Robotics: Introduction to perception

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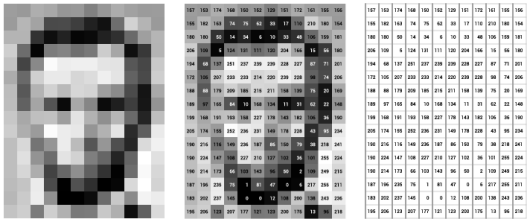
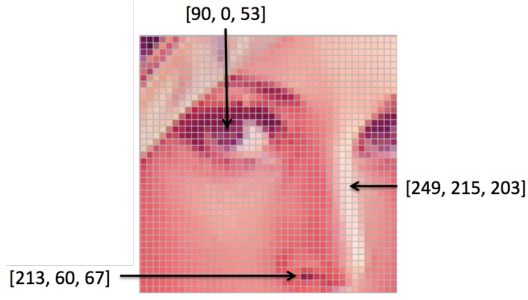
What is image?

- Camera connected to computer produces images
- Image is array of numbers[1]

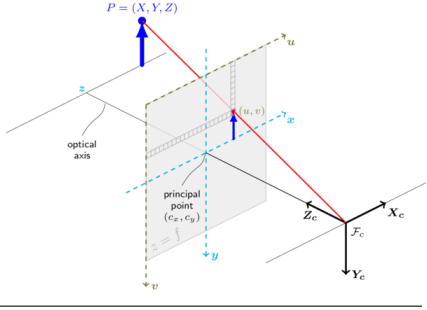


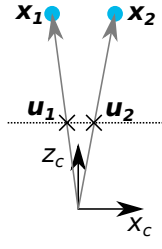


[1]Images are from: `https://ai.stanford.edu/~syyeung/cvweb/tutorial1.html`

How is the image formed?

- Perspective camera
  - pinhole camera model[2]
  - projects spatial point $\boldsymbol{x}_c$ into image point $\boldsymbol{u} = \begin{pmatrix} u & v \end{pmatrix}^\top$ by intersecting
    - image plane and
    - the line connecting $\boldsymbol{x}_c$ with the projection center
  - all points on a ray project to the same pixel





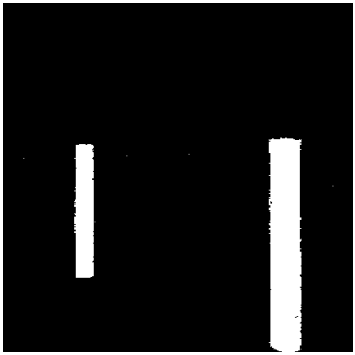
[2] `docs.opencv.org`

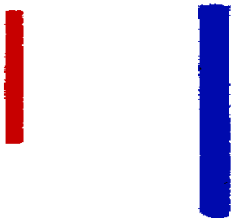
Projection of pinhole camera

- $\boldsymbol{u}_H = K\boldsymbol{x}_c$
  - $\boldsymbol{u}_H$ is pixel in homogeneous coordinates
  - if $\boldsymbol{u}_H = \begin{pmatrix} u_H & v_H & w_H \end{pmatrix}^\top$, then pixel coordinates are $\begin{pmatrix} u_H/w_H & v_H/w_H \end{pmatrix}^\top$
  - alternatively, we can represent it as: $\lambda \begin{pmatrix} u, v, 1 \end{pmatrix}^\top = K\boldsymbol{x}_c$
- K is camera matrix
  - $K = \begin{pmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{pmatrix}$
  - what does λ represent?
    - λ is non-zero real number
    - if you know λ value, you can compute Cartesian coordinate $\boldsymbol{x} = \lambda K^{-1}\boldsymbol{u}$
    - otherwise, only ray is computable
  - how to find K from points?

What we can study on images?

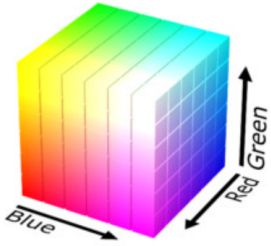
- Segmentation masks (where are the objects of interest)
- Objects classification (labeling)

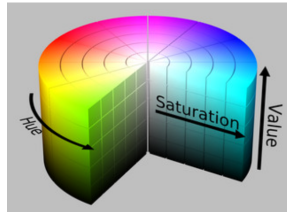




Segmentation masks - color thresholding

- Thresholding
  - RGB pixel values for coordinates $\boldsymbol{u}$: $I_{\text{RGB}}(\boldsymbol{u})$
  - $M(\boldsymbol{u}) = 1$, if $I_{\text{RGB}}(\boldsymbol{u}) = \begin{pmatrix} 0 & 255 & 0 \end{pmatrix}^\top$?
  - $M(\boldsymbol{u}) = 1$, if $\boldsymbol{\tau}_l < I_{\text{RGB}}(\boldsymbol{u}) < \boldsymbol{\tau}_u$, for all channels
  - $M(\boldsymbol{u}) = 1$, if $\boldsymbol{\varphi}_l < I_{\text{HSV}}(\boldsymbol{u}) < \boldsymbol{\varphi}_u$, for all channels
- Post-processing
  - compute connected components
  - remove small or deformed segments
  - assign label based on thresholds

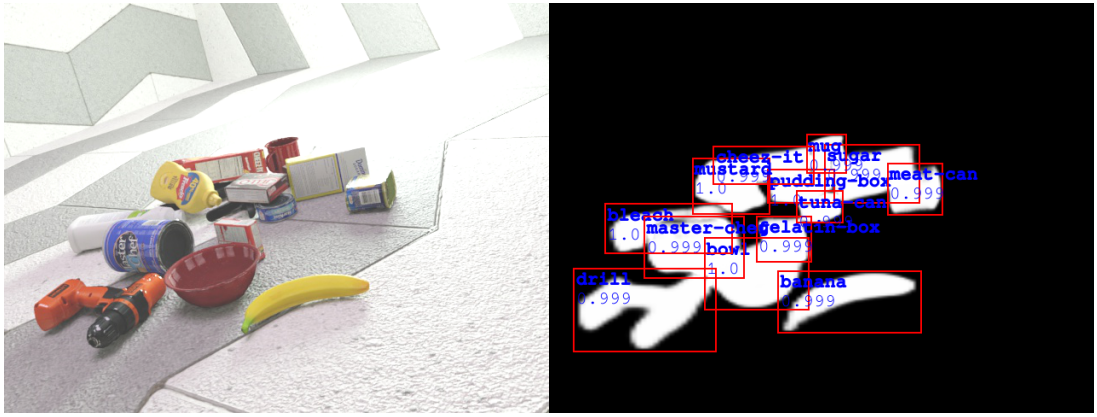




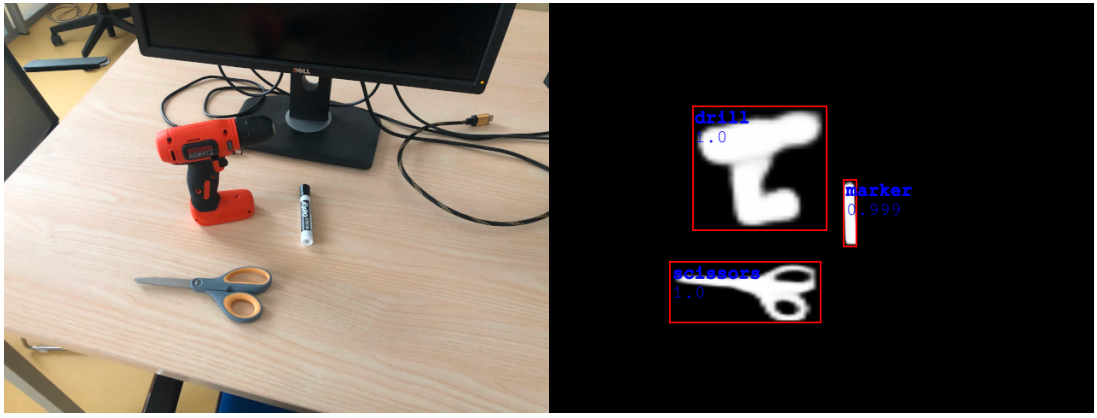
Segmentation masks for known 3D objects

- Neural Network (*e.g.* Mask R-CNN)
- Training inputs:
  - dataset of images, masks and labels, or
  - dataset of known 3D objects (meshes)
  - quality depends on the training data (augumentations)
- Inference:
  - Input: image
  - Output: segmentation mask, bounding box, label, and confidence

Mask R-CNN results

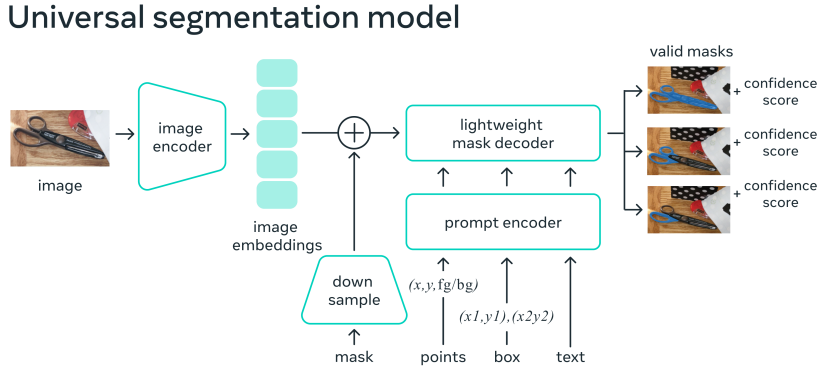


Mask R-CNN results

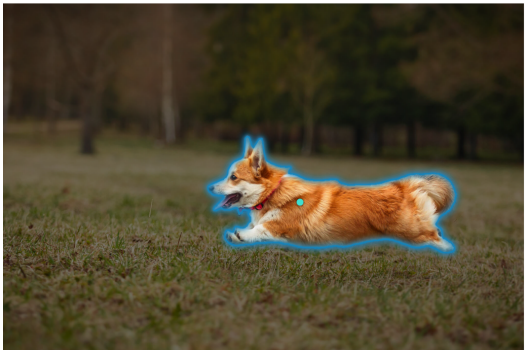


Segmentation masks without re-training

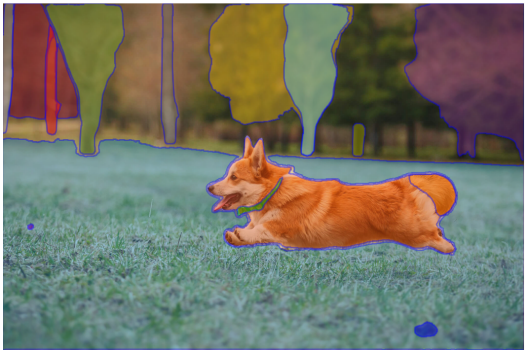
- Segment Anything Model (SAM)
  - segment any object, in any image, with a single click
  - dataset of 10M images, 1B masks



SAM results



SAM results



Segmentation

- Segmentation finds objects in image
  - segmentation mask
  - bounding box
  - label
  - confidence score
- Information only in image space
- How to use it in robot space?

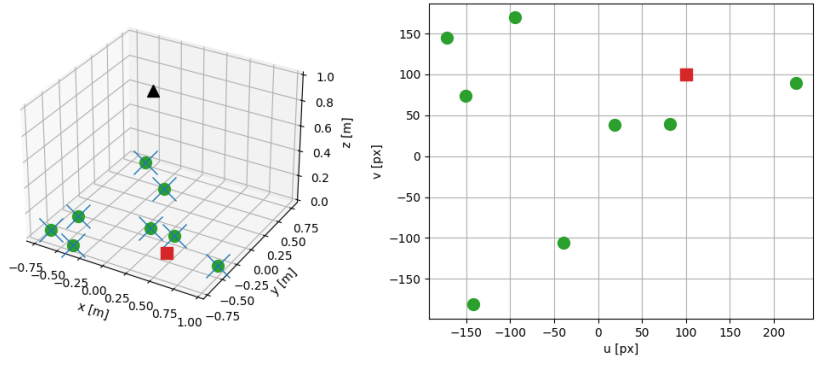
External camera

- Assume camera mounted rigidly to the reference frame
  - if we know K and T_{RC}, how to project points $\boldsymbol{x}_R$ to image?
- Unknown K and T_{RC} and planar problem
  - *e.g.* cubes with the same high on table desk
  - what is the position of cube on 2D table w.r.t. 2D image/pixels coordinates?
  - analyzed by **homography**

Homography

- Homography matrix H is 3×3 matrix that maps points from one plane to another
  - image plane to table desk
  - one image plane to another image plane (different view)
- $s \begin{pmatrix} x & y & 1 \end{pmatrix}^\top = H \begin{pmatrix} u & v & 1 \end{pmatrix}^\top$
  - x, y are coordinates in the first plane
  - u, v are coordinates in the second plane
- 9 elements but only 8 DoF, usually added constraint $h_{33} = 1$
- How to find H?
  - `H, _ = cv2.findHomography(U, X)`
  - U, X are $N \times 2$ correspondence points
  - *e.g.* measure manually
    - position of cube center w.r.t. table corner
    - position of cube center in image

Homography example

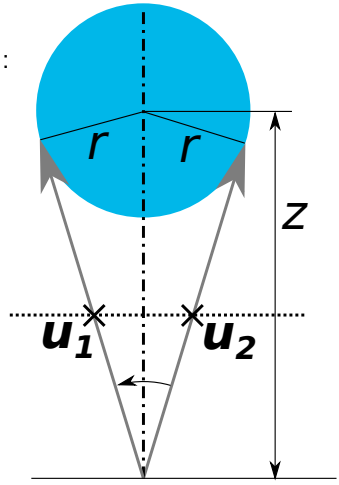


Non-planar pose estimation

- Homography maps only plane to plane
- More general object pose estimation in **camera** frame
  - get depth by mapping from area in pixels to depth for fixed size objects
  - get depth by additional scene information, *e.g.* known size/model of the objects
  - RGBD camera
  - additional markers

Using prior knowledge about size

- We know radius is fixed
- From detected pixels $\boldsymbol{u}_1, \boldsymbol{u}_2$, we can compute rays $\boldsymbol{x}_1, \boldsymbol{x}_2$: $\frac{1}{\lambda_i}\boldsymbol{x}_i = K^{-1}\boldsymbol{u}_i$
- Angle between vectors: $\cos\alpha = \frac{\frac{1}{\lambda_1\lambda_2}}{\frac{1}{\lambda_1\lambda_2}} \frac{\boldsymbol{x}_1 \cdot \boldsymbol{x}_2}{\|\boldsymbol{x}_1\|\|\boldsymbol{x}_2\|}$
- Depth: $z = \frac{r}{\sin(\alpha/2)}$

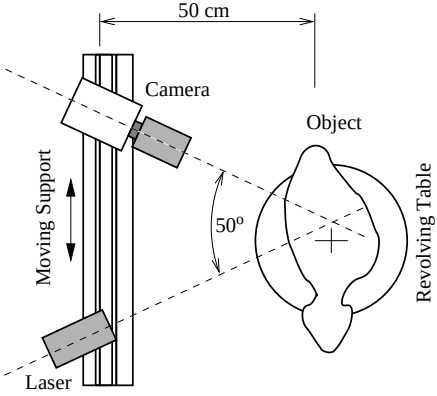


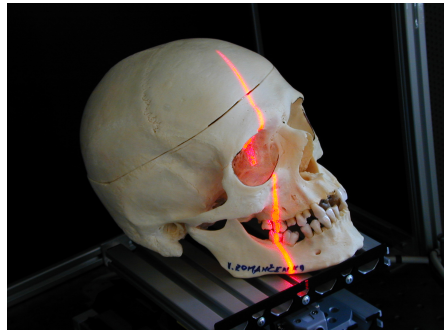
Using depth sensor

- RGB**D** sensors
  - RGB image $(H \times W \times 3)$
  - Depth map $(H \times W \times 1)$, distance in meters for each pixel
  - Structured point cloud $(H \times W \times 3)$, $\begin{pmatrix} x_c & y_c & z_c \end{pmatrix}$ for each pixel

How depth sensor works

- Laser projects pattern and camera recognizes it
- Depth information is computed using triangulation



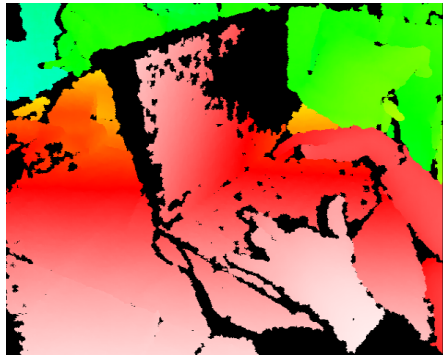


2D depth sensors

- Based on the structured light
- Projects 2D infra red patterns
- One projector and two cameras (RGB + IR)

Issues with depth sensors

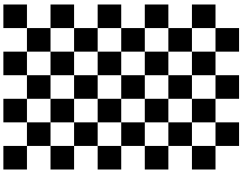
- Depth reconstruction is not perfect (black areas in the image[3])
- In python represented by NaN
- Not every pixel in RGB has reconstructed depth value
- RGB and Depth data are not aligned (you need to calibrate them)

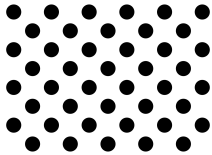


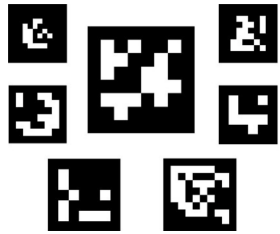
[3] https://commons.wikimedia.org, User:Kolossos

Additional markers

- Can we compute the pose of patterns[4]?
  - the size and structure needs to be known
  - subpixel accuracy
  - it has to be completely visible
- Can we compute the pose of ArUco markers?
  - less accurate than regular patterns
  - provides marker id and the pose
  - it has to be completely visible

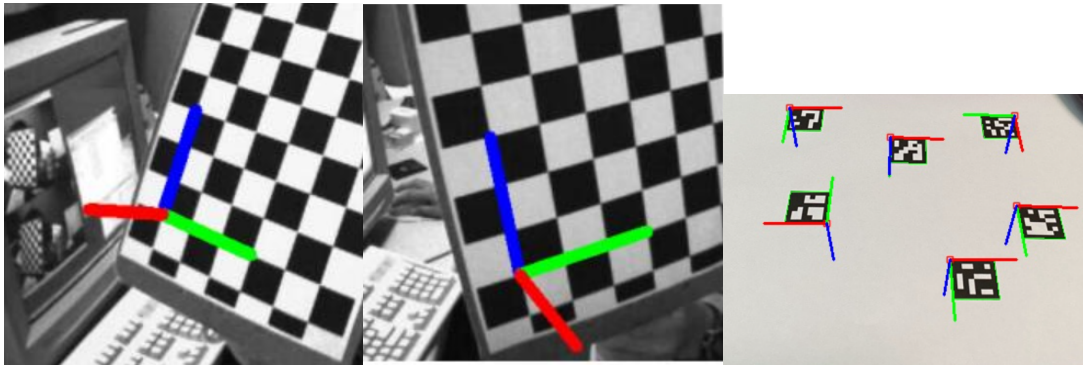






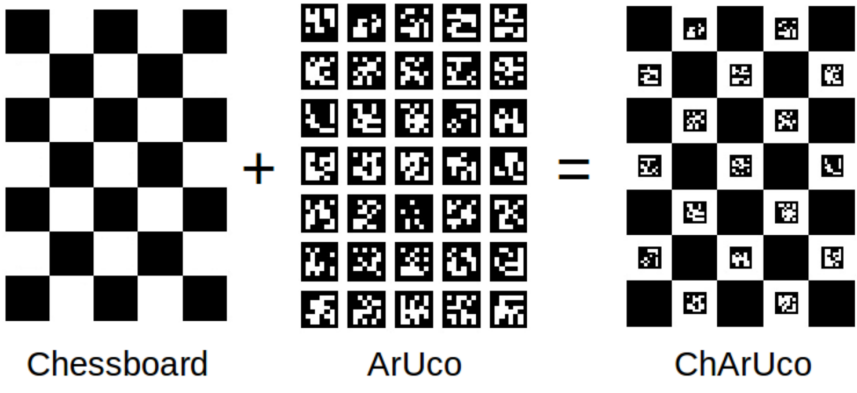
[4] `docs.opencv.org`

Markers pose example



ChArUco board for calibration

- Combines accuracy of pattern with detections of ArUco
- Partial visibility detections



Charuco definition

Camera matrix estimation with boards

- We can estimate camera matrix from correspondences in image space and spatial space
  - collect images of the board from different views
  - detect boards
  - compute correspondences between image points and board frame points
  - ```
    _, K, dist_coeffs, rvecs, tvecs = cv2.calibrateCamera(
        obj_points, img_points, img_shape)
    ```
- In addition we get
  - distortion coefficients that compensates defects of objective

    ```
    Knew, roi = cv.getOptimalNewCameraMatrix(K, dist_coeffs,
        img_shape, 1, img_shape)
    img_undistorted = cv.undistort(img, K, dist_coeffs, None, Knew)
    ```
  - $SE(3)$ poses of boards in camera frame
    ```

Pose estimation from RGB(D)

- Pose estimation methods
  - use prior knowledge about the task, *e.g.* fixed height objects on a plane
  - use prior knowledge about the objects (size)
  - use depth sensor
  - use ArUco markers
- Where is robot?
  - homography estimates poses of objects w.r.t. plane frame
  - other methods estimate poses in camera frame
  - we need to estimate/calibrate T_{RC}

HandEye calibration

- Camera can be mounted w.r.t.
  - robot base frame (eye-to-hand calibration)
  - gripper frame (eye-in-hand calibration)
- Solve $A^i X = Y B^i$
  - measurements: $A^i, B^i \in SE(3)$
  - estimated parameters: $X, Y \in SE(3)$
- `X, Y = calibrateRobotWorldHandEye(A, B)`
- Eye-to-hand calibration
  - $A^i = T^i_{\mathsf{RG}}$
  - $B^i = T^i_{\mathsf{CT}}$
  - $X = T_{\mathsf{GT}}$
  - $Y = T_{\mathsf{RC}}$
- Eye-in-hand calibration
  - $A^i = T^i_{\mathsf{CT}}$
  - $B^i = T^i_{\mathsf{GR}}$
  - $X = T_{\mathsf{TR}}$
  - $Y = T_{\mathsf{CG}}$

Summary

- Image representation
- Projection to/from image
- Segmentation in image space
- Homography
- Pose estimation from image
- Camera calibration

Laboratory

- No new homework this week
- Homography estimation on toy example in Python/OpenCV
- HandEye calibration on toy example in Python/OpenCV