

➤ **AUTOMOTIVE SYSTEMS – PERCEPTION AND SITUATION UNDERSTANDING**

SIMULATIVE ROBOT DETECTION WITH DIFFERENT SENSORS AND KALMAN-FILTER

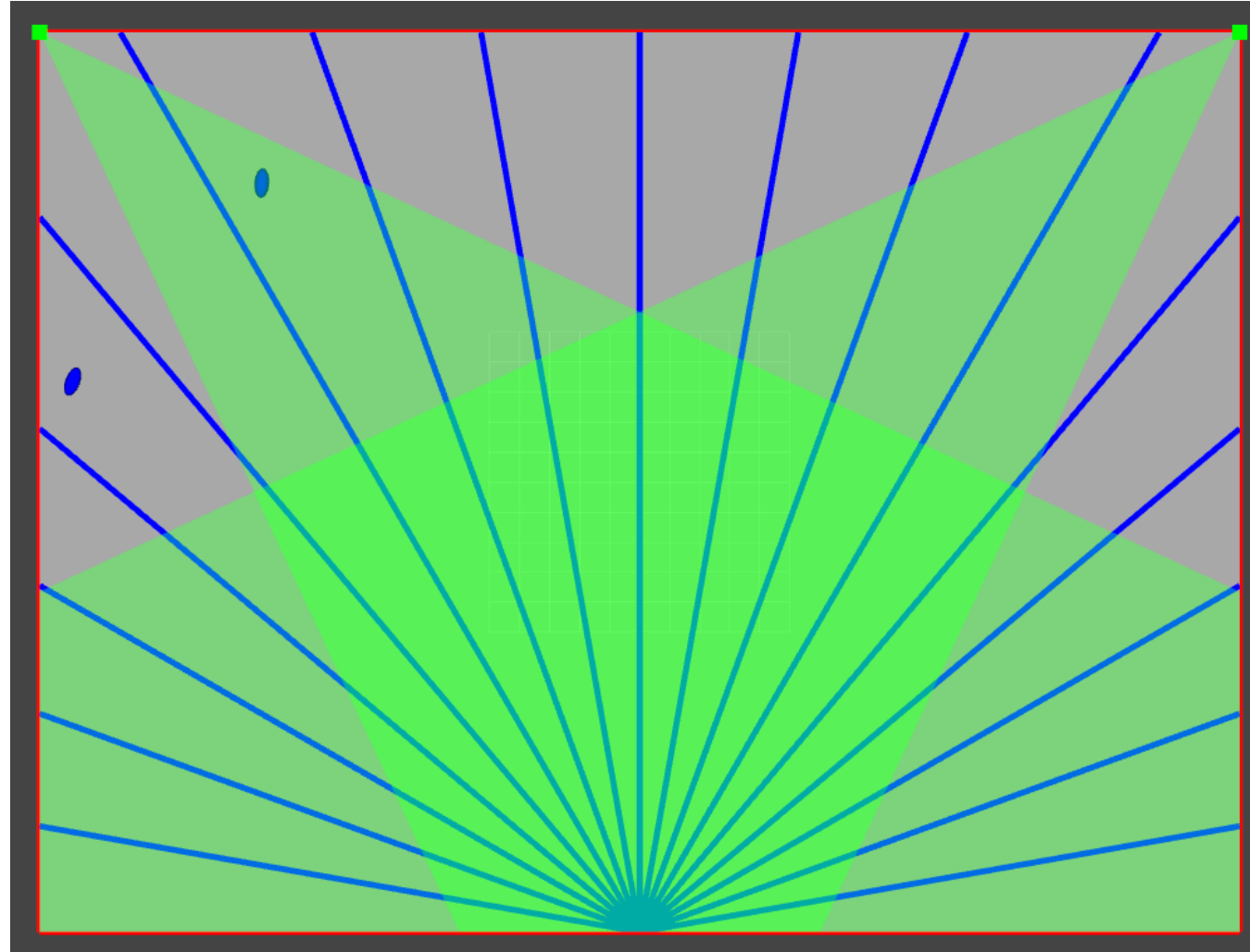
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- Observation of Robots in a room
- Two Cameras with limited Field of View
- One LiDAR with low angular resolution
- Only position measurable
- Known state equation of robots

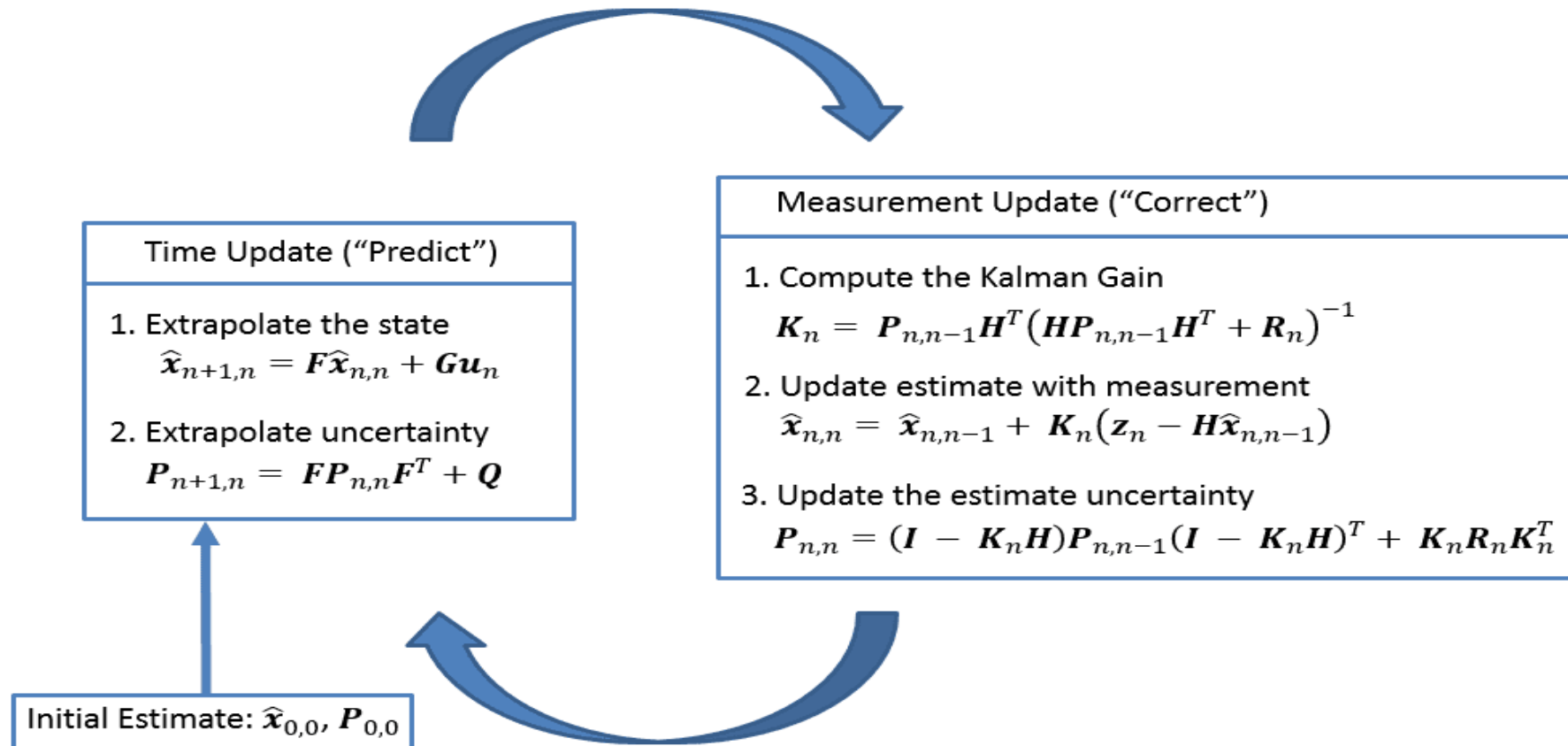
- Room Size 2D = $[40\text{ m}, 30\text{ m}]$
- Cameras
 - Located in the upper two corners of the room
 - FOV of 40°
 - Measures position in x and y and orientation θ
 - Normally distributed uncertainty with $\sigma = 0,3$
- LiDAR
 - Located in the lower middle of the room
 - Angular resolution of 10°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

- 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 three seconds change of direction randomly between 0 and 2π
 - Reflection from the walls



CHOSEN SOLUTION APPROACH

- Multi Target Tracking with Mahalanobis distance-based data association
- Extended Kalman-Filer



MAHALANOBIS DISTANCE & MULTI-TARGET DATA ASSOCIATION

- **Goal:** Assign measurements to EKF tracks 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 tracks. Only one detection can be assigned to one track.
- **Primary allocation:** $d^2 \leq 20$
- **Secondary allocation:** $20 < d^2 < 100$ *with increased R*

- **Purpose:** Estimates the state of a nonlinear 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: $z_{camera} = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$
 $z_{lidar} = \begin{bmatrix} x \\ y \end{bmatrix}$

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

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

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

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

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

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 function: $h_{\text{camera}}(\mathbf{x}) = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$

$$h_{\text{lidar}}(\mathbf{x}) = \begin{bmatrix} x \\ y \end{bmatrix}$$

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

- 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:

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

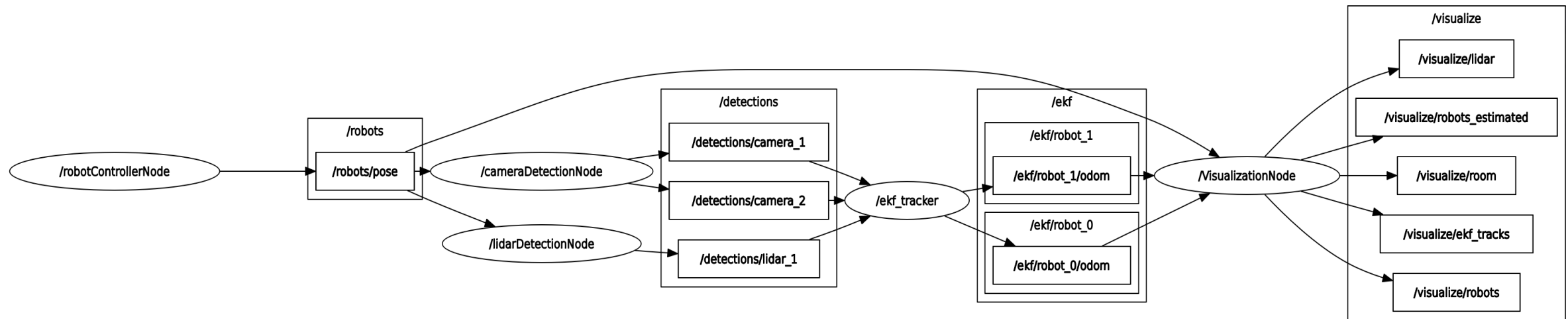
- Observability at state x_0 : $x_0 = \left[12 \text{ m} \quad 20 \text{ m} \quad 2\pi \text{ rad} \quad 0.9 \frac{\text{m}}{\text{s}} \quad 0.2 \frac{\text{rad}}{\text{s}} \right]^T$

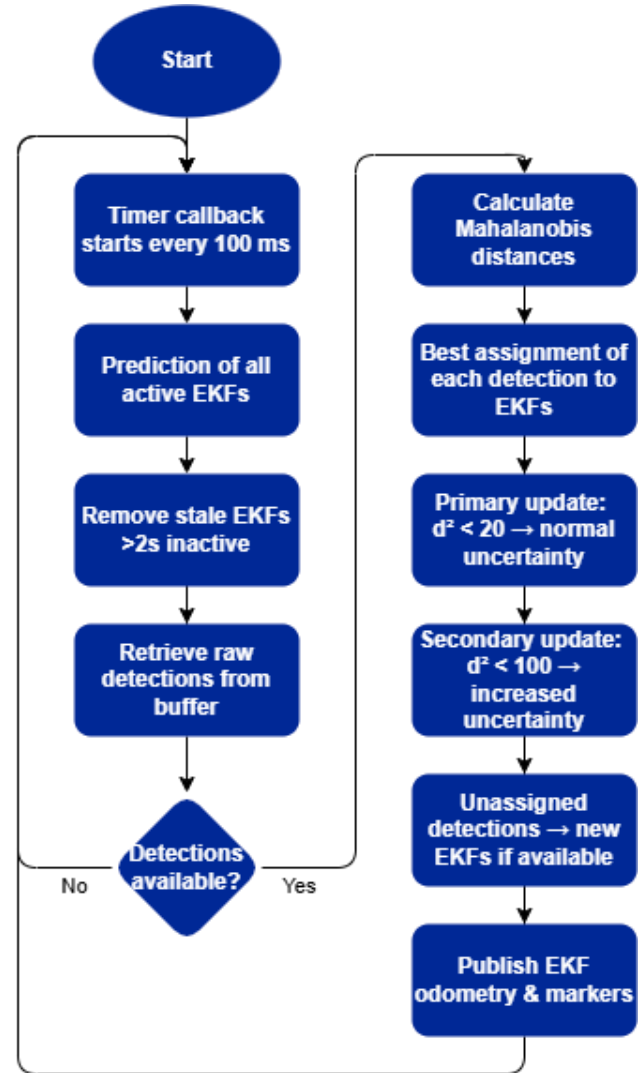
- Observability matrix O :
$$O = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & \frac{1}{10} & 0 \\ 0 & 1 & \frac{9}{100} & 0 & 0 \\ 1 & 0 & 0 & \frac{1}{5} & 0 \\ 0 & 1 & \frac{9}{50} & 0 & \frac{9}{1000} \\ 1 & 0 & 0 & \frac{3}{10} & 0 \\ 0 & 1 & \frac{27}{100} & 0 & \frac{27}{1000} \\ 1 & 0 & 0 & \frac{2}{5} & 0 \\ 0 & 1 & \frac{9}{25} & 0 & \frac{27}{500} \end{bmatrix}$$

- Observability matrix rank: $rank = 5 == length(x) \rightarrow$ System observable

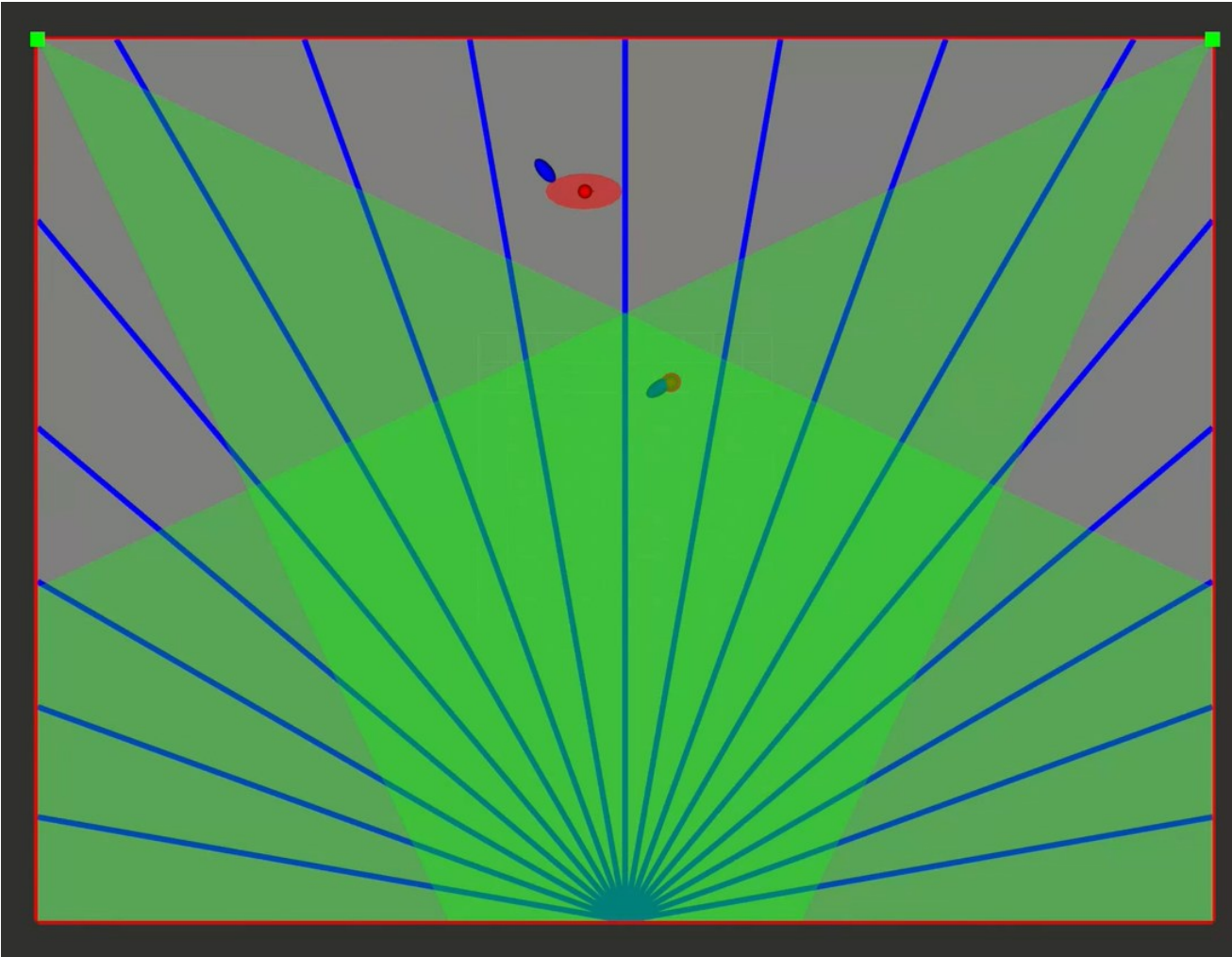
STRUCTURE OF THE IMPLEMENTED PROGRAM

- 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

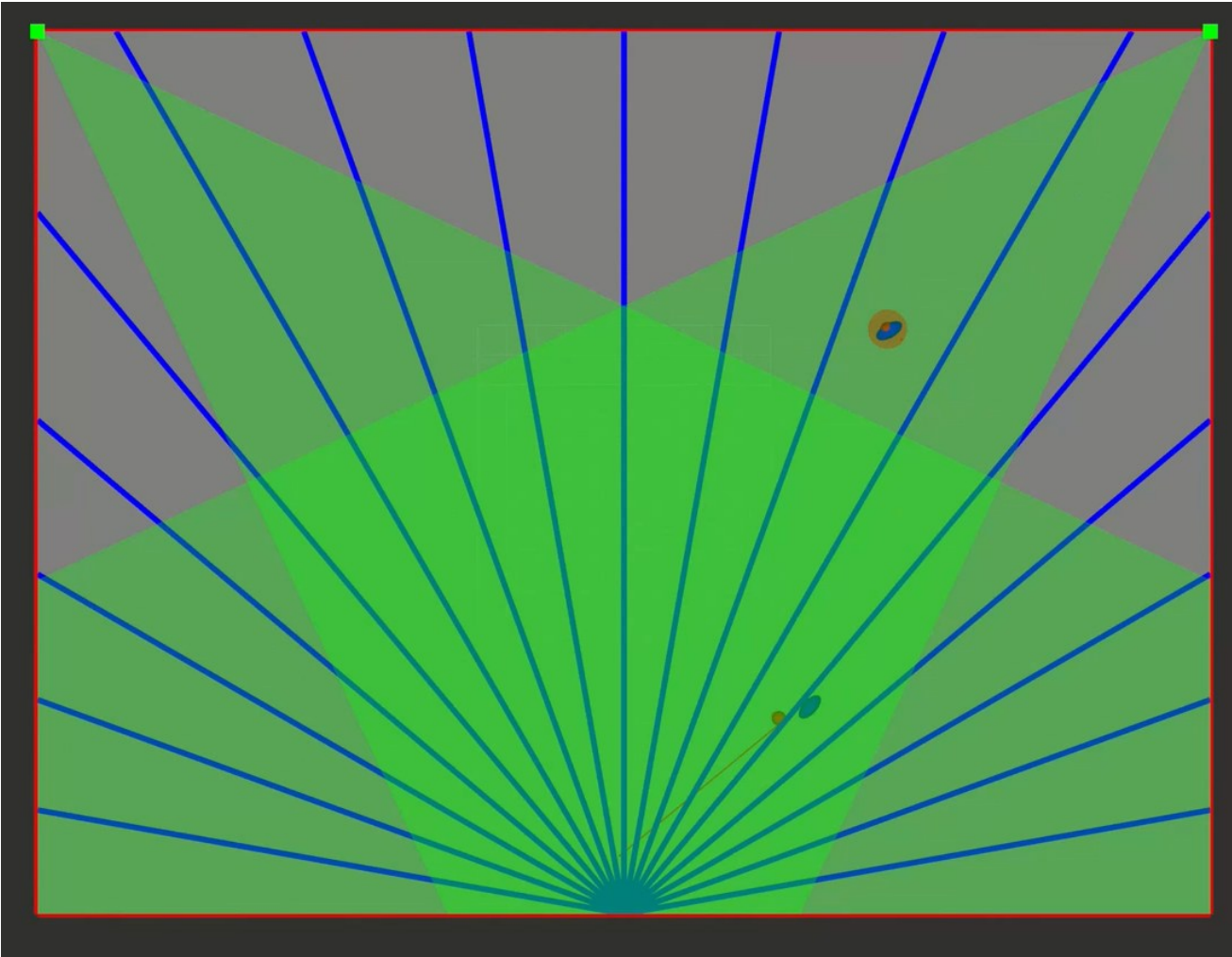




- Currently limited to two robots (assumption for Kalman filter)
- Rejection of measurements above threshold
- Uncertainty when robots are close to each other
- Deletion of the Kalman filter if no assignable measurement was received for two second
→ Robots are no longer detected after two second if they 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



[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



[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: $d^2 = 52.37$

[Mahalanobis] Detection 0 to State 1: $d^2 = 2438.62$

[Mahalanobis] Detection 1 to State 0: $d^2 = 1970.24$

[Mahalanobis] Detection 1 to State 1: $d^2 = 41.30$

[Mahalanobis] Detection 2 to State 0: $d^2 = 1215.47$

[Mahalanobis] Detection 2 to State 1: $d^2 = 2.38$

[Mahalanobis] Detection 3 to State 0: $d^2 = 0.88$

[Mahalanobis] Detection 3 to State 1: $d^2 = 1577.47$

[Mahalanobis] Detection 4 to State 0: $d^2 = 1349.87$

[Mahalanobis] Detection 4 to State 1: $d^2 = 13.19$

[Update] Detection 0 assigned to State 0 (Secondary Threshold, $d^2=52.37$).

Updated Position: (-13.41, 8.34)

[Update] Detection 1 assigned to State 1 (Secondary Threshold, $d^2=41.30$).

Updated Position: (-7.53, -6.34)

[Update] Detection 2 assigned to State 1 (Primary Threshold, $d^2=2.38$).

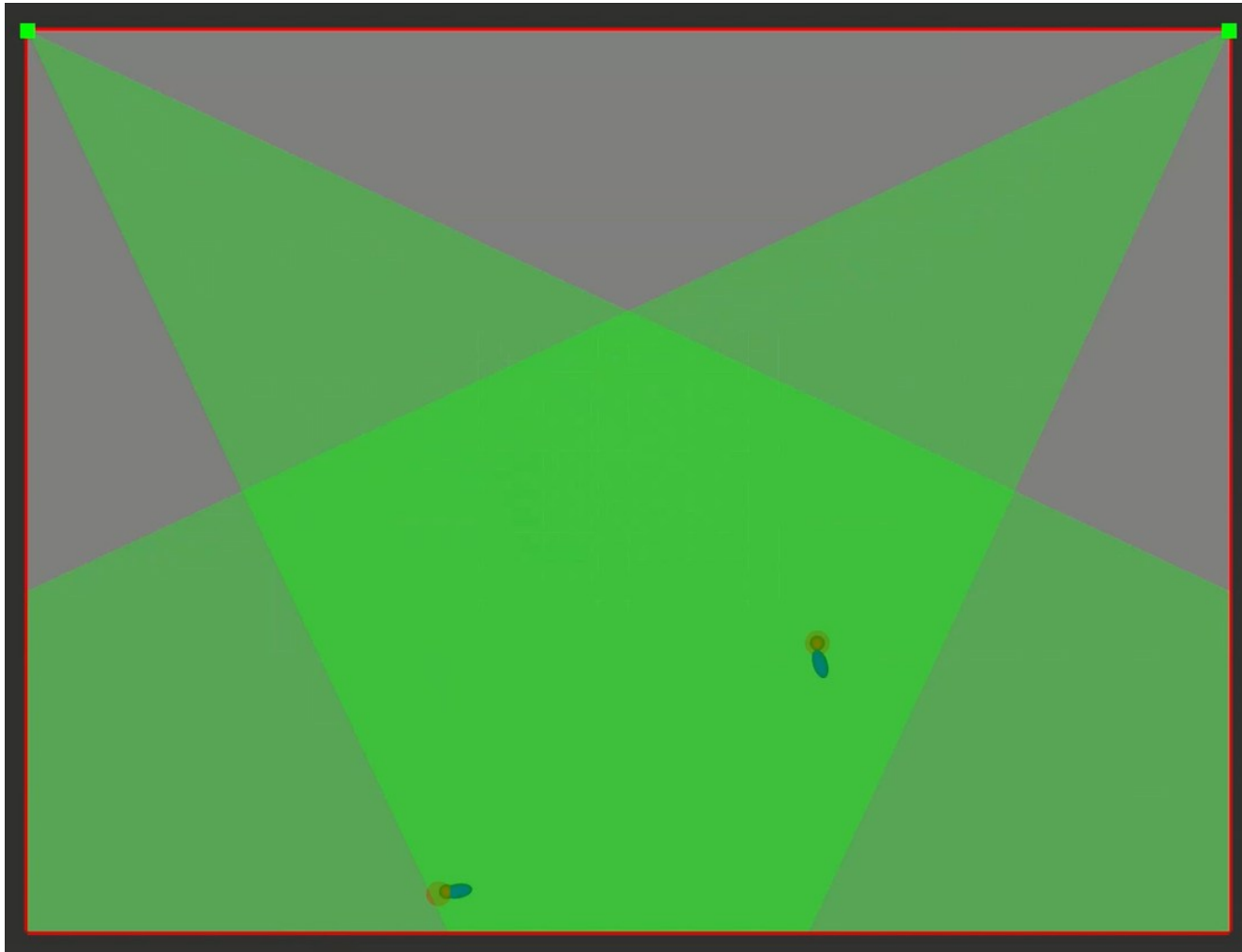
Updated Position: (-7.56, -6.36)

[Update] Detection 3 assigned to State 0 (Primary Threshold, $d^2=0.88$).

Updated Position: (-13.31, 8.41)

[Update] Detection 4 assigned to State 1 (Primary Threshold, $d^2=13.19$).

Updated Position: (-7.49, -6.47)



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

› **THANK YOU FOR YOUR ATTENTION**

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