Exercise 1 *Internal Sensors*

1. Sensor characteristics

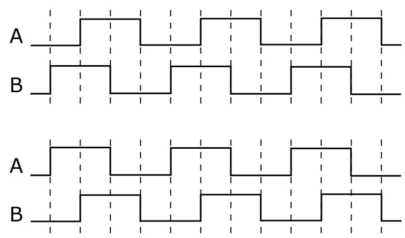
   (a) Four sensor characteristics

   - Range (Messbereich)
   - Resolution (Auflösung)
   - Sensitivity (Empfindlichkeit)
   - Repeatability (Wiederholgenauigkeit)
   - Bandwidth (Bandbreite)
   - Linearity (Linearität)
   - Response Time (Reaktionszeit)

   (b) Three types of measurement errors

   - Bias (Offset)
   - Hysteresis (Hysterese)
   - Random noise (Zufälliger Fehler)
   - (Temperature) drift (Drift)

2. Quadrature encoder output



3. Advantage of Gray code

   - Problem: During the transition between two positions two bits might not change at the exact same time, causing **erroneous transient states**. In Gray-code encoded discs **only one bit changes between two adjacent positions** → **Transient states do not occur**.

4. One advantage and one disadvantage each for accelerometers and gyroscopes

	Advantage	Disadvantage
Accelerometer	Not susceptible to drift	Susceptible to errors caused by lateral accelerations
Gyroscope	Not susceptible to errors caused by lateral accelerations	Prone to orientation drift due to numerical integration

5. Two filter algorithms for fusing acceleration and gyroscope readings

   - Kalman filter **or** Bayes filter
   - Complementary filter

6. Formula and computation for R_2

   - Formula: $R_2 = \frac{R_1 U_2}{U_1}$
   - Value: $R_2 = \frac{10\Omega * 4V}{2V} = 20\Omega$

Exercise 2 *External Sensors*

1. Advantage of proximity sensors:

   Proximity sensors can detect an object before contact is established. No interaction is required. No force is exerted.

2. Capacitive proximity sensor

   - *phenomena*: Electric field
   - *interaction*: no force interaction, change in dielectric constant
   - *what is measured*: change in capacity
   - *how is it measured*: amount of charge that is transferred to the capacitor for a given voltage

3. Computation of depth information:

   Features are extracted in both camera images The disparity between the two images is used to triangulate the position of the features.

4. Principal drawing of a stereo vision system:

5. Calculation of the disparity d:

   $d = x_L - x_R$ or $d = x_R - x_L$.

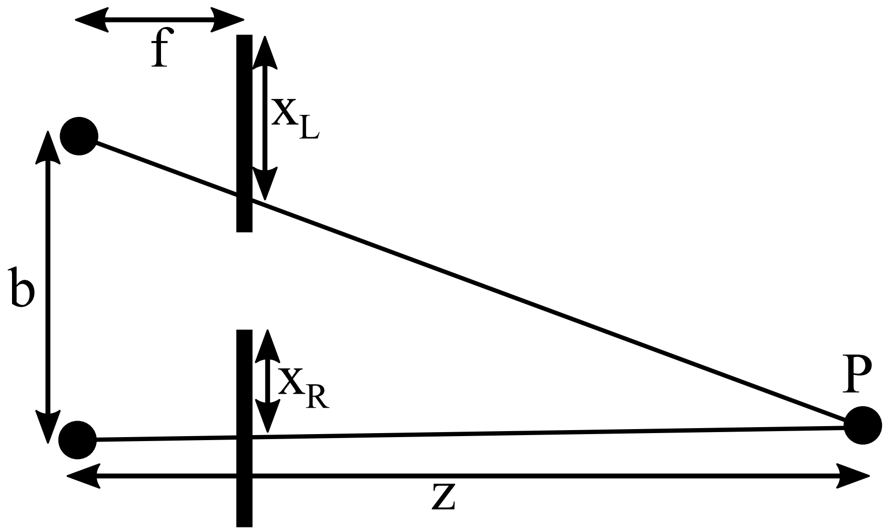
6. Equation for calculating Z:

   $Z = \frac{f \cdot b}{d}$

7. Value of Z:

   $Z = \frac{1\text{cm} \cdot 5\text{cm}}{1\text{mm}} = 50\text{cm}$

8. Working principle of spacial codification:
   A spacial pattern is projected onto the scene. The distortion of the projected pattern is used to calculate the depth information.



Exercise 3 *Active Vision and Gaze Stabilization*

1. Active vision: Manipulate the camera viewpoint in order to enhance the current perception. Makes ill-posed problems tractable and can resolve ambiguity or occlusion problems.
2. (a) Vestibulo-Ocular Reflex (VOR). Advantages: High Sampling Rate and easy too implement. Limitations: Controls only the eye joints, cannot compensate for external perturbations and requires an IMU.
   (b) Optokinectic reflex (OKR). Advantages: can stabilize the image in a dynamic environment. Limitations: low input frequency and controls only the eye joint.
   (c) Inverse kinematics control (IK). Avantages: Reactive and controls both head and eye joints. Limitations: Requires a target point, stabilizes only self-induced perturbations and depends on the accuracy of the robot's kinematic model.
3. The control output of the VOR is given by

$$\dot{q} = -k_{vor} \cdot [\omega_{yaw}\omega_{pitch}]^T.$$

Exercise 4 *SLAM*

1. (a) Jacobi H_t: 4

$$H_t = h'(\mathbf{x}_t) = \frac{\partial h}{\partial \mathbf{x}_t} = \left(\left(\frac{\partial h_i}{\partial x_{R,t}} \right) \left(\frac{\partial h_i}{\partial y_{R,t}} \right) \right) \quad \text{with} \quad i \in 1, 2, 3$$

$$\frac{\partial h_i}{\partial x_{R,t}} = \frac{\partial (e^{-\|\mathbf{m}_i - \mathbf{x}_t\|^2})}{\partial x_{R,t}} = \frac{\partial (e^{-((x_{m,i} - x_{R,t})^2 + (y_{m,i} - y_{R,t})^2)})}{\partial x_{R,t}} = (-1) \cdot 2(x_{m,i} - x_{R,t}) \cdot (-1) \cdot e^{-\|\mathbf{m}_i -}$$

$$\frac{\partial h_i}{\partial y_{R,t}} = \frac{\partial (e^{-\|\mathbf{m}_i - \mathbf{x}_t\|^2})}{\partial y_{R,t}} = \frac{\partial (e^{-((x_{m,i} - x_{R,t})^2 + (y_{m,i} - y_{R,t})^2)})}{\partial y_{R,t}} = (-1) \cdot 2(y_{m,i} - y_{R,t}) \cdot (-1) \cdot e^{-\|\mathbf{m}_i - \mathbf{x}}$$

$$H_t = \begin{pmatrix} 2(x_{m,1} - x_{R,t}) \cdot e^{-\|\mathbf{m}_1 - \mathbf{x}_t\|^2} & 2(y_{m,1} - y_{R,t}) \cdot e^{-\|\mathbf{m}_1 - \mathbf{x}_t\|^2} \\ 2(x_{m,2} - x_{R,t}) \cdot e^{-\|\mathbf{m}_2 - \mathbf{x}_t\|^2} & 2(y_{m,2} - y_{R,t}) \cdot e^{-\|\mathbf{m}_2 - \mathbf{x}_t\|^2} \\ 2(x_{m,3} - x_{R,t}) \cdot e^{-\|\mathbf{m}_3 - \mathbf{x}_t\|^2} & 2(y_{m,3} - y_{R,t}) \cdot e^{-\|\mathbf{m}_3 - \mathbf{x}_t\|^2} \end{pmatrix}$$

The general solution is not required. Values for m_1, m_2 and m_3 can already be filled in.

(b) Evaluate at $\mathbf{x}_t = (5, 7)^T$: 2 P.

$$\|\mathbf{m}_1 - \mathbf{x}_t\|^2 = ((1-5)^2 + (11-7)^2) = (4^2 + 4^2) = 16 + 16 = 32$$

$$\|\mathbf{m}_2 - \mathbf{x}_t\|^2 = ((2-5)^2 + (12-7)^2) = (3^2 + 5^2) = 9 + 25 = 34$$

$$\|\mathbf{m}_3 - \mathbf{x}_t\|^2 = ((3-5)^2 + (13-7)^2) = (2^2 + 6^2) = 4 + 36 = 40$$

$$H_t((5,7)^T) = \begin{pmatrix} 2(1-5) \cdot e^{-\|\mathbf{m}_1 - \mathbf{x}_t\|^2} & 2(11-7) \cdot e^{-\|\mathbf{m}_1 - \mathbf{x}_t\|^2} \\ 2(2-5) \cdot e^{-\|\mathbf{m}_2 - \mathbf{x}_t\|^2} & 2(12-7) \cdot e^{-\|\mathbf{m}_2 - \mathbf{x}_t\|^2} \\ 2(3-5) \cdot e^{-\|\mathbf{m}_3 - \mathbf{x}_t\|^2} & 2(13-7) \cdot e^{-\|\mathbf{m}_3 - \mathbf{x}_t\|^2} \end{pmatrix} = \begin{pmatrix} -8 \cdot e^{-32} & 8 \cdot e^{-32} \\ -6 \cdot e^{-34} & 10 \cdot e^{-34} \\ -4 \cdot e^{-40} & 12 \cdot e^{-40} \end{pmatrix}$$

2. EKF SLAM vs. GraphSLAM 2 P.

Only four differences are required.

(a) EKF SLAM is an online SLAM algorithm. It calculates the current robot pose every iteration. GraphSLAM is a full/offline SLAM algorithm. It collects information online and calculates the robot trajectory offline.

(b) EKF represents its state as a Gaussian distribution (mean and covariance, μ, Σ). GraphSLAM represents its state as a sparse graph. Robot poses and landmarks are nodes, edges represent soft constraints (motion and measurement).

(c) EKF SLAM uses an Extended Kalman filter to estimate the robot pose. GraphSLAM uses constrained optimization to find an optimal robot pose trajectory.

(d) EKF SLAM is proactive. Every new information is directly incorporated into the pose estimate. GraphSLAM is lazy. New information is collected until a batch process produces a pose trajectory.

(e) EKF SLAM uses a constant amount of memory over time ($O(1)$). GraphSLAM requires more memory, the longer data is collected ($O(t)$).

3. FastSLAM

   (a) RBPF vs. traditional particle filter: **1 P.**
   RBPF uses a particle filter to track one part of the state and a Gaussian filter to track others (e.g. an EKF).

   (b) FastSLAM particle: **1 P.**
   In FastSLAM, a single particle contains the robot trajectory $\mathbf{x}_{1:t}$ and M landmark estimations for each landmark. Each landmark estimation uses EKF representation μ_j, Σ_j (mean and covariance).

Exercise 5 *Feature Extraction*

1. Reason for falsely detected edges: The Moravec operator is not invariant to orientation. It is sensitive for points on edges, that have a deviation to the predefined shift-directions

2. Right image operator: Harris Corner

3. Image Structure Tensor:
   M is a $2\times$ 2 matrix
   The two eigenvalues λ_1 and λ_2 of M give information about the distribution of gradients:
   Flat region: λ_1 and λ_2 small
   Edge region: λ_1 large and λ_2 small (or swapped)
   Corner region: λ_1 and λ_1 large

4. MSER Algorithm: Apply a series of thresholds to calculate binary images. Find regions that do not vary in a large number of threshold-steps and do not change shape and size