}_{\mathbf{x}_k^m},\ \underbrace{\mathbf{p}_k^1, \dots, \mathbf{p}_k^{N_k}}_{\mathbf{x}_k^\ell}\Big]^T$$

- $\mathbf{x}_k^m = [x_k,\ y_k,\ \theta_k]^T$: the pose of the mobile platform, namely the 2D location and heading of the mobile platform
- $\mathbf{x}_k^\ell = \left[\mathbf{p}_k^1, \dots, \mathbf{p}_k^{N_k}\right]^T$: vector of landmarks registered in the system, each $\mathbf{p}_k^n = [p_k^n(x),\ p_k^n(y)]$.
- the total number of landmarks N_k will vary with time as landmarks are added and removed

[1] H. Lee, J. Chun, and K. Jeon, '*Experimental results and posterior cramér–rao bound analysis of EKF-based radar SLAM with odometer bias compensation*', IEEE Transactions on Aerospace and Electronic Systems, vol. 57, no. 1, pp. 310–324, 2020.

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Our Approach:

↬ Consider each landmark can return multiple radar detections (the number is unknown and varies with time)

↬ Handle the tedious landmark management problem: initialization, association, removal and merge

↬ Able to deal with slow dynamics: landmarks leave or enter the scene

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Landmark Management → Landmark Initialization

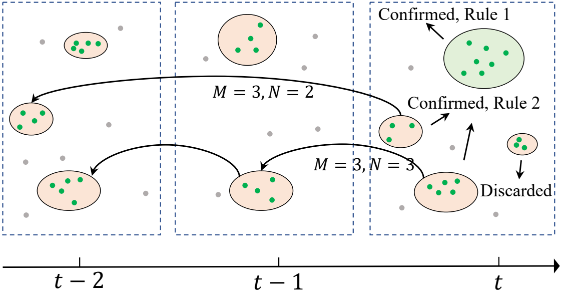


Illustration of landmark initialization

- Rule 1 (maximum point criteria), the number of radar detections in a cluster exceeds threshold N_{c_1}
- Rule 2 (multi-frame criteria, if Rule 1 is not satisfied), during M consecutive time steps, if there are at least N times that this cluster is detected/observed

Landmark Management → Landmark Removal

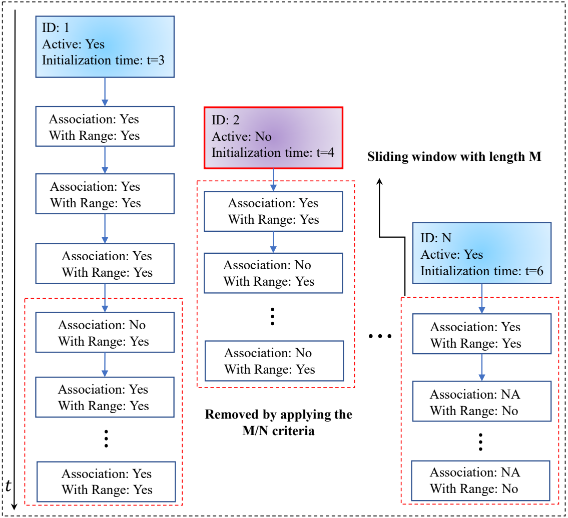


Illustration of landmark removal

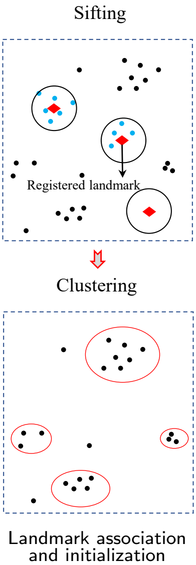
EKF-SLAM Algorithm

- **EKF Prediction:** $(x^a_{k|k-1}, P^a_{k|k-1})$
  1. Predict mobile platform state based on odometry
  2. Predict landmark state

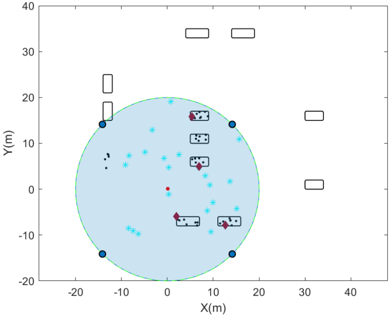
$$\mathbf{x}^a_{k|k-1} = \begin{bmatrix} f_m\left(\mathbf{x}^m_{k-1|k-1},\ \bar{\mathbf{u}}_k\right) \\ \mathbf{x}^\ell_{k-1|k-1} \end{bmatrix}$$

- **EKF Update:** $(x^u_{k|k}, P^u_{k|k})$
  1. Associate radar detections to registered landmarks
  2. State update for each landmark
  3. Remove spurious landmarks (M/N association logic)
  4. Cluster the remaining radar detections
  5. New landmark initialization
  6. Landmark merge

$$\mathbf{x}^{a,u}_{k|k} = \mathbf{x}^a_{k|k-1} + W_k\left(\mathbf{z}_k - h_n\left(\mathbf{x}^a_{k|k-1}\right)\right),$$
$$P^{a,u}_{k|k} = P^a_{k|k-1} - W_k S_k W_k^T.$$

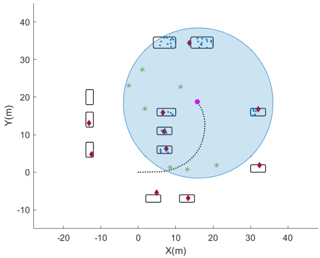


Example Landmark Initialization

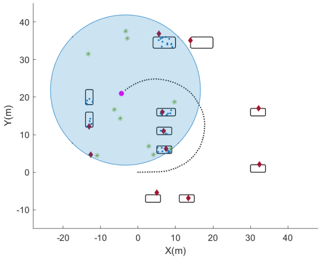


↬ A false landmark is intialized and later removed from the system by using a M/N removal logic.

Landmark Management In Low Dynamics



(a) A previously registered landmark vehicle leaves the scene

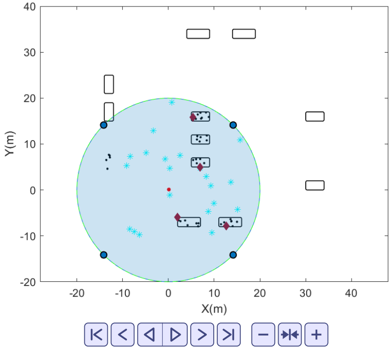


(b) The non-existing landmark is identified and removed

↬ The proposed M/N logic based landmark management can maintain the landmarks in a consistent manner.

Typical Simulation Results

Example of the whole SLAM process simulated in a car park scene:



↬ Landmarks are managed in a consistent manner.

Monte Carlo Simulation Results

Metric	Low Clutter	High Clutter
Platform position avg. RMSE (m)	0.81	0.90
Platform heading avg. RMSE (deg)	3.26	3.50
Landmark estimation MAE (m)	1.23	1.34
Landmark inclusion mean delay	2.45	3.22
Landmark removal mean delay	10.85	11.00
Mean (Max) false landmarks	0.13 (4)	3.02 (7)
Mean (Max) missed landmarks	0.2 (4)	0.23 (5)

Conclusions

M/N logic for landmark management

- Straightforward to be implemented
- Handle landmark initialization, maintenance, removal and merge in an consistent manner

Simulation Results

- Demonstrated in a car park scene for vehicle landmarks
- Capable of estimating pose of the mobile platform and landmark state (centroid location) simultaneously
- Manage landmarks in a consistent manner

Code available at:
https://github.com/shuai000/SLAM_LandmarkManagement

The End

Thank you for listening