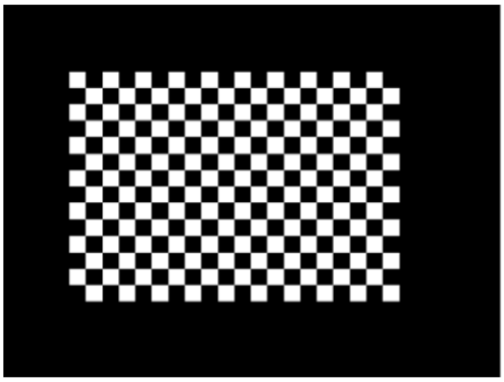
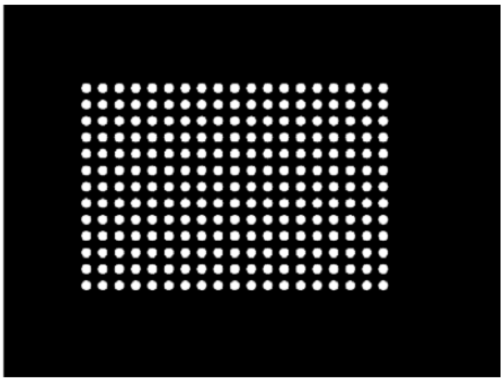
Camera Calibration

In order to identify and locate points in an image, the camera which produces the image has to be calibrated. Therefore, the *intrinsic* and *extrinsic parameters* of the camera (system) have to be determined.

1. Discuss the use of regular squares and circles as calibration patterns. Which points would you use as calibration points? How would you detect them?

2. Consider a single camera C with the following intrinsic parameters:
   - f the focal length,
   - r_x and r_y as the resolution of the camera in x and y direction,
   - c_x and c_y as the x and y coordinates of the camera central point,

   and the following extrinsic parameters:
   - $\boldsymbol{R}$ the rotation matrix of the camera to the world coordinate system, and
   - $\boldsymbol{t}$ the translation vector between the optical center of the camera and the center of the world coordinate system.

   In homogeneous coordinates the projection $\boldsymbol{p}$ of a point $\boldsymbol{P}$ onto the image plane is then computed with a projection matrix $\boldsymbol{M}$ as

   $$\boldsymbol{p} = \boldsymbol{M}\boldsymbol{P} = \boldsymbol{K}(\boldsymbol{R}\,\boldsymbol{t})\boldsymbol{P}$$

   with the intrinsic camera calibration matrix $\boldsymbol{K}$ defined as

   $$\boldsymbol{K} = \begin{pmatrix} fk_x & 0 & c_x \\ 0 & fk_y & c_y \\ 0 & 0 & 1 \end{pmatrix}$$

   (a) Which parameters can be calibrated given a plane calibration pattern?

   (b) How can they be estimated?

   (c) Which parameters cannot be calibrated? How can this problem be tackled?

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3. Consider a stereo camera system which consists of the two cameras C and C'. Analogously, C' also has a set of intrinsic parameters (f', r'_x, r'_y, c'_x, and c'_y). The relevant extrinsic parameter are now $\boldsymbol{R}$ as the rotation matrix between the both cameras and $\boldsymbol{t}$ as the translation vector between both optical centers. Point $\boldsymbol{P}$ is now projected onto $\boldsymbol{p}$ in the one camera and $\boldsymbol{p}'$ in the other camera. If $\boldsymbol{p}$ and $\boldsymbol{p}'$ represent the same point, they must lie on the same plane, i.e. the constraint

$$\boldsymbol{p}[\boldsymbol{t} \times (\boldsymbol{R}\boldsymbol{p}')] = 0$$

must hold. This can be rewritten to form the essential matrix $\boldsymbol{E}$

$$\boldsymbol{p}^\top \boldsymbol{E}\boldsymbol{p}' = 0.$$

If both cameras are not calibrated, i.e. the calibration matrices $\boldsymbol{K}$ and $\boldsymbol{K}'$ are unknown, the problem can be reformulated as

$$\boldsymbol{p}^\top (\boldsymbol{K}^\top)^{-1} \boldsymbol{E} (\boldsymbol{K}')^{-1} \boldsymbol{p}' = \boldsymbol{p}^\top \boldsymbol{F} \boldsymbol{p}' = 0$$

where $\boldsymbol{F}$ is the fundamental matrix of the stereo system.

   (a) What is the rank of $\boldsymbol{F}$?

   (b) How many points are required to compute $\boldsymbol{F}$?

   (c) How can $\boldsymbol{F}$ be estimated given a set of corresponding points?

4. Which parameters are required to calibrate a time-of-flight (TOF) system? How would you calibrate it?

5. Which parameters are required to calibrate a structured-light (e.g. KINECT) system? How would you calibrate it?

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