HOCHSCHULE HEILBRONN

❯ AUTOMOTIVE SYSTEMS – PERCEPTION AND SITUATION UNDERSTANDING

SIMULATIVE ROBOT DETECTION WITH DIFFERENT SENSORS AND KALMAN-FILTER

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PROBLEM DESCRIPTION

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- Observation of Robots in a room
- Two Cameras with limited Field of View
- One LiDAR with low angular resolution
- Only position measurable
- Known state equation of robots

BOUNDARY CONDITIONS

- Room Size 2D = $[40\ m, 30\ m]$
- Cameras
  - Located in the upper two corners of the room
  - FOV of 40°
  - Measures position in x and y and orientation θ
  - Normally distributed uncertainty with $\sigma = 0{,}3$
- LiDAR
  - Located in the lower middle of the room
  - Angular resolution of 10°
  - Measures distance to robot and angle of hitten beam
  - Normally distributed uncertainty of distance with $\sigma = 0{,}5$, angular $\sigma = 0{,}1$

BOUNDARY CONDITIONS

- Robots
  - Differential drive → direction of velocity is orientation of robot
  - One step every $100\ ms$
    - $0.3\ m$ movement per step
    - Change of direction randomly between -0.2 and 0.2 per step
  - Every ten seconds change of direction randomly between 0 and 2π
  - Reflection from the walls

VISUALIZATION OF ROOM, SENSORS AND ROBOTS

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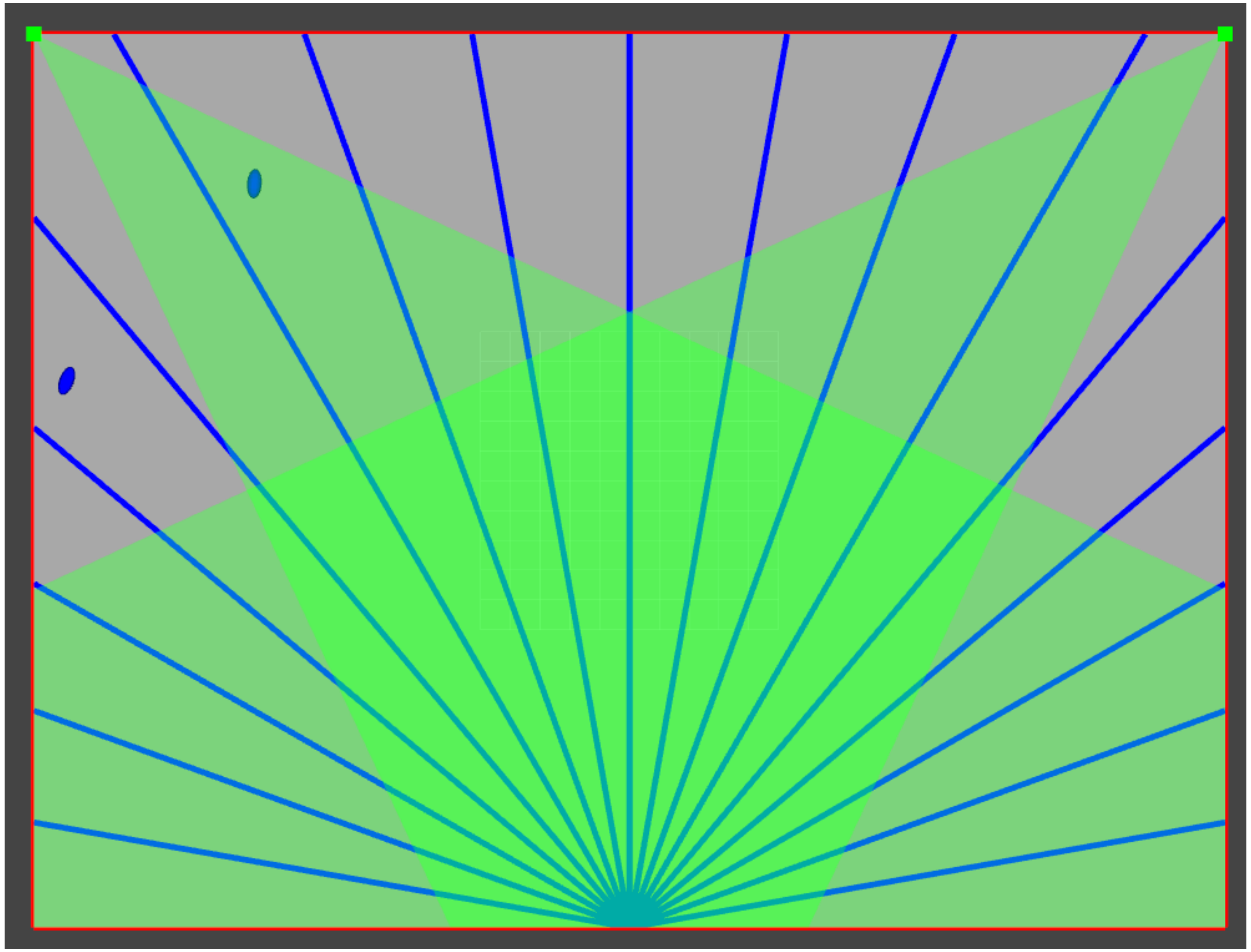
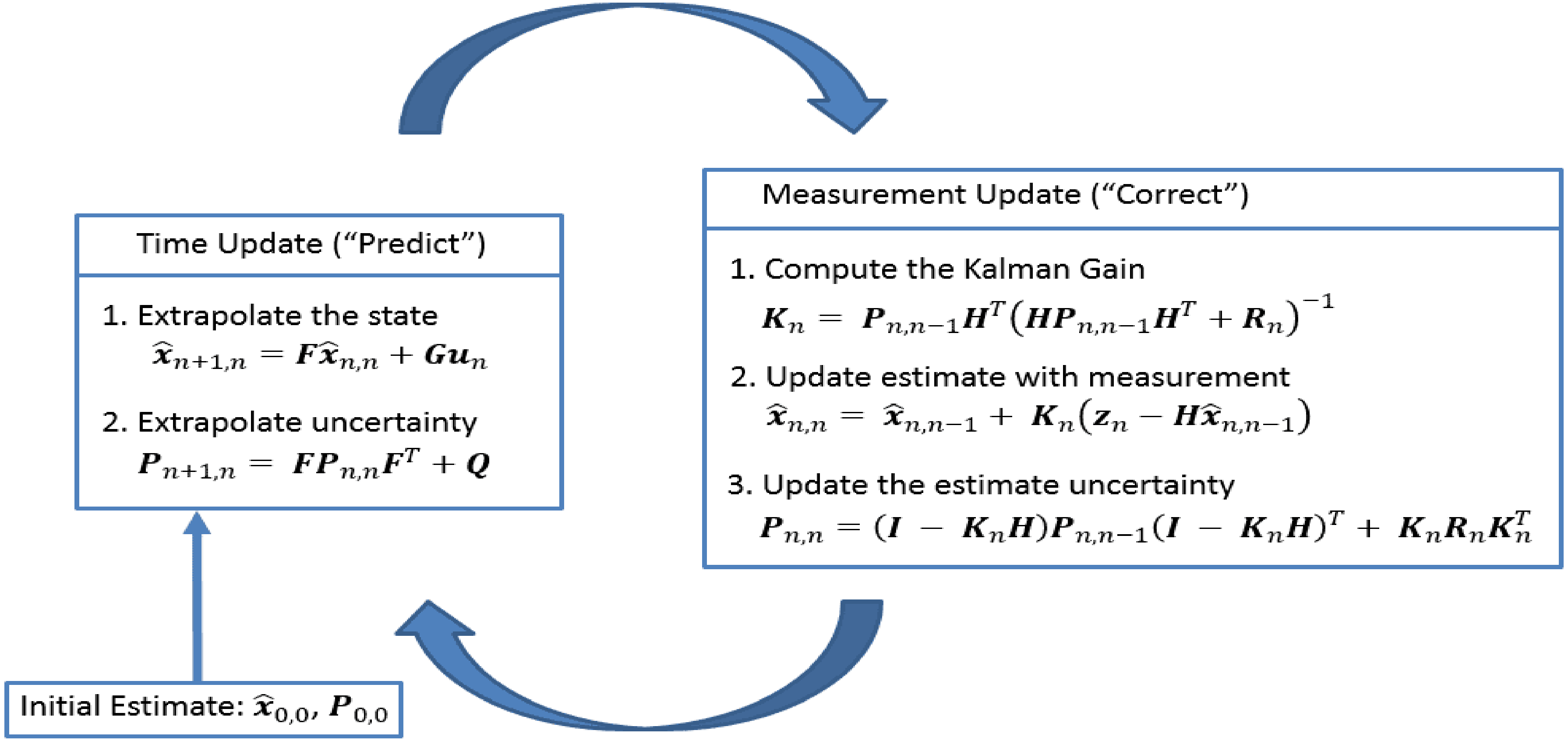


CHOSEN SOLUTION APPROACH

- Multi Target Tracking with Mahalanobis distance-based data association
- Extended Kalman-Filer to estimate position and velocity



https://www.kalmanfilter.net/img/summary/KalmanFilterDiagram.png

MAHALANOBIS DISTANCE & MULTI-TARGET DATA ASSOCIATION

- **Goal:** Assign measurements to EKF states based on statistical compatibility.
- **Mahalanobis distance:** $d^2 = (z - h(x))^T S^{-1} (z - h(x))$, with $S = HPH^T + R$
- **Assignment logic:** Distances between all detections and states. Only one detection can be assigned to one state
- **Primary allocation:** $d^2 <= 20$
- **Secondary allocation:** $20 < d^2 < 100\, with\, increased\, R$

EXTENDED KALMAN FILTER

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- **Purpose**: Estimates the state of a nonlineaar system with noisy measurements
- **Approach**: Extends Kalman Filter by linearizing nonlinear models with Jacobian
- **Steps**:

1. Prediction
   - Predict state and uncertainty from state $t - 1$ to state t by the given model
2. Correction
   - Measurement update of state with all available measurements
   - Incorporate the uncertainty of measurements

STATE VECTOR, MEASUREMENT VECTOR

- State vector: $x = \begin{bmatrix} x \\ y \\ \theta \\ v \\ \omega \end{bmatrix}$
- Input vector: $u = [\,]$
- Measurement vector: $z_{camera} = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$

$$\mathrm{z}_{lidar} = \begin{bmatrix} x \\ y \end{bmatrix}$$

MOTION / TRANSITION MODEL

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$$x_k = x_{k-1} + v_{k-1} \cdot \cos(\theta_{k-1}) \cdot \mathrm{dt}$$

$$y_k = y_{k-1} + v_{k-1} \cdot sin(\theta_{k-1}) \cdot \mathrm{dt}$$

$$\theta_k = \theta_{k-1} + \omega_k \cdot \mathrm{dt}$$

$$v_k = \frac{\sqrt{(x_k - x_{k-1})^2 + (y - y_{k-1})^2}}{dt}$$

$$\omega_k = \frac{\theta_k - \theta_{k-1}}{dt}$$

System dynamics function: $f(x) = \begin{bmatrix} x + v \cdot \cos(\theta_k) \cdot dt \\ y + v \cdot sin(\theta_k) \cdot dt \\ \theta + \omega \cdot dt \\ v \\ \omega \end{bmatrix}$

MEASUREMENT MODEL

- Measurement function: $\mathrm{h}_{\mathrm{camera}}(\mathrm{x}) = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$

$$\mathrm{h}_{\mathrm{lidar}}(\mathrm{x}) = \begin{bmatrix} x \\ y \end{bmatrix}$$

JACOBI-MATRICES

- System matrix:

$$F = \frac{\partial f}{\partial x} = \begin{bmatrix} 1 & 0 & -v \cdot \sin(\theta) \cdot dt & \cos(\theta) \cdot dt & 0 \\ 0 & 1 & v \cdot \cos(\theta) \cdot dt & \sin(\theta) \cdot dt & 0 \\ 0 & 0 & 1 & 0 & dt \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

- Measurement matrix:

$$H_{camera} = \frac{\partial h_{camera}}{\partial x} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

$$H_{lidar} = \frac{\partial h_{lidar}}{\partial x} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$

PARAMETERIZATION OF THE FILTER

- Process noise covariance:

$$Q = \begin{bmatrix} 0.0025 & 0 & 0 & 0 & 0 \\ 0 & 0.0025 & 0 & 0 & 0 \\ 0 & 0 & 0.0004 & 0 & 0 \\ 0 & 0 & 0 & 0.04 & 0 \\ 0 & 0 & 0 & 0 & 0.04 \end{bmatrix}$$

- Measurement noise covariance:

$$R_{camera} = \begin{bmatrix} 0.3^2 & 0 & 0 \\ 0 & 0.3^2 & 0 \\ 0 & 0 & 0.1^2 \end{bmatrix}$$

$$R_{lidar} = \begin{bmatrix} 0.5^2 & 0 \\ 0 & 0.5^2 \end{bmatrix}$$

- Error covariance matrix:

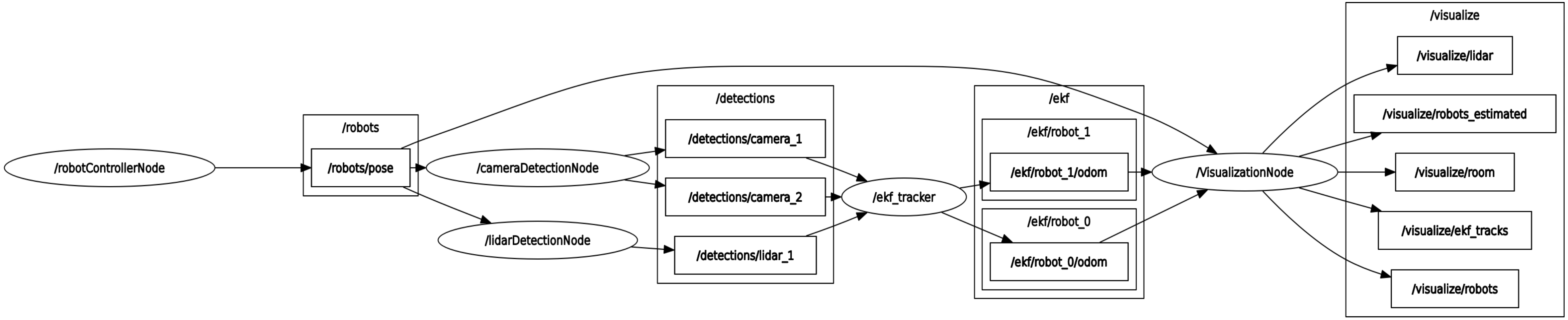
$$P_{init} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

OBSERVABILITY

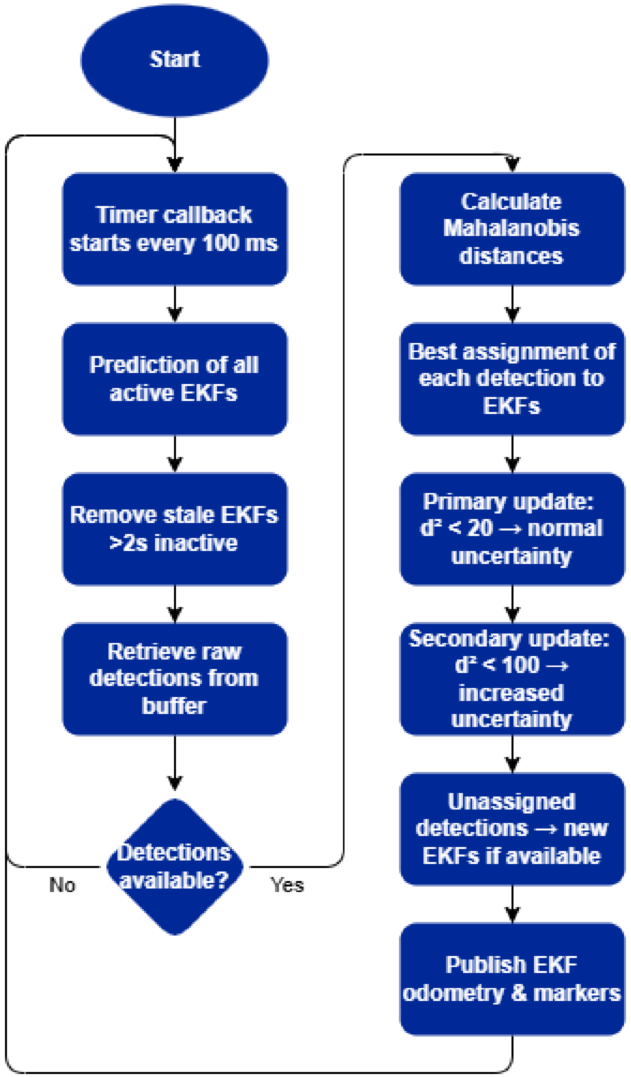
- Observability at state x_0: $x_0 = \left[12\,m \quad 20\,m \quad 2\pi\,rad \quad 0.9\,\frac{m}{s} \quad 0.2\,\frac{rad}{s}\right]^T$
- Observability matrix O: $$O = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & \frac{1}{10} & 0 \\ 0 & 1 & \frac{9}{100} & 0 & 0 \\ 1 & 0 & 0 & \frac{1}{5} & 0 \\ 0 & 1 & \frac{9}{50} & 0 & \frac{9}{1000} \\ 1 & 0 & 0 & \frac{3}{10} & 0 \\ 0 & 1 & \frac{27}{100} & 0 & \frac{27}{1000} \\ 1 & 0 & 0 & \frac{2}{5} & 0 \\ 0 & 1 & \frac{9}{25} & 0 & \frac{27}{500} \end{bmatrix}$$
- Observability matrix rank: $rank = 5 == length(x)$ → System observable

STRUCTURE OF THE IMPLEMENTED PROGRAM

- Implementation in ROS2 Nodes
  - robotControllerNode → Simulation of roboter movement
  - *DetectionNode → Simulation of detection with added noise
  - ekfNode → extended Kalman-Filter
  - visualizationNode → Visualization of room, roboters, sensors, covariance



FLOWCHART


Start
Timer callback starts every 100 ms
Prediction of all active EKFs
Remove stale EKFs >2s inactive
Retrieve raw detections from buffer
Detections available?
No
Yes
Calculate Mahalanobis distances
Best assignment of each detection to EKFs
Primary update: d² < 20 → normal uncertainty
Secondary update: d² < 100 → increased uncertainty
Unassigned detections → new EKFs if available
Publish EKF odometry & markers

SYSTEM LIMITATIONS

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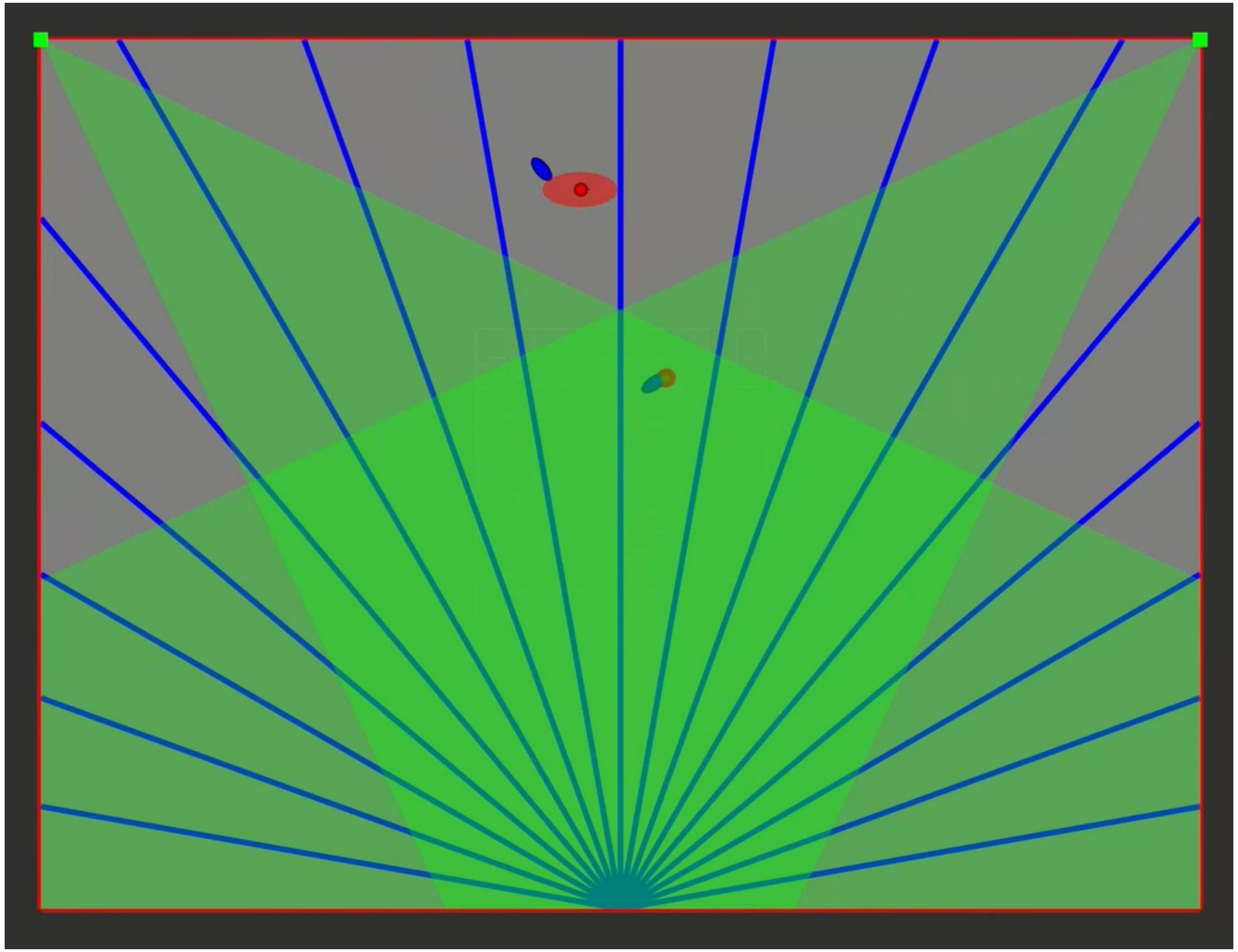
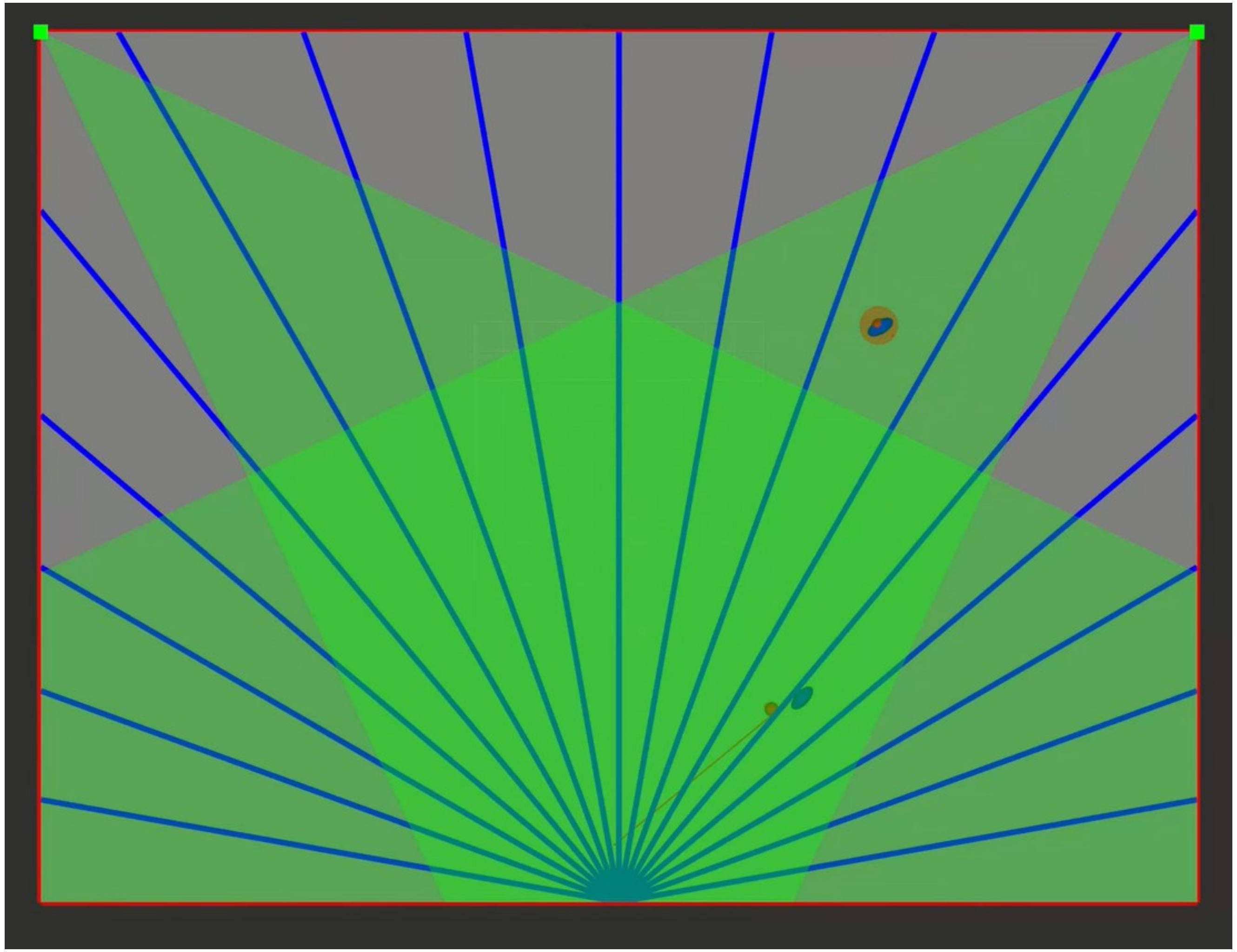
- Currently limited to two robots (assumption for Kalman filter)
- Rejection of measurements above threshold
- Uncertainty when robots are close to each other
- Deletion of the Kalman filter if no assignable measurement was received for two second
  → Robots are no longer detected after two second if they are not measured
- Second EKF on the same robot, if only this one has been measured in the last 2 seconds, when detection over threshold 100

RESULTS



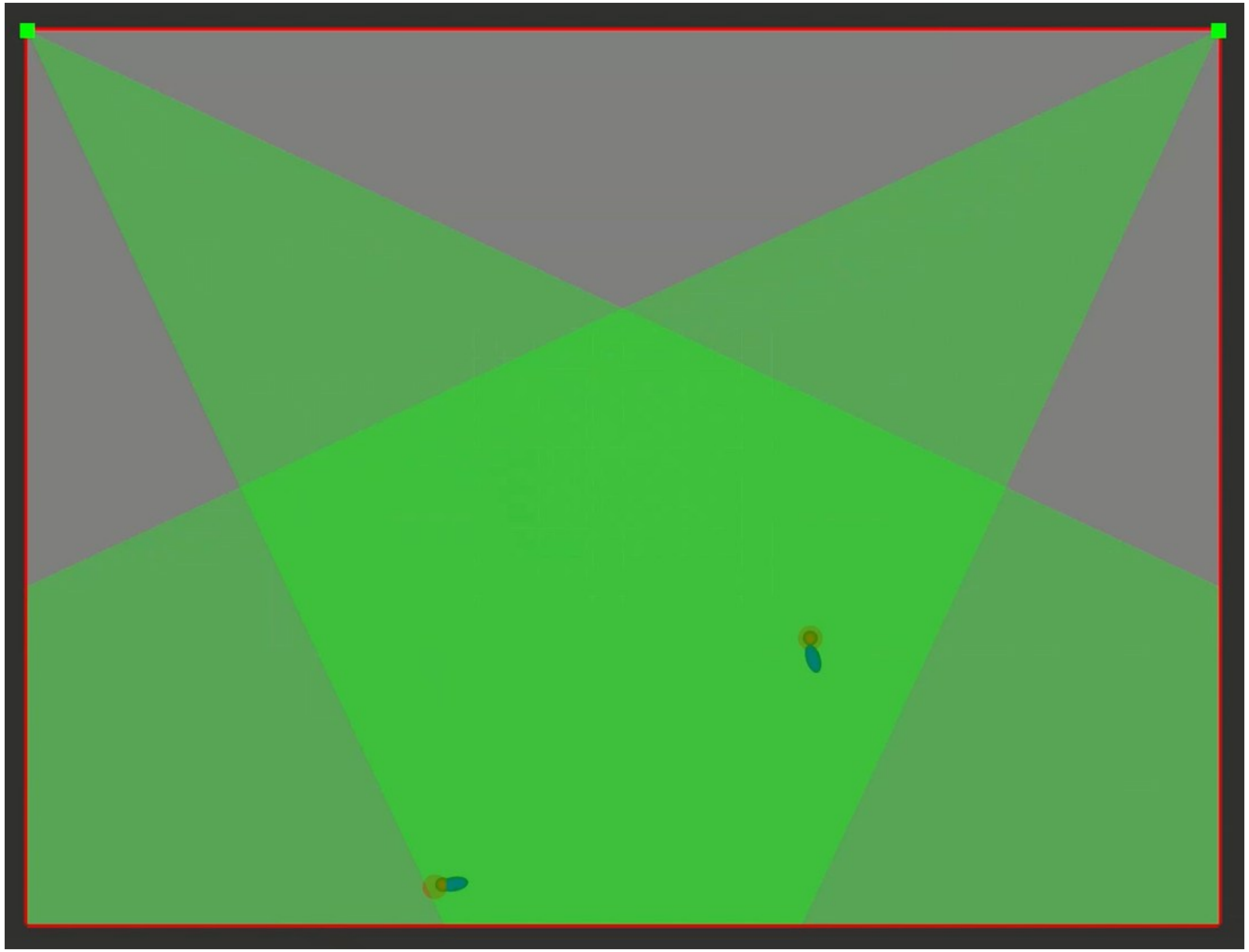
[Prediction] State 0: Predicted Position: (-16.95, 8.61)
[Prediction] State 1: Predicted Position: (-16.13, -10.44)
[Stale Removal] Removing EKF 0 after 2s timeout.
[Detection] 2 detections received.
[Detection Info] Detection 0: Sensor=camera_1, Position= (-16.15, -11.96)
[Detection Info] Detection 1: Sensor=camera_2, Position= (-17.00, 8.36)
[Mahalanobis] Detection 0 to State 1: d^2 = 16.88
[Mahalanobis] Detection 1 to State 1: d^2 = 2577.87
[Update] Detection 0 assigned to State 1 (Primary Threshold, d^2=16.88). Updated Position: (-16.14, -10.64)
[No Update] Detection 1 could not be assigned.
Initialized EKF for Robot 0 at (-17.00, 8.36)
[Init] New EKF State 0 from Detection -17.00, 8.36

RESULTS



[Prediction] State 0: Predicted Position: (-12.96, 8.51)
[Prediction] State 1: Predicted Position: (-7.63, -5.99)
[Detection] 5 detections received.
[Detection Info] Detection 0: Sensor=lidar, Position=(-15.02, 7.79)
[Detection Info] Detection 1: Sensor=lidar, Position=(-7.55, -7.82)
[Detection Info] Detection 2: Sensor=camera_1, Position=(-7.65, -6.57)
[Detection Info] Detection 3: Sensor=camera_2, Position=(-12.67, 8.75)
[Detection Info] Detection 4: Sensor=camera_2, Position=(-7.29, -7.35)
[Mahalanobis] Detection 0 to State 0: d² = 52.37
[Mahalanobis] Detection 0 to State 1: d² = 2438.62
[Mahalanobis] Detection 1 to State 0: d² = 1970.24
[Mahalanobis] Detection 1 to State 1: d² = 41.30
[Mahalanobis] Detection 2 to State 0: d² = 1215.47
[Mahalanobis] Detection 2 to State 1: d² = 2.38
[Mahalanobis] Detection 3 to State 0: d² = 0.88
[Mahalanobis] Detection 3 to State 1: d² = 1577.47
[Mahalanobis] Detection 4 to State 0: d² = 1349.87
[Mahalanobis] Detection 4 to State 1: d² = 13.19
[Update] Detection 0 assigned to State 0 (Secondary Threshold, d²=52.37).
Updated Position: (-13.41, 8.34)
[Update] Detection 1 assigned to State 1 (Secondary Threshold, d²=41.30).
Updated Position: (-7.53, -6.34)
[Update] Detection 2 assigned to State 1 (Primary Threshold, d²=2.38).
Updated Position: (-7.56, -6.36)
[Update] Detection 3 assigned to State 0 (Primary Threshold, d²=0.88).
Updated Position: (-13.31, 8.41)
[Update] Detection 4 assigned to State 1 (Primary Threshold, d²=13.19).
Updated Position: (-7.49, -6.47)

RESULTS



→ **LiDAR detection increases uncertainty because of high measurement noise and no measurement of orientation angle**

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› THANK YOU FOR YOUR ATTENTION

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