Robot's perception in natural interaction skills learning

Bozorgmehr Aminian

Idiap

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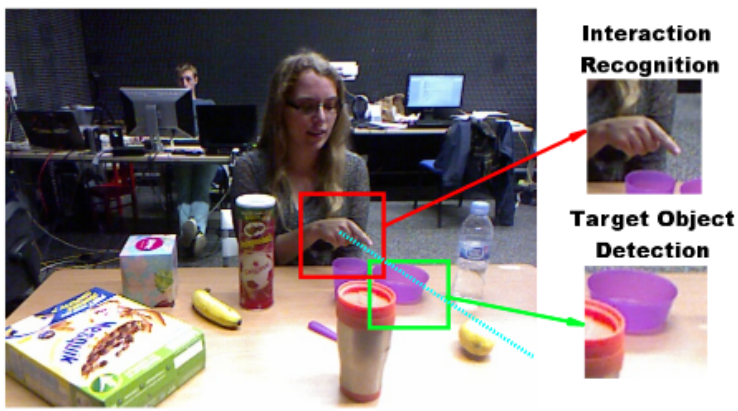
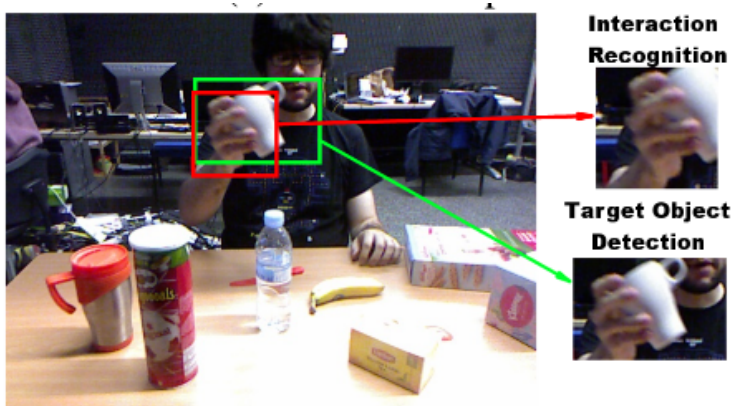
Provides the required measurements about :

- People
- Scene object
- Gestures
- Verbal and non-verbal communication



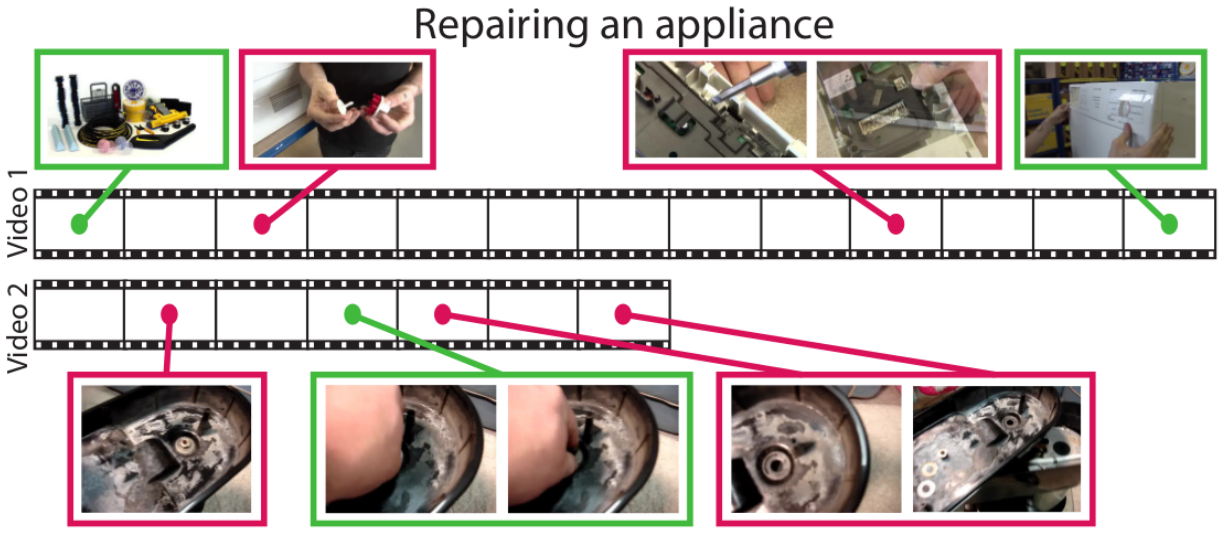
(a) Point Example

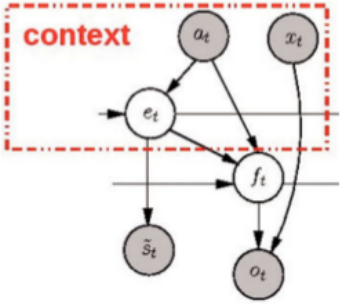


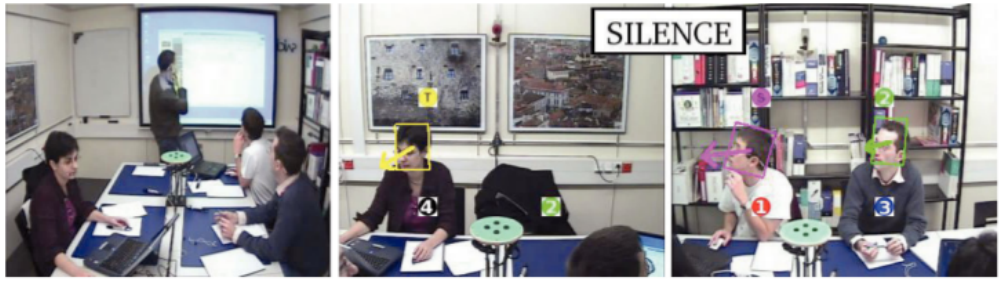
(b) Show Example

Understanding of the teacher's natural behavior :

- Segmentation (start, end, reference-action sequence)
- Attention (person/object of interest)
- Feedback (positive/negative, interruption)





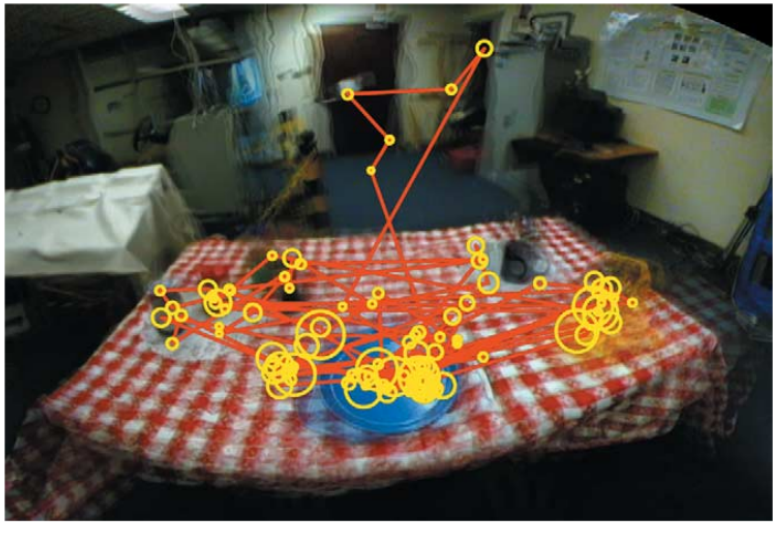


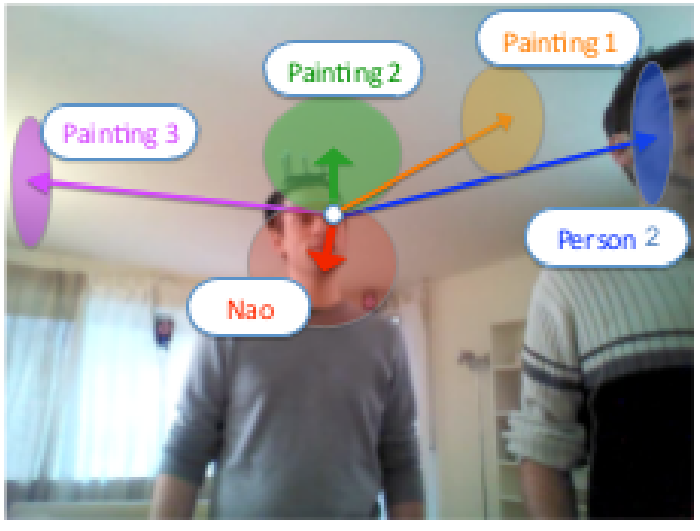
Use sensors in a every day's life framework (natural behavior) :

- RGB camera
- Depth sensor (kinect v2)
- Microphone

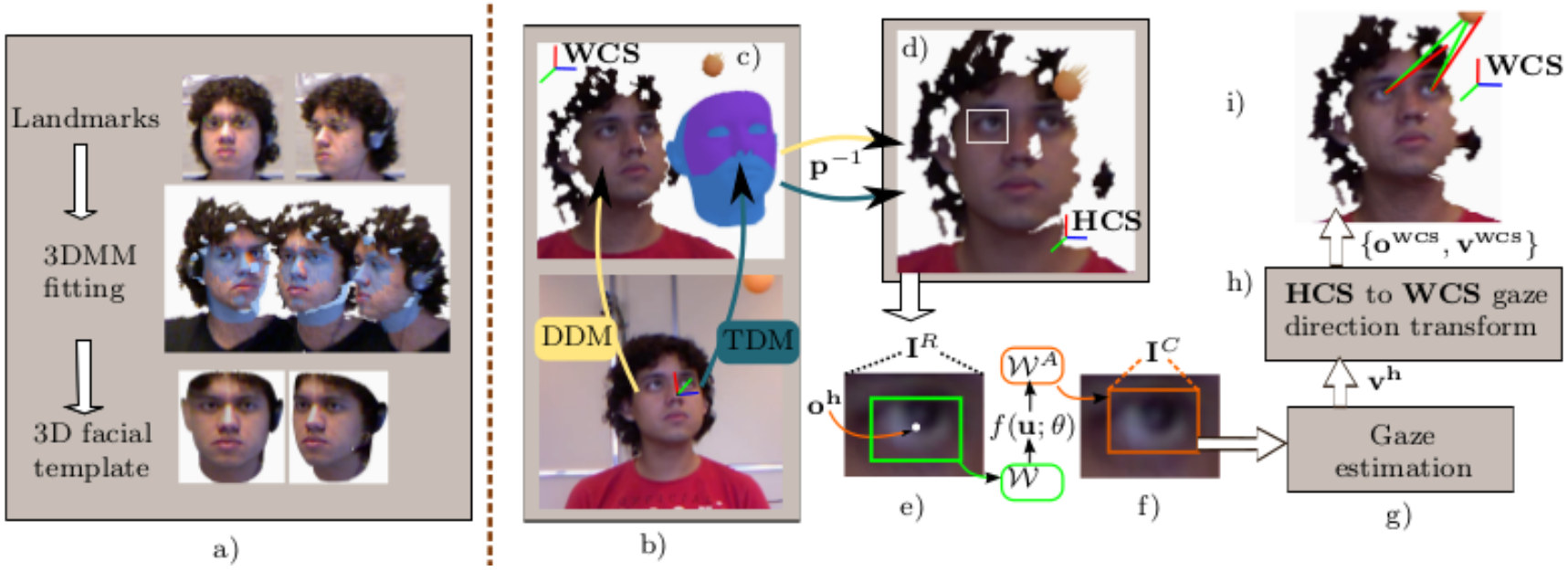
Gaze tracking and attention modeling :

- Unsupervised gaze calibration
  - Head tracker (3DMM, ICP).
  - Gaze tracker (G3E, kNN, H-SVR, R-SVR).
  - Gaze calibration (interaction prior based, LSMed).
- Contextual interaction models for gaze activity interpretation (VFOA)





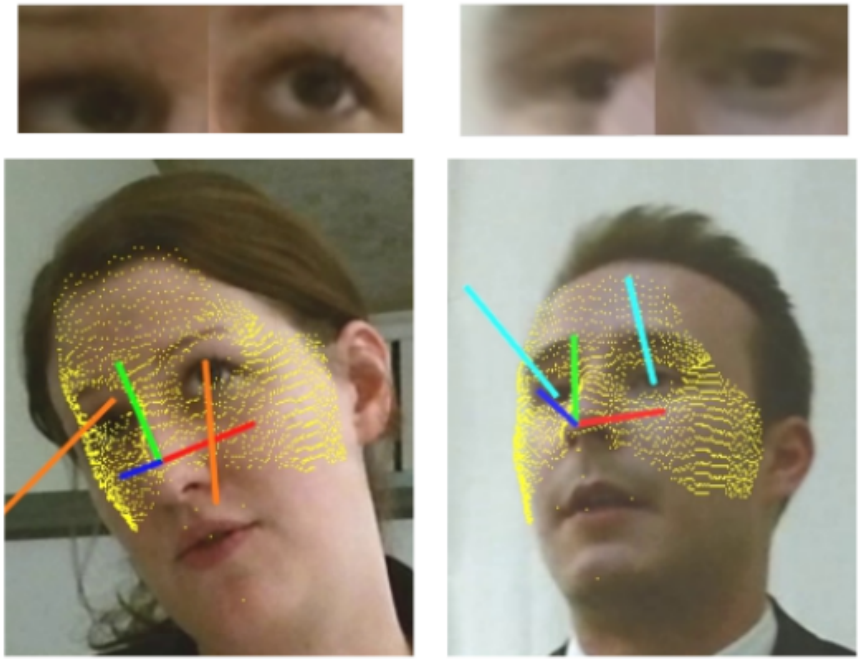
Gaze Tracker

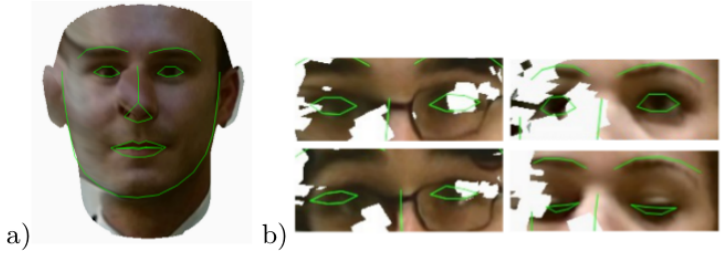


Gaze Tracker

Wrong Head pose
⇒ Wrong cropping

Correct Head pose
⇒ Correct cropping

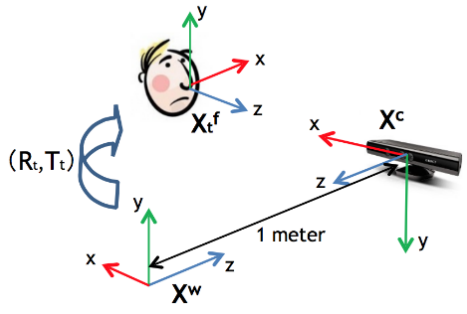


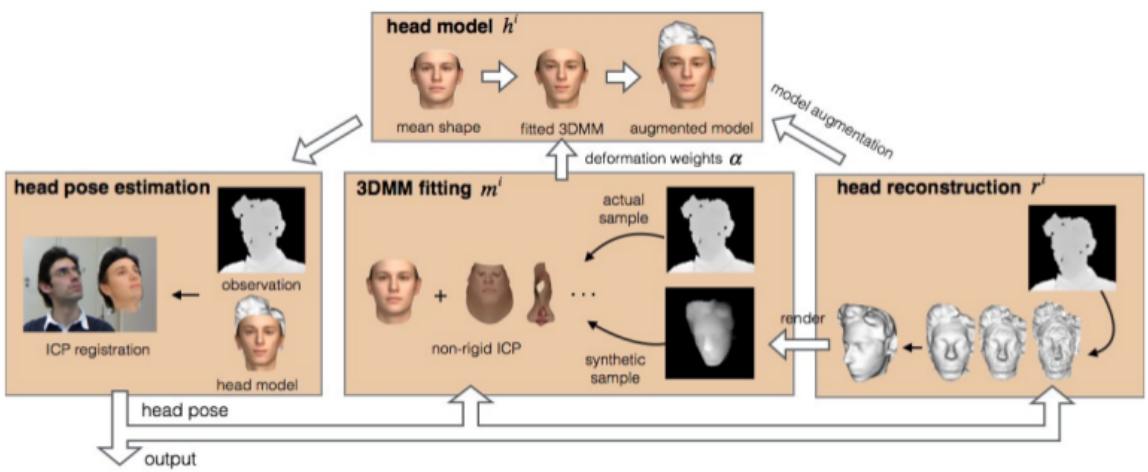


Head Pose :

Rotation matrix $R_t \in SO(3)$, $T_t \in \mathbb{R}^3$ vector at time $t \in \mathbb{R}$. The head pose is defined by

$$p_t := (R_t, T_t) \tag{1}$$

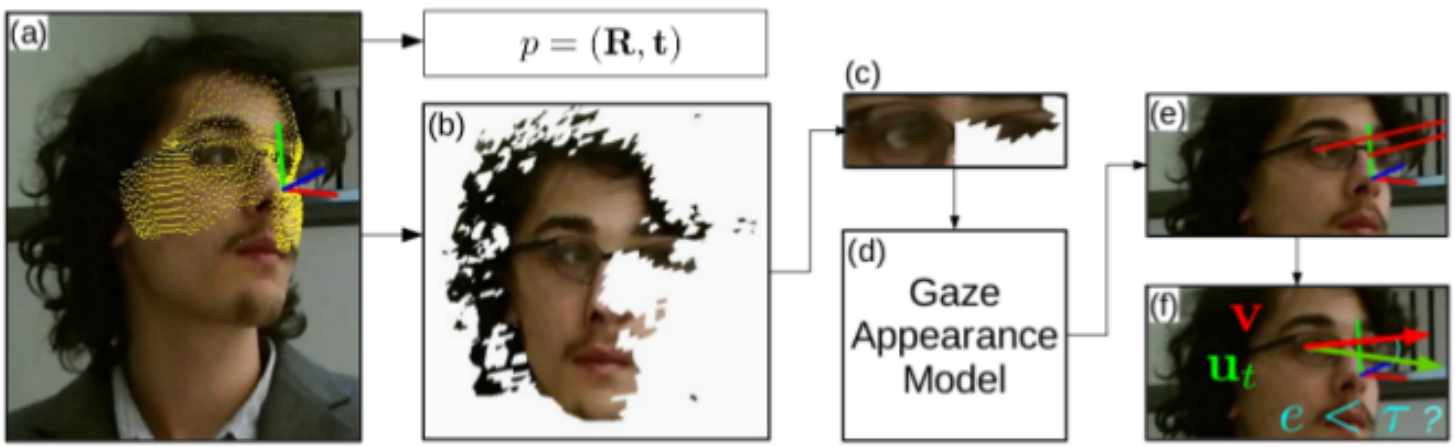




Eye Center :
Coordinate of the eye center $o_t \in \mathbb{R}^3$.

Gaze Direction :
Tilt angle $\phi_t \in [-\pi/2, \pi/2]$ and pan angle $\theta_t \in [-\pi/2, \pi/2]$ at time t in a *head coordinate system*. The gaze direction is defined by

$$g_t = (\phi_t, \theta_t) \tag{2}$$



Unitary Gaze Direction Vector :
There exists a mapping $\Phi : \mathbb{R}^2 \to \mathbb{R}^3$ such that the unitary gaze direction vector is given by

$$\Phi(g_t) = v_t, \ \forall t \in \mathbb{R}. \tag{3}$$

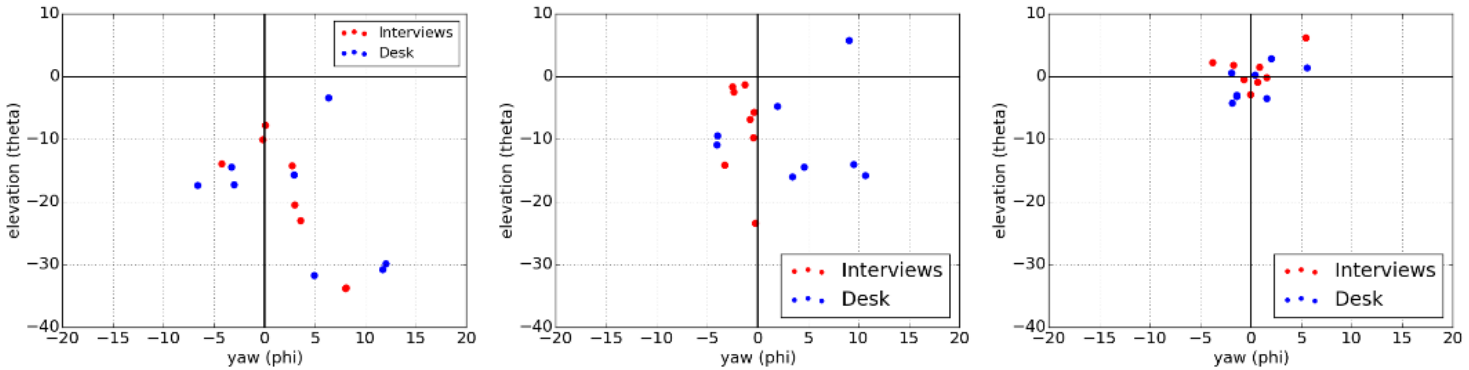
Ground Truth :
For an object coordinate $x \in \mathbb{R}^3$. The ground truth is defined by

$$\bar{v}_t = \frac{x - o_t}{\|x - o_t\|} \text{ and } \bar{g}_t = \Phi^{-1}(\bar{v}_t) \tag{4}$$

Gaze Calibration

For a set of parameters $\alpha = \{\alpha_1, ..., \alpha_k\}$. The gaze calibration consists in the optimization problem

$$\text{minimize } \|G(p_t, g_t; \alpha) - \bar{g}_t\| \text{ for } t \in \mathbb{R}. \tag{5}$$



(a) *Baseline* (b) *Lm* (c) *Lm + Spk-Med*

Gaze Calibration Experiment :

Forward kinematics :
For $\theta \in \mathbb{R}^k$, define $X : \mathbb{R}^k \to \mathbb{R}^n$ such that

$$X = X(\theta). \tag{6}$$

Inverse kinematics :
For $Y \in \mathbb{R}^n$, find $\theta \in \mathbb{R}^k$ such that

$$X(\theta) - Y = 0 \tag{7}$$

- Cost function :

$$E(\theta) = \frac{1}{2}\|X(\theta) - Y\|^2 \tag{8}$$

- Gradient :

$$\begin{aligned}\frac{\partial E}{\partial \theta}(\theta) &= (X(\theta) - Y)^T \frac{\partial X}{\partial \theta}(\theta) \\ &= (X(\theta) - Y)^T J \\ &=: d\theta\end{aligned}$$

- Update rule

$$\theta^{m+1} = \theta^m - \eta d\theta^m \tag{9}$$

- Constraints :

$$\theta^- \preceq \theta \preceq \theta^+ \tag{10}$$

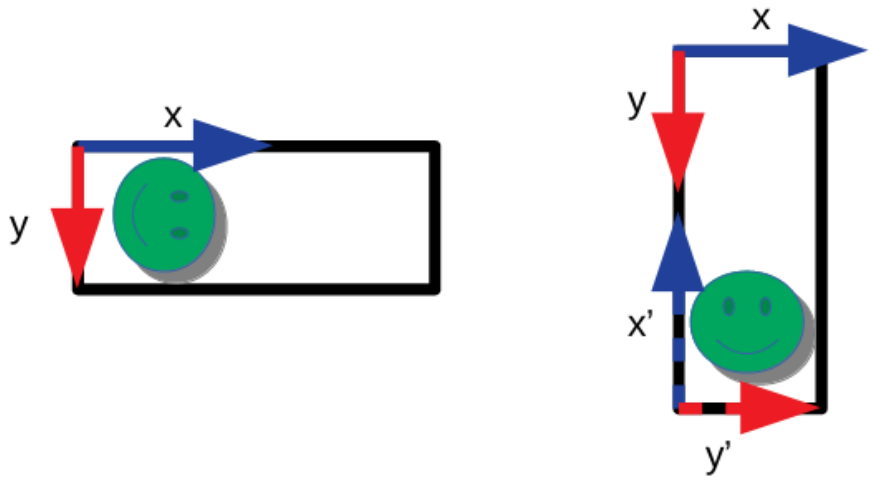
- Indicator : for $i = 1, ..., k$,

$$[\mathrm{Idc}(\theta)]_i = \mathbb{1}_{\{\theta_i^- \leq \theta_i \leq \theta_i^+\}^c} = \begin{cases} 0 & \text{if } \theta_i^- \leq \theta_i \leq \theta_i^+, \\ 1 & \text{otherwise.} \end{cases} \tag{11}$$

- Update rule (identity matrix $I_k \in \mathbb{R}^{k \times k}$)

$$\theta^{m+1} = \theta^m - (\eta I_k - \lambda \mathrm{diag}(\mathrm{Idc}(\theta^m)))d\theta^m, \ \lambda \geq \eta. \tag{12}$$

Camera rotation :



$$x' = -y \text{ and } y' = x \tag{13}$$

Hence

$$P = \begin{pmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{14}$$

Camera intrinsic :

- Camera matrix :

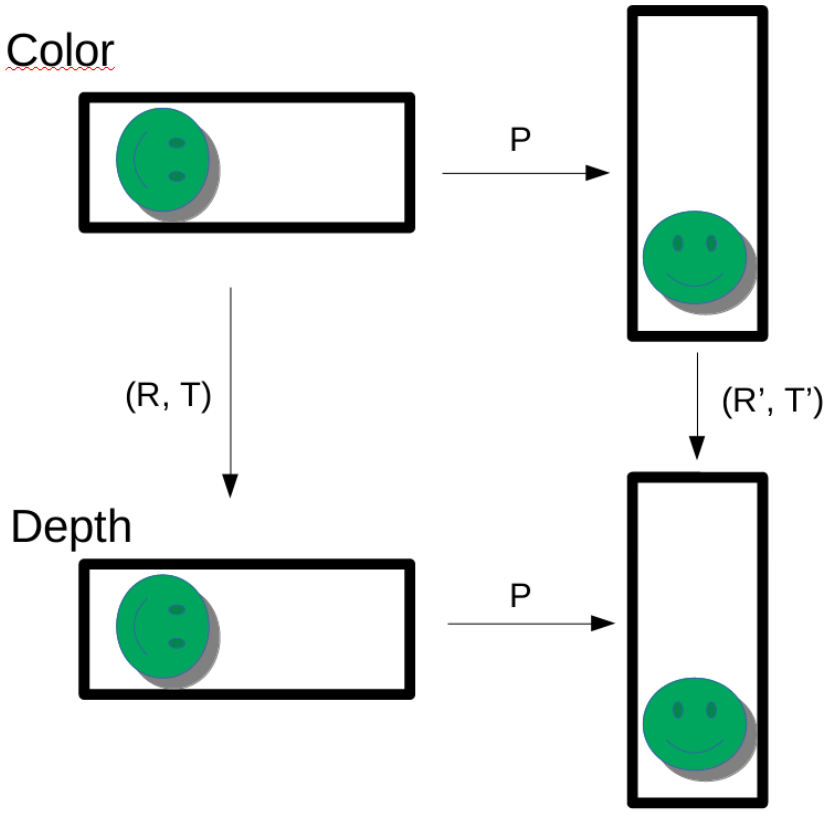
$$K = \begin{pmatrix} f_x & 0 & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{pmatrix}. \tag{15}$$

- After rotation :

$$K' = \begin{pmatrix} f_y & 0 & c_y \\ 0 & f_x & s_x - c_x \\ 0 & 0 & 1 \end{pmatrix} \tag{16}$$

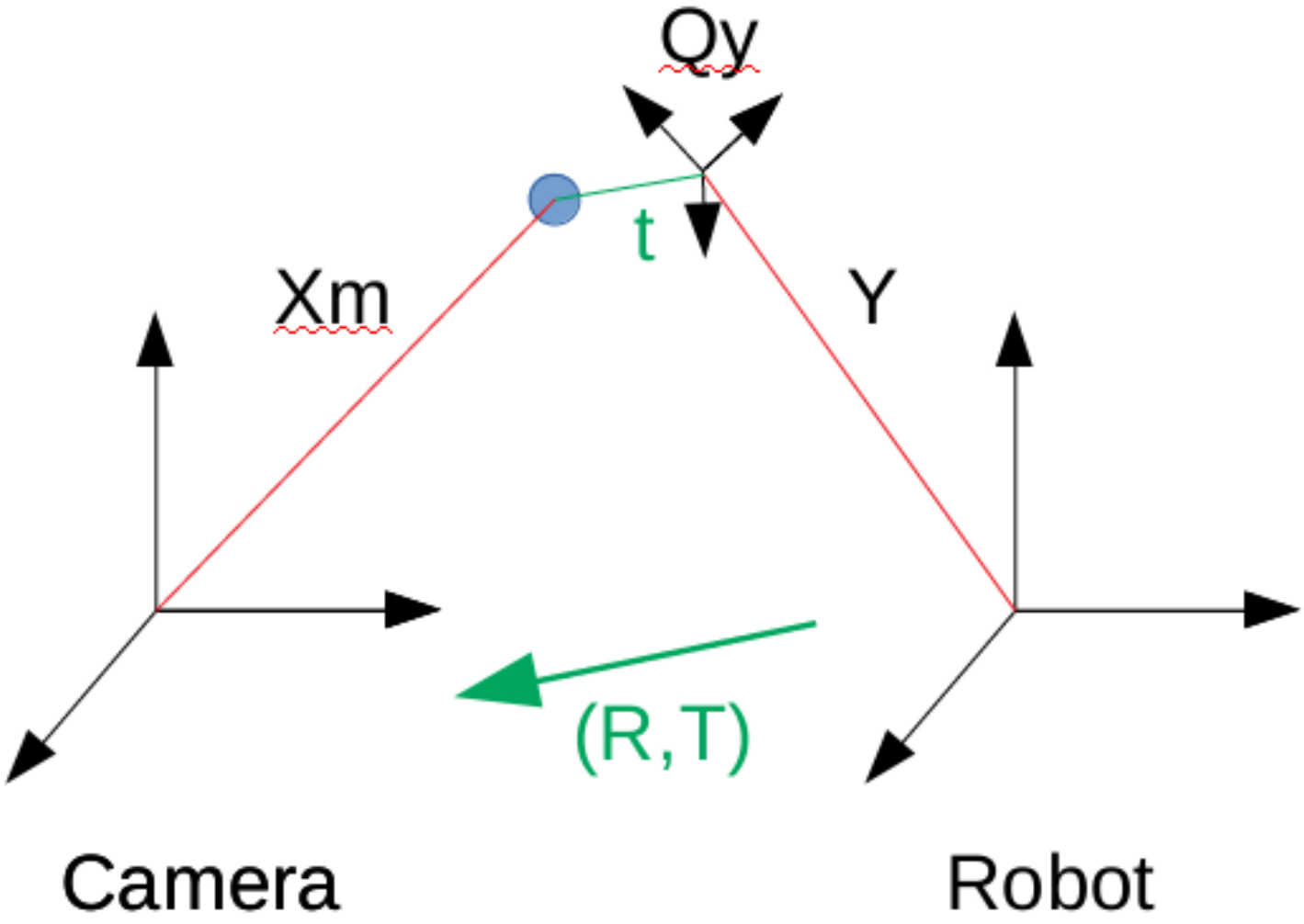
where (s_x, s_y) is the size of the original image.

Camera extrinsic :



$$R' = PRP^{-1} \text{ and } T' = PT \tag{17}$$

Robot-camera calibration



- $\mathcal{F}_X$ $\mathcal{F}_Y$: camera frame, resp. robot frame.
- X, Y : coordinate of the end-effector in $\mathcal{F}_X$, resp. in $\mathcal{F}_Y$.
- X_m Y_m : coordinate of the marker in $\mathcal{F}_X$, resp. in $\mathcal{F}_Y$.
- $\mathcal{F}_{Q_Y}$: end-effector frame.
- t : coordinate of the marker in $\mathcal{F}_{Q_Y}$.
- $Q_Y \in \mathbb{R}^{3\times3}$: basis vector of the frame $\mathcal{F}_{Q_Y}$ expressed in frame $\mathcal{F}_Y$. It corresponds to the rotation matrix from $\mathcal{F}_Y$ to $\mathcal{F}_{Q_Y}$.

- Known data (n images) : $X_m = \{X_m^i\}_{i=1}^n$, $Y = \{Y^i\}_{i=1}^n$ and $Q_Y = \{Q_Y^i\}_{i=1}^n$.
- Unknowns : rigid transform (R, T) from $\mathcal{F}_Y$ to $\mathcal{F}_X$ and vector $t \in \mathbb{R}^3$:

$$RY + T = X \text{ and } RY_m + T = X_m \tag{18}$$

- Remark :
  - $R = R_\gamma R_\beta R_\alpha$ where (α, β, γ) are Euler angles.
  - $Q_Y = Q_Y(q_Y)$ where q_Y is the quaternion coordinates of the orientation of the end-effector in $\mathcal{F}_Y$.

- Solve for images $i = 1, ..., n$:

$$R\left(Y^i + Q_Y^i t\right) + T = X_m^i \tag{19}$$

- Substract mean :

$$R\left(\bar{Y}^i + \bar{Q}_Y^i t\right) = \bar{X}_m^i \tag{20}$$

where

$$\bar{Y}^i = \left(Y^i - \frac{1}{n}\sum_{k=1}^{n} Y^i\right), \ \bar{Q}_Y^i = \left(Q_Y^i - \frac{1}{n}\sum_{k=1}^{n} Q_Y^i\right)$$

$$\bar{X}_m^i = \left(X_m^i - \frac{1}{n}\sum_{k=1}^{n} X_m^i\right)$$

- Cost function :

$$E(\alpha, \beta, \gamma, t) = \frac{1}{2}\sum_{i=1}^{n} \left\| R\left(\bar{Y}^i + \bar{Q}_Y^i t\right) - \bar{X}_m^i \right\|^2 \tag{21}$$

Procrustes problem :
For $X,\ Y \in \mathbb{R}^{3\times N}$

$$R = \underset{\Omega}{\operatorname{argmin}} \|\Omega X - Y\| \text{ subject to } \Omega^T\Omega = I \tag{22}$$

Procrustes solution :
For $M := YX^T = U\Sigma V^T$ a singular value decomposition (SVD), then

$$R = UV^T. \tag{23}$$

Synchronize robot and camera time :

- Robot has its own time.
- Camera's time is computer time (- latency)
- Set robot's time to computer time (latency is small for robot topics).

Output of perception :

- Task
  - Make a cup of tea (intelligent robot)
  - This is a cup (idiot robot but may improve !)
  - Take the cup in front. Take the kettle. Pour the cup.
- Interraction
  - What is a cup ?
  - How to grasp it ?
  - Where is the cup ?
  - Non-verbal communication from the robot (gaze, legible motion)

Input of perception :

- Object
  - Detection (ID)
  - Recognition (name)
  - Position/Orientation
  - Affordance
  - Color
  - ...
- Posture
  - Tronc
  - Hands (and gesture)
  - Arms
  - Head pose
- Verbal and non-verbal communication
  - Speech
  - Gaze
  - Emotion

Actual Work :

- Gaze classification (Rémy, 1 papers)
- Gaze as prior for task recognition (2 papers)
- Unsupervised gaze calibration
- Design of experiment
  - House benchmark
  - Work benchmark
- Building machines that learn and think like people