i3PosNet: instrument pose estimation from X-Ray in temporal bone surgery

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Learning for X

Application/ Domain ← → **Learning**

Dataset
(x, y)

Mathematical Model
f: Model function

Parameters & Training
ω

Augmentation

Architecture

Optimization

Loss

Regularization

Problem Design

Hyperparameter

Learning for CAI

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Bedside Application

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Surgical Outcome

Clinical Implementation

Augmentation

Surgeon Interaction

Evaluation

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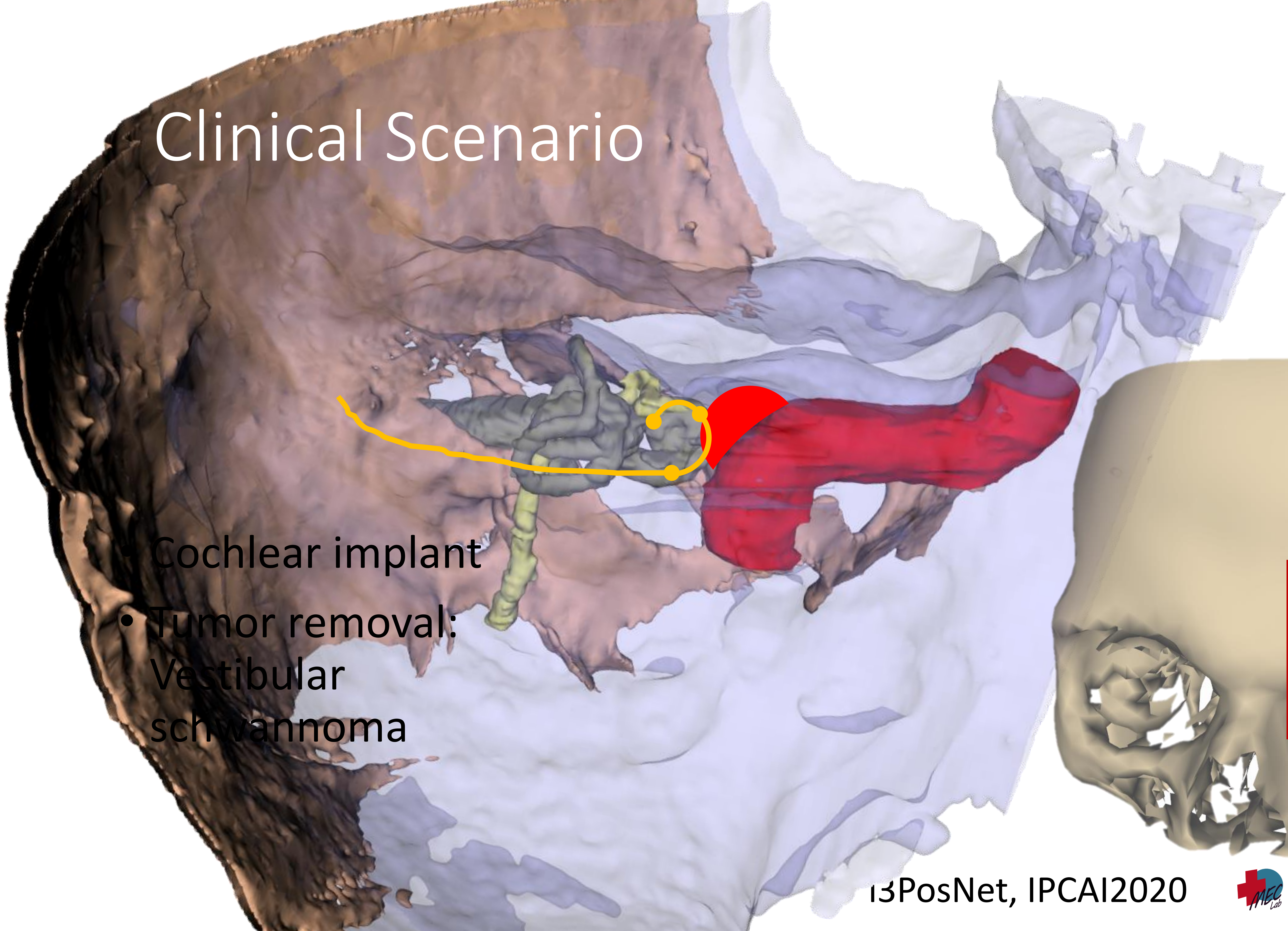
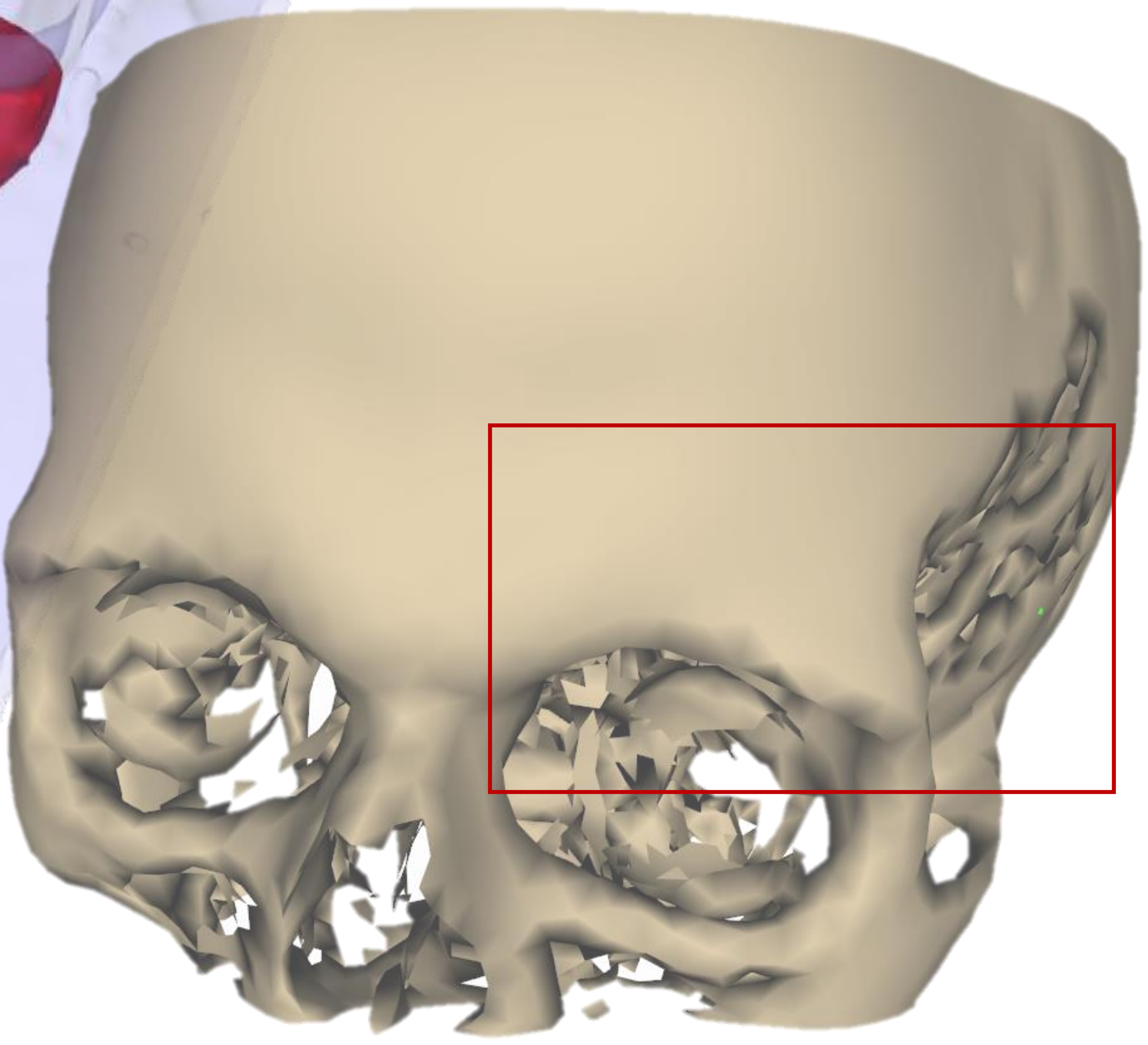
Clinical Scenario



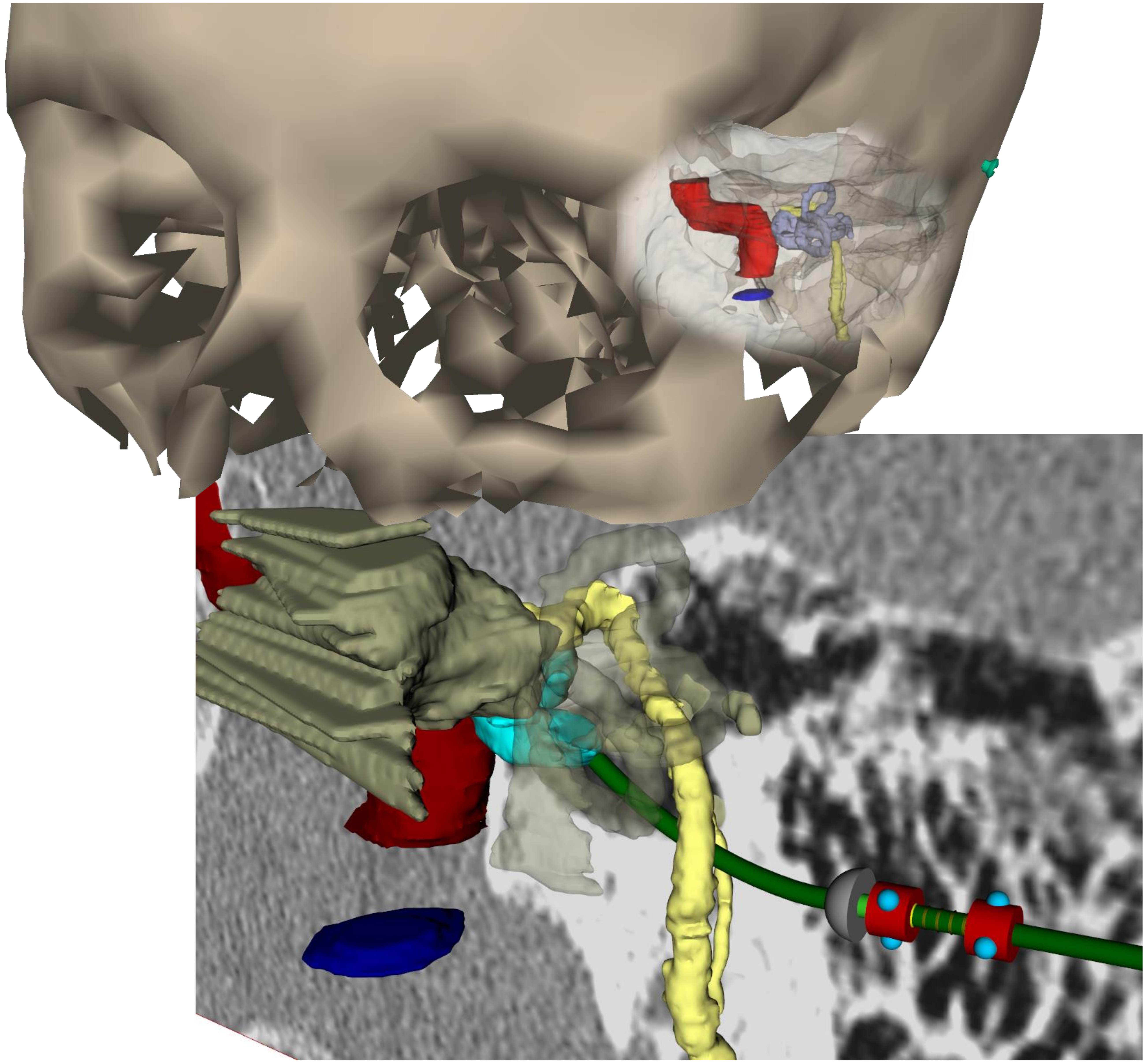
- Cochlear implant
- Tumor removal: Vestibular schwannoma



Workflow

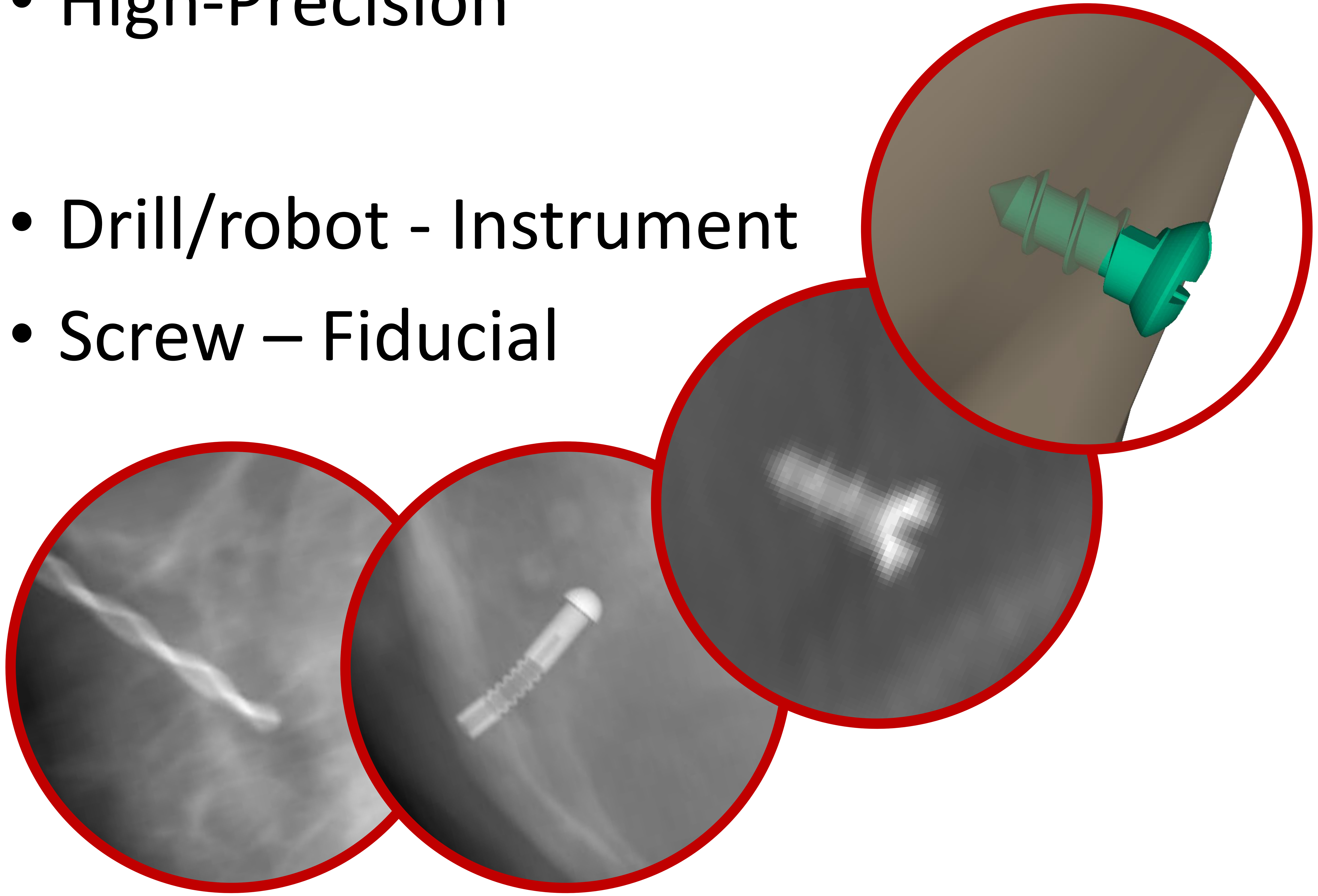
Imaging & Planning - Pose Estimation / Tracking - Navigation

Temporal bone surgery



- Minimally-Invasive
- High-Precision

- Drill/robot - Instrument
- Screw – Fiducial



i3PosNet, IPCAI2020

AI-readiness of CAI

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Images

Problem Design

Hyperparameter

Evaluation

Generating a CAI Dataset

Images/Annotation - Augmentation - Problem Design

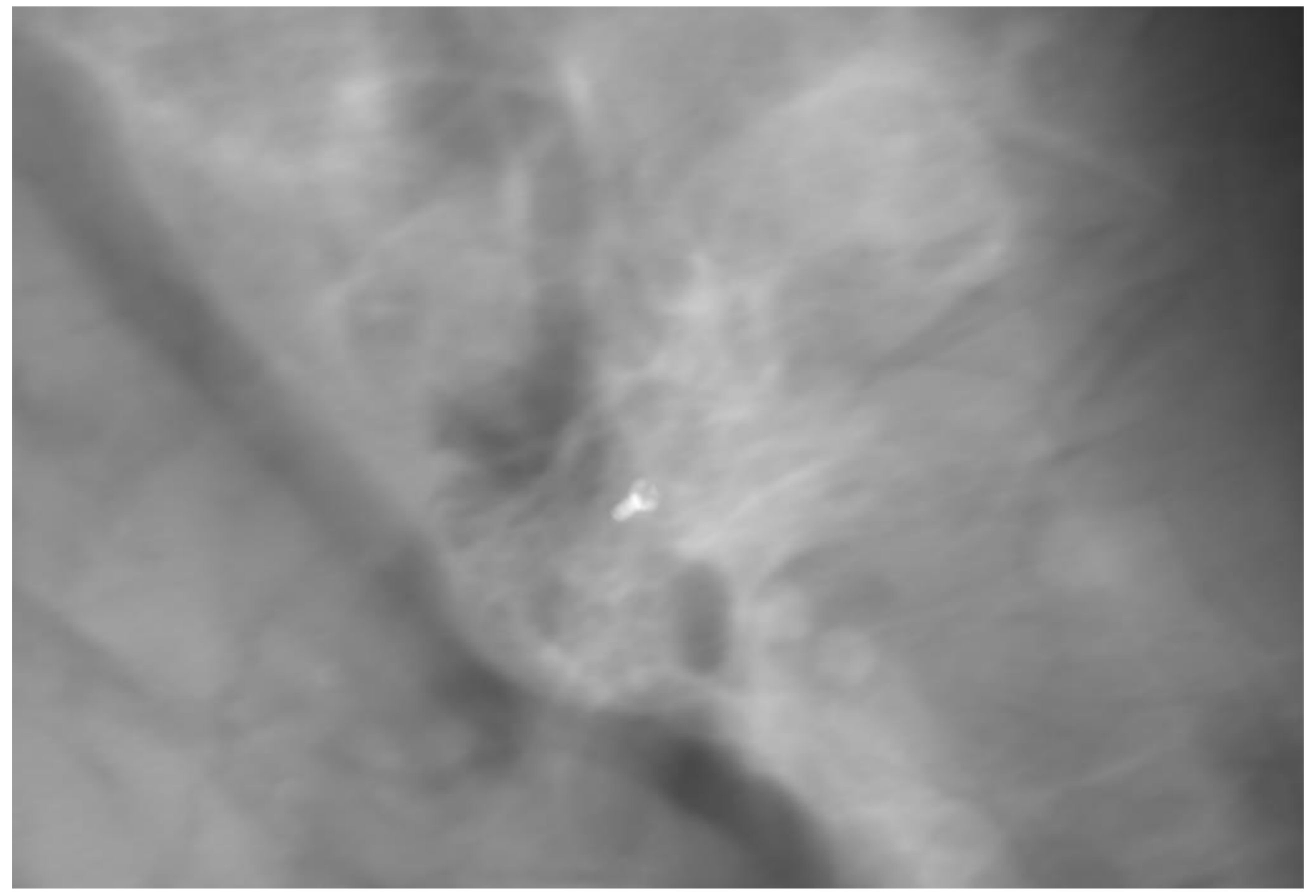
Dataset

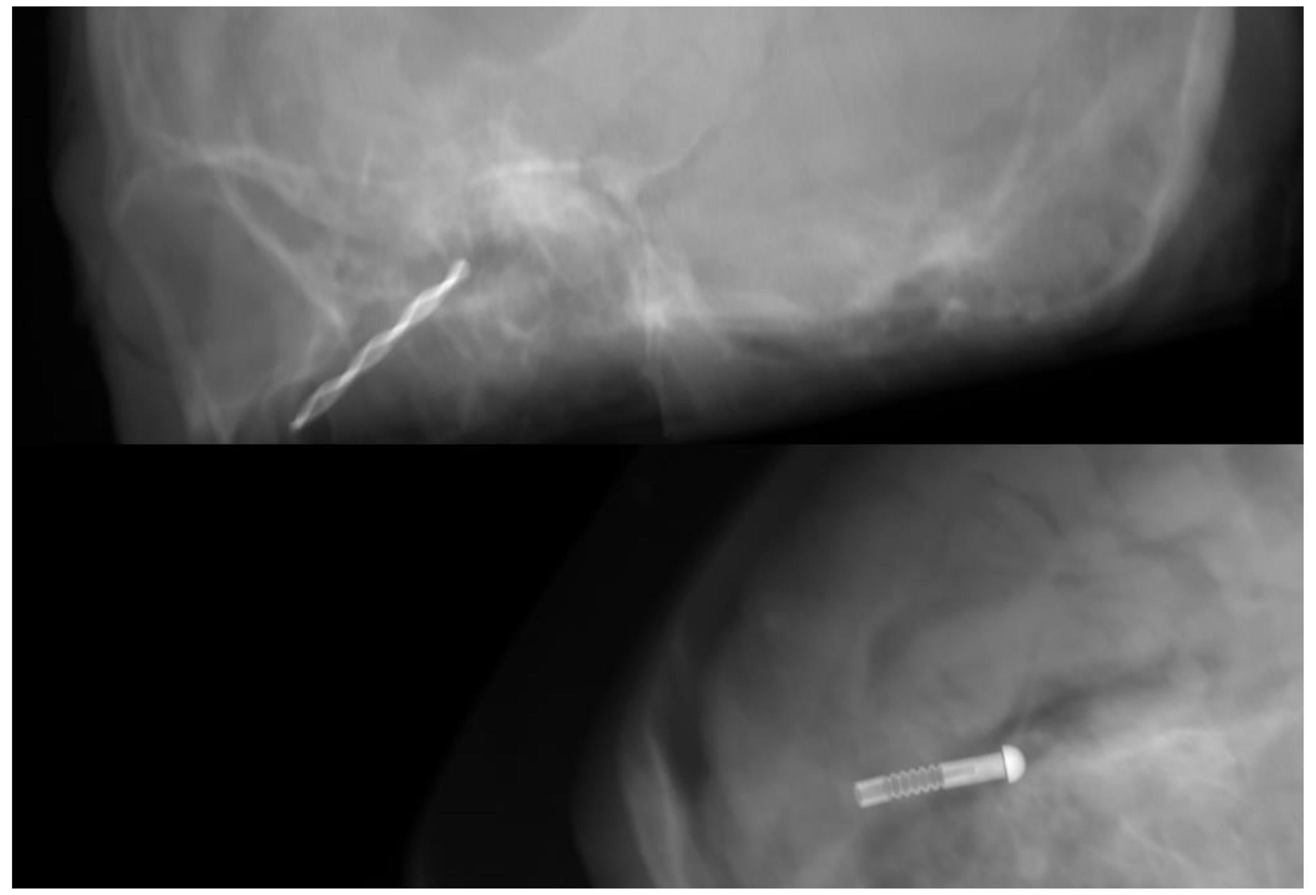
https://i3posnet.david-kuegler.de/

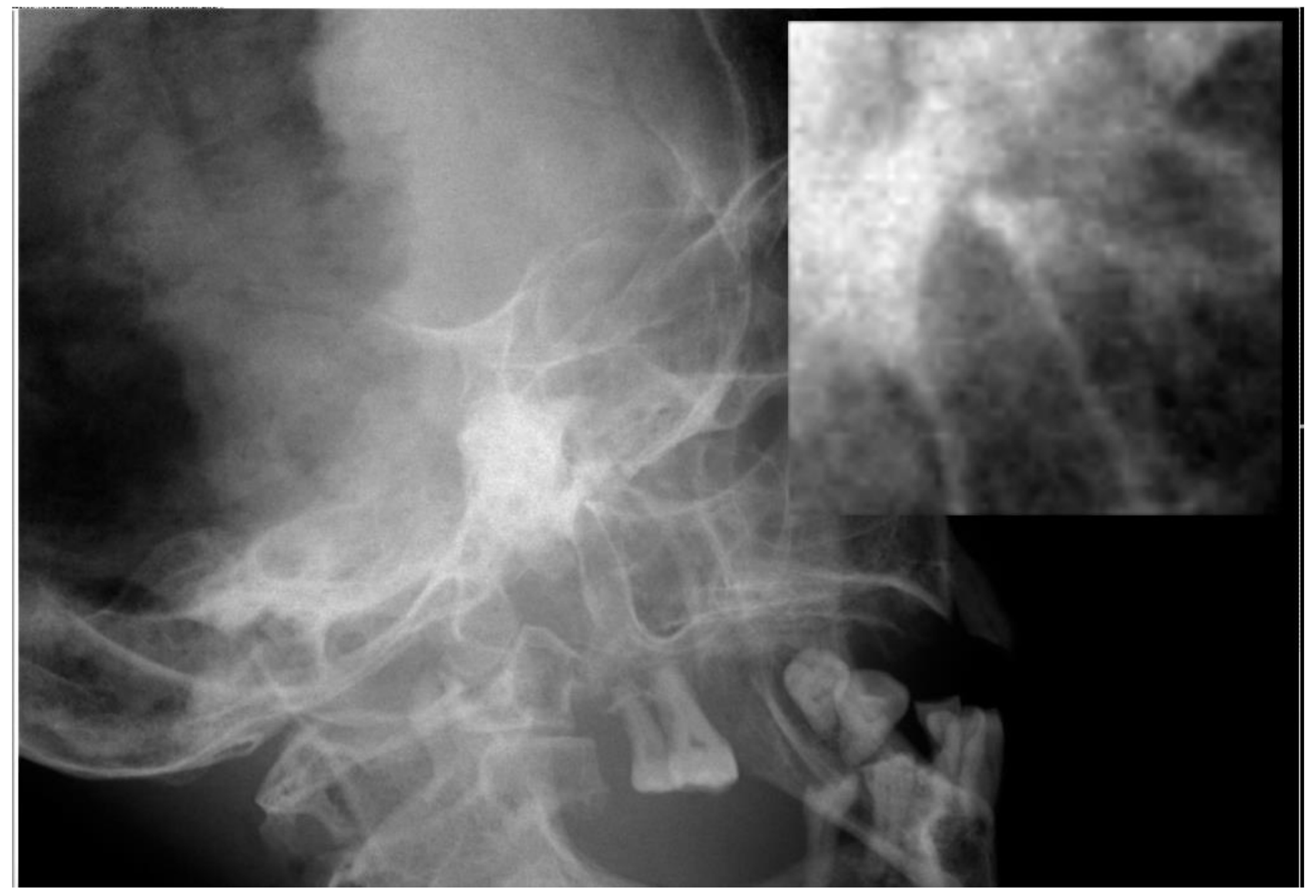
Synthetic Images (DRR)

Real X-ray

Dataset A	Dataset B	Dataset C
• Screw	• Robot and drill	• Screw
• Geometric annotation		• Manual annotation
• 18k images	• 2x 18k images	• 540 images

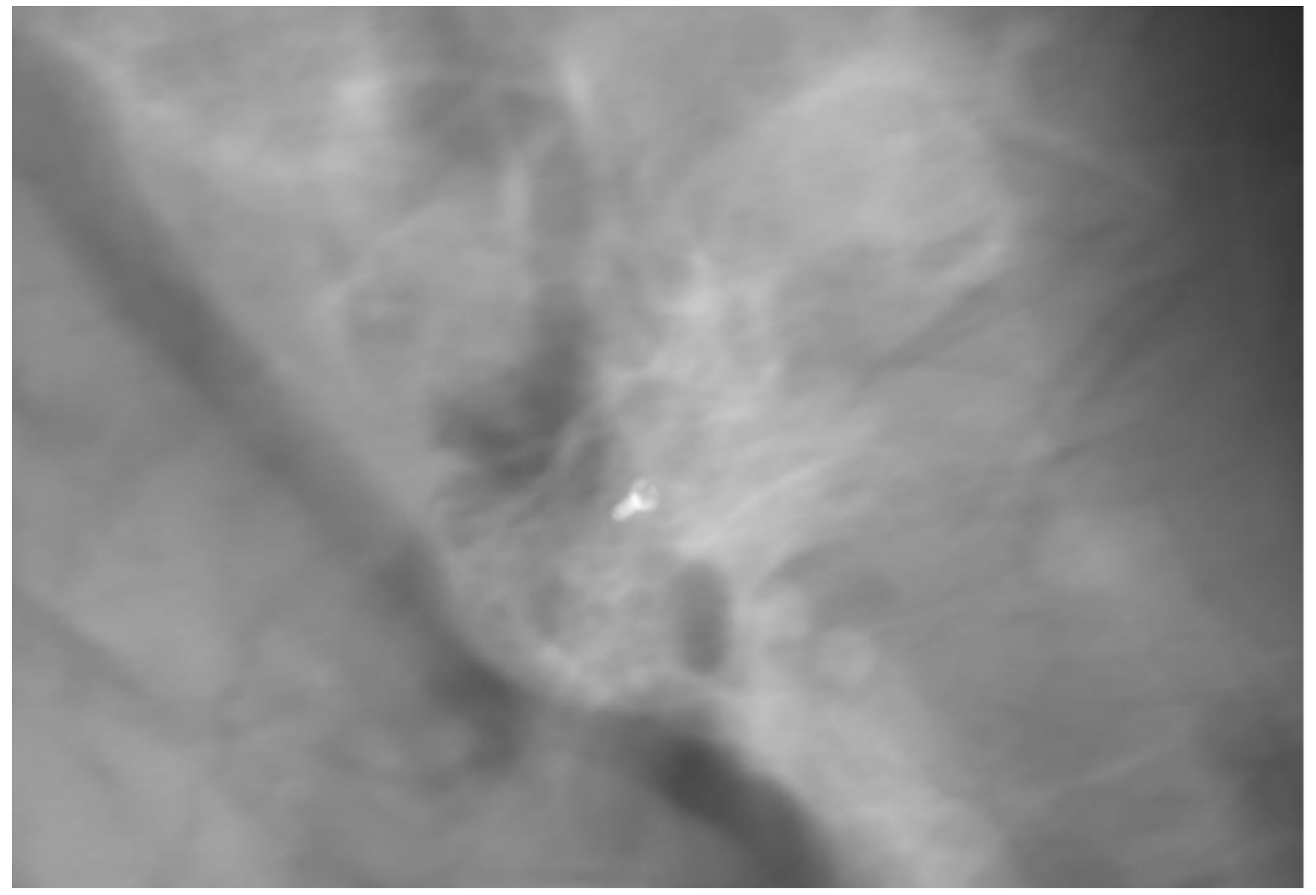


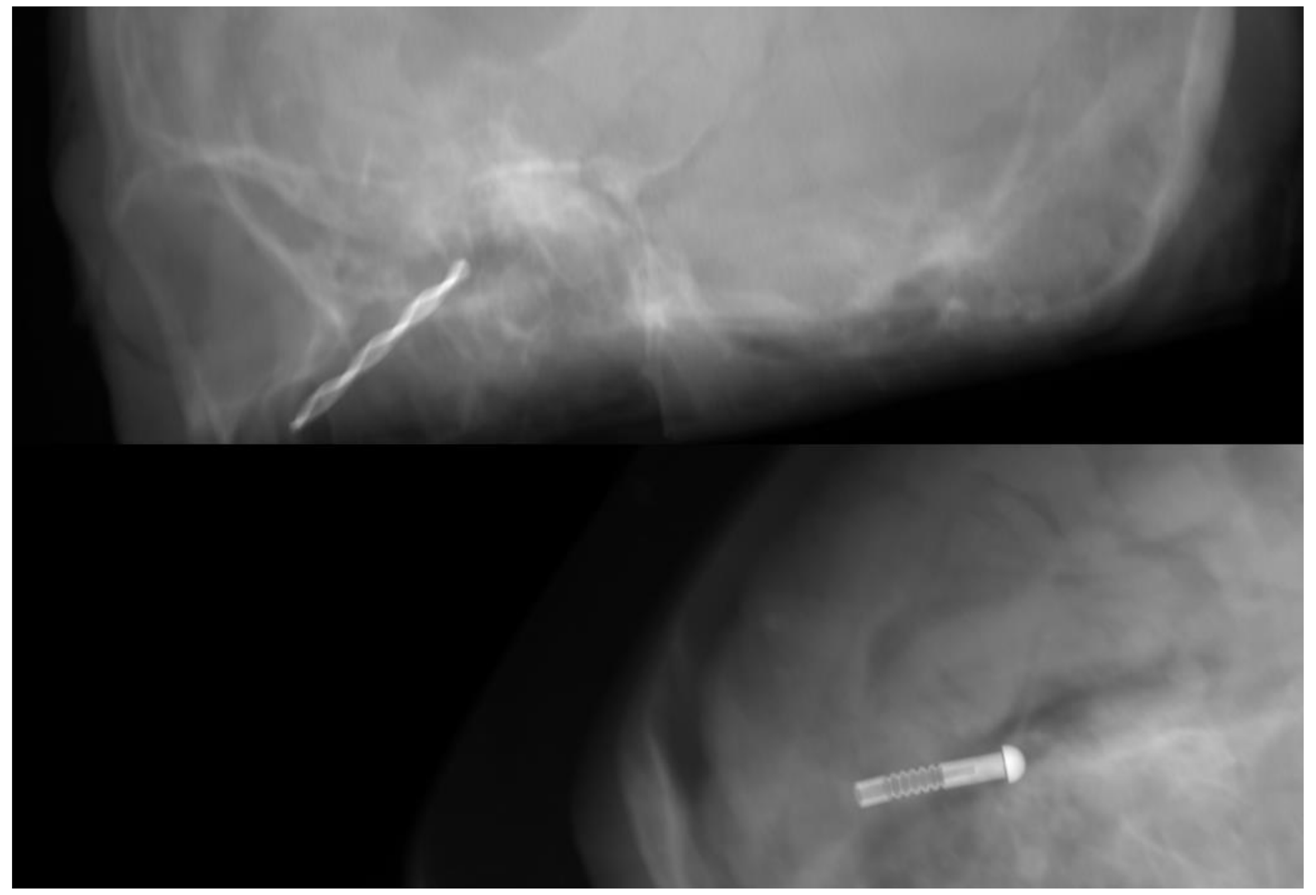


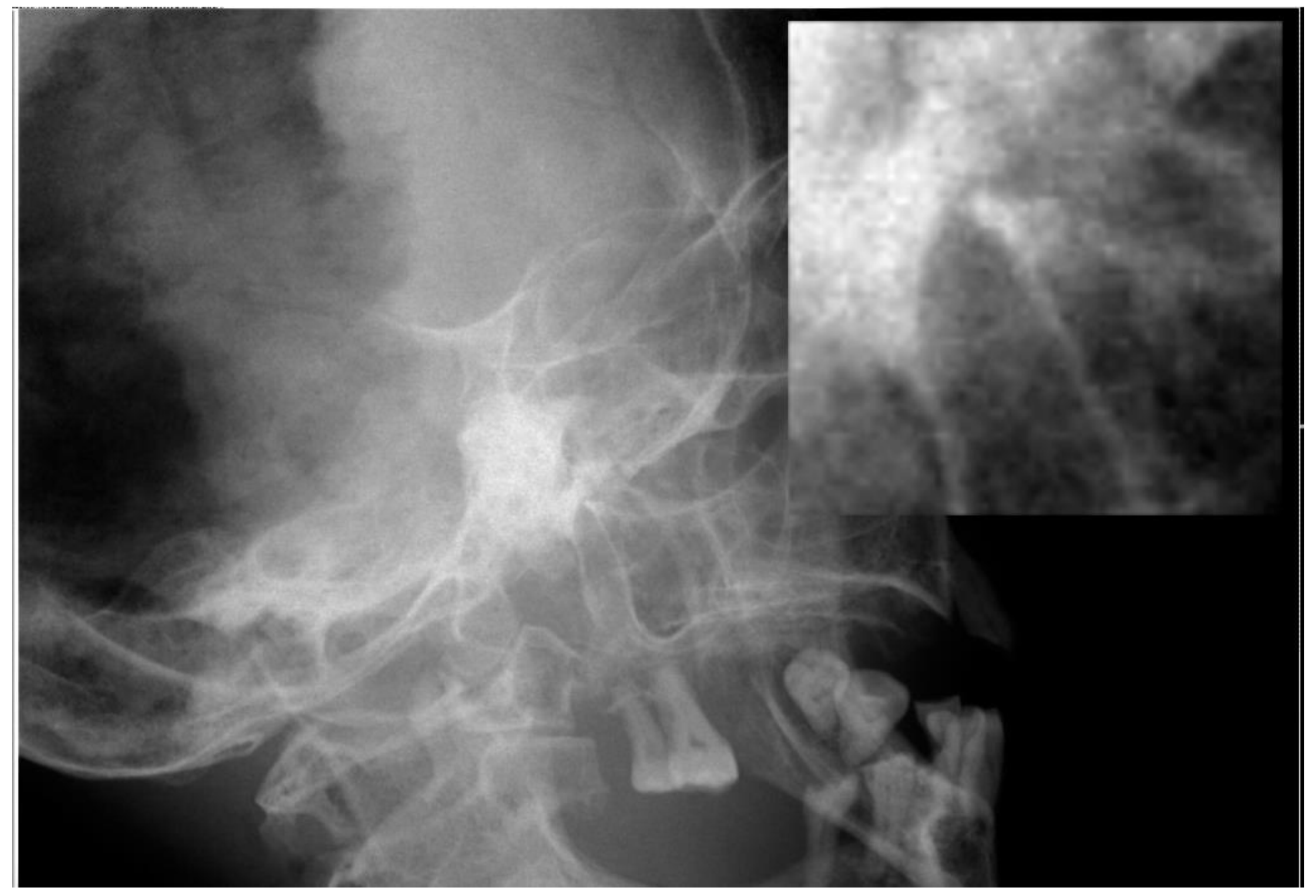


Dataset limitations

Generation	Image Realism	Annotation Quality	Cost / size







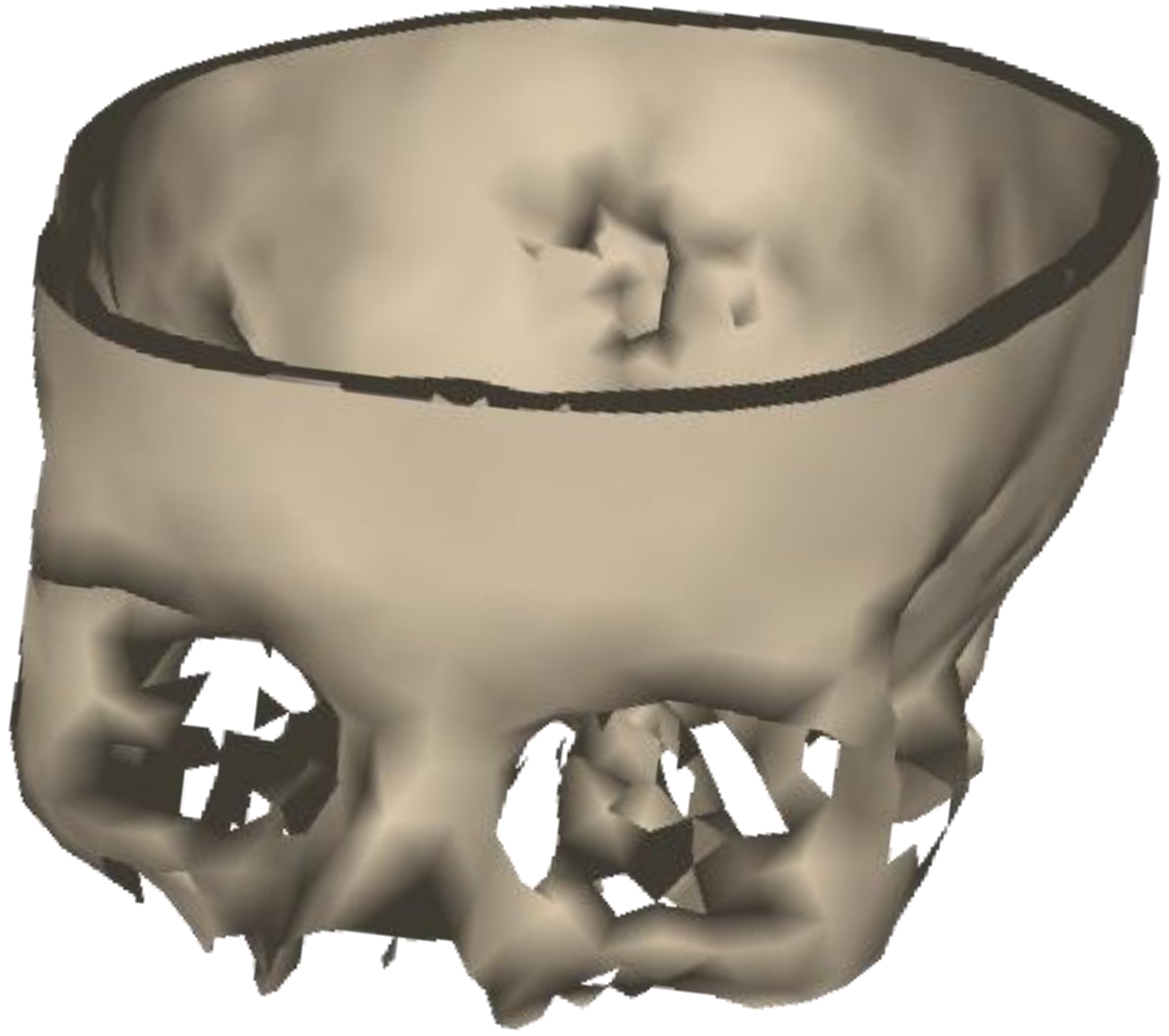
Real x-ray - images

- Phantom and manufacturing differences → only proxy
- Ethics → no actual humans
- Non-destructive

Synthetic - Images

- Complex Physics
- Non-deterministic

Generation of a Dataset



Stochastic Sampling of

- Projection and
- Pose Parameters

Algorithm 1: Generation of DRRs for training and testing

Input: Distributions $\mathcal{P}(\vec{x}_{instr})$, $\mathcal{P}(\vec{n}_{instr})$ and $\mathcal{P}(P)$, Polygons $\vec{x}_{poly,i}$ for $i \in \{lower, upper\}$, CTVolumeData, InstrumentMesh

Output: Image, pose $\boldsymbol{\theta}$

repeat
  $\vec{x}_{instr} \leftarrow$ draw_position($\mathcal{P}(\vec{x}_{instr})$)
  $\vec{n}_{instr} \leftarrow$ draw_orientation($\mathcal{P}(\vec{n}_{instr})$)
  repeat
    $P \leftarrow$ draw_projection($\mathcal{P}(P)$)
    $\boldsymbol{\theta} \leftarrow$ project_point($P, \vec{x}_{instr}$) ▷ Output pose
    $\theta_{poly,i} \leftarrow$ project_point($P, \vec{x}_{poly,i}$)
    valid $\leftarrow$ **not** any(inside_polygon($\vec{x}_{instr}, \theta_{poly,i}$))
  until valid ▷ Fail after a defined number of
until valid ▷ unsuccessful iterations.
Anatomy $\leftarrow$ interpolate(CTVolumeData)
Mesh $\leftarrow$ transform(($\vec{x}_{instr}, \vec{n}_{instr}$), InstrumentMesh)
Instrument $\leftarrow$ rasterize_mesh(Mesh)
Volume $\leftarrow$ combine(Anatomy, Instrument)
Image $\leftarrow$ project(P, Volume)

Parameter		Training	Evaluation
Position	$\mathcal{P}(\vec{x}_{instr})$	$\mathcal{N}(0, (5\,\text{mm})^2)^3$	$\mathcal{N}(0, (1\,\text{mm})^2)^3$
Orientation (Rotations)	$\mathcal{P}(\vec{n}_{instr})$	$\mathcal{U}(0°, 360°) \times \mathcal{N}(0, (30°)^2)^2$	$\mathcal{U}(0°, 360°) \times \mathcal{N}(0, (15°)^2)^2$
Projection	$\mathcal{P}(P)$		
• Source-Object-Distance	$\mathcal{P}(d_{SOD})$	$\mathcal{U}(362.8\,\text{mm}, 725.61\,\text{mm})$	
• Object Offset	$\mathcal{P}((r, \varphi))$	$\mathcal{U}(0\,\text{mm}, 100\,\text{mm}) \times \mathcal{U}(0°, 360°)$	
• Rotations	$\mathcal{P}(P_{Rot})$	$\mathcal{U}(0°, 360°) \times \mathcal{U}(-60°, 60°) \times \mathcal{U}(0°, 360°)$	

TABLE I
PARAMETERS OF THE DRR GENERATION WITH $\mathcal{N}(\mu, \sigma^2)$ FOR NORMAL AND $\mathcal{U}$(MIN, MAX) FOR UNIFORM DISTRIBUTIONS

Meaningful Annotation

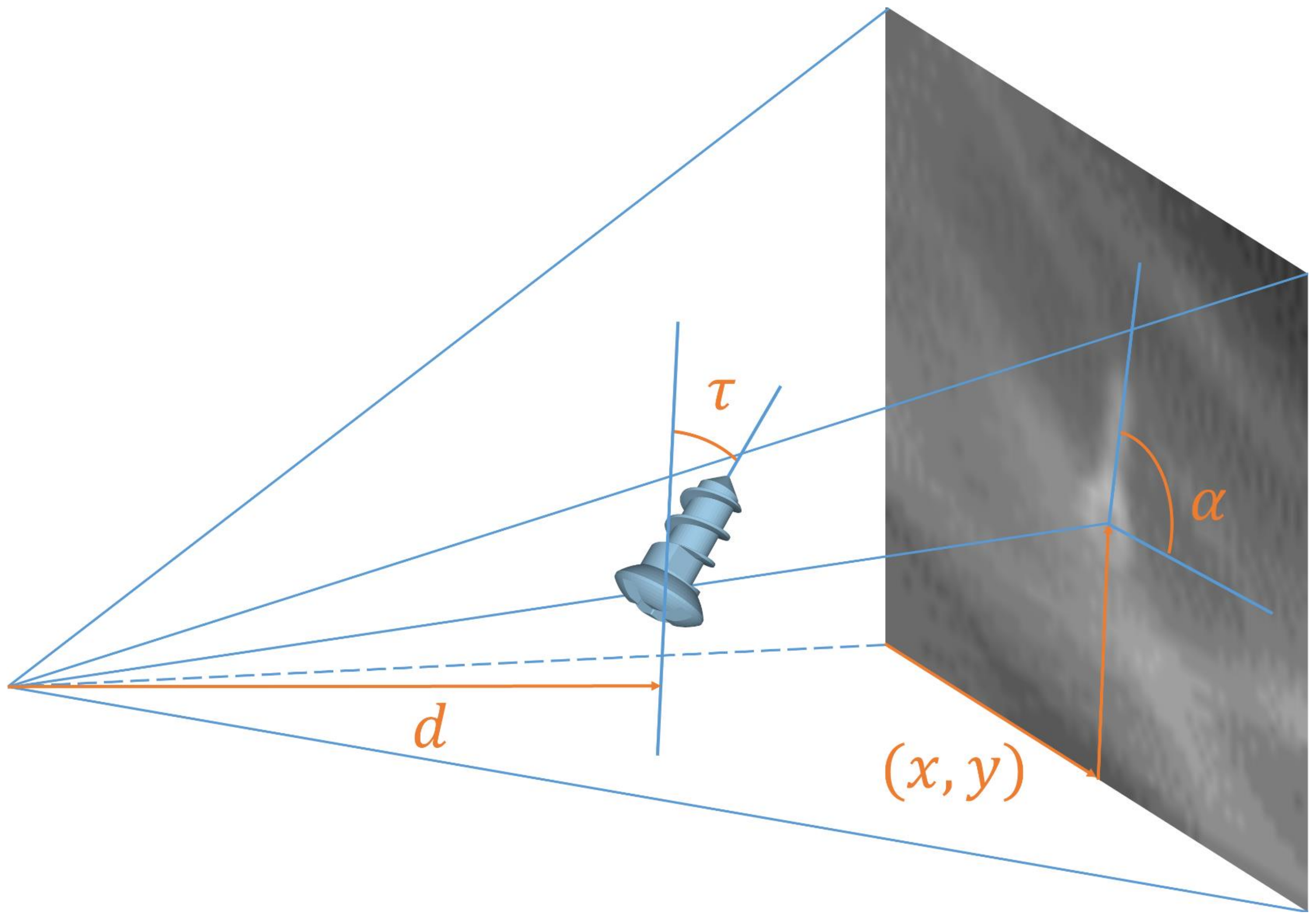
- In projection space

Synthetic annotation

- Perfect knowledge

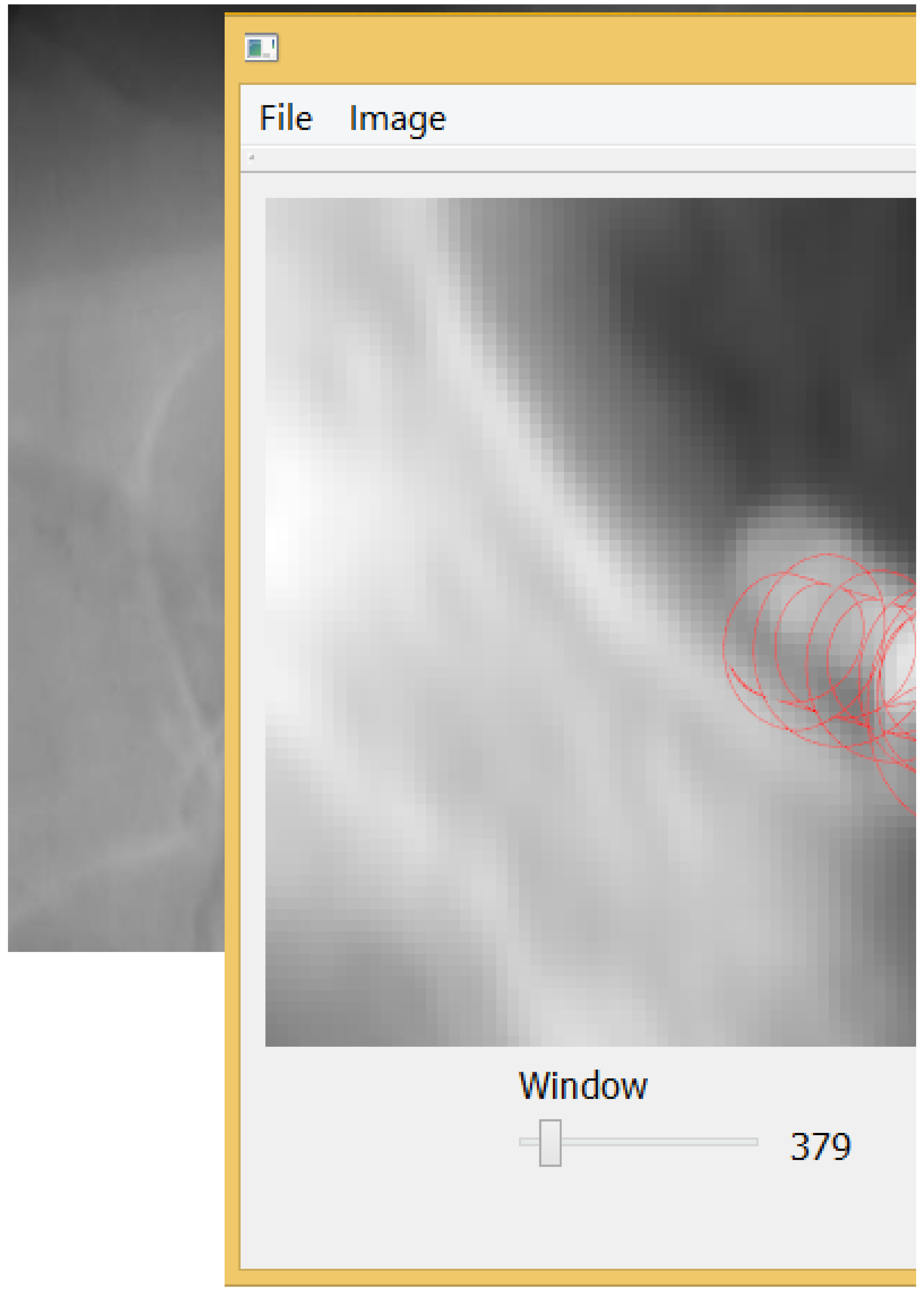
Real x-ray

- Reference method (Registration)
- Manual
- Calibration

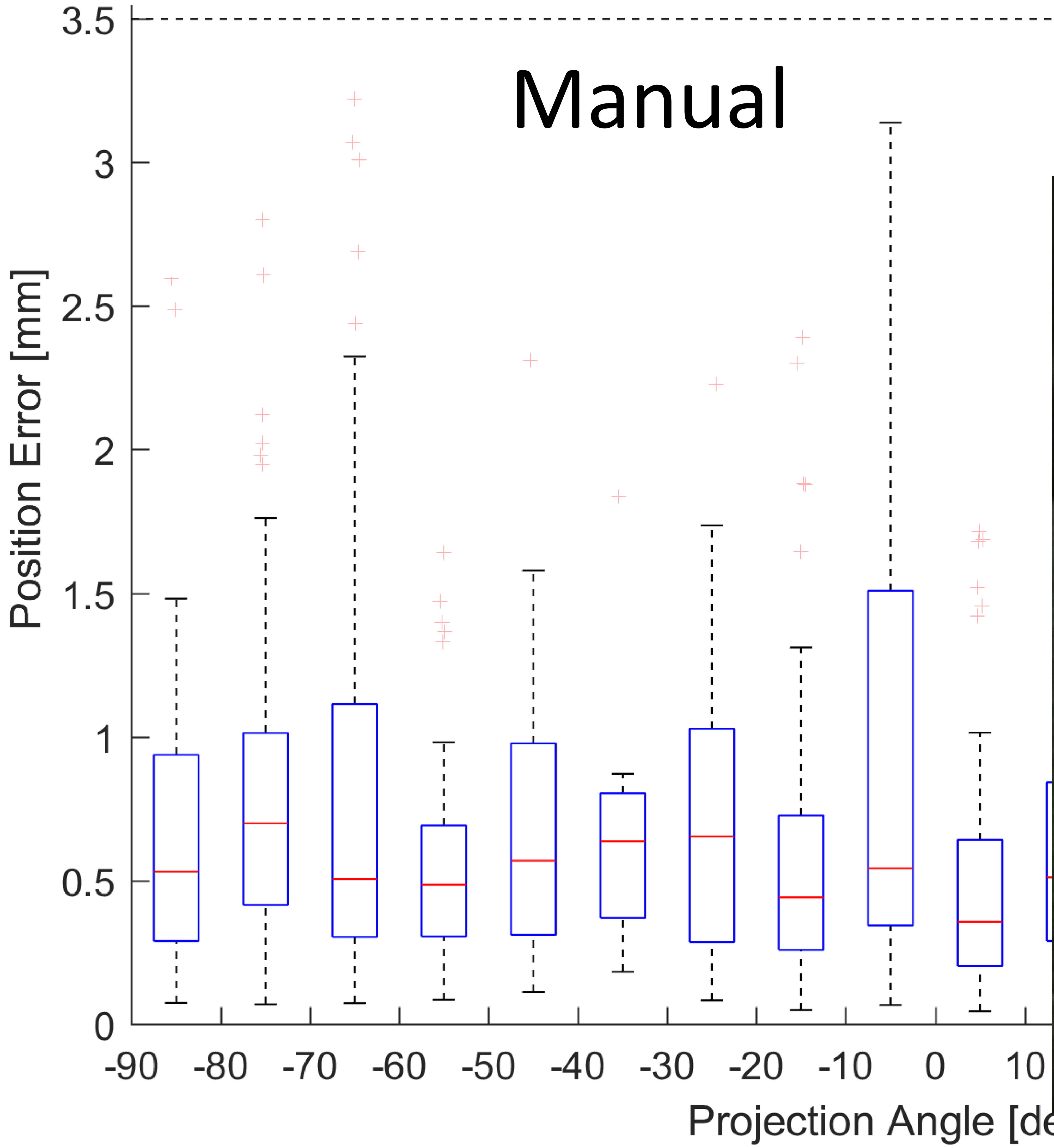


Real x-ray - Annotation

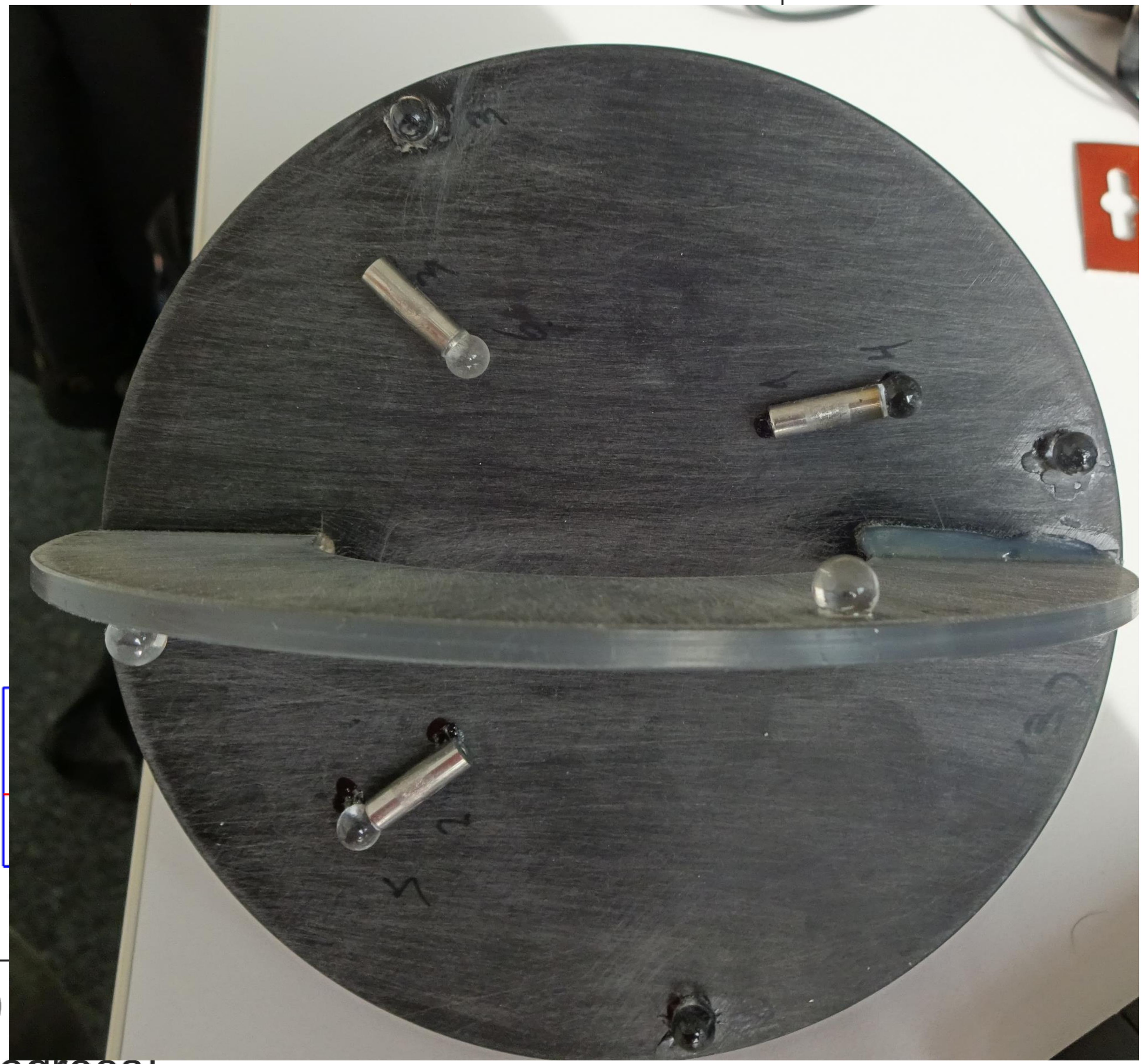
Registration



Manual



Calibration



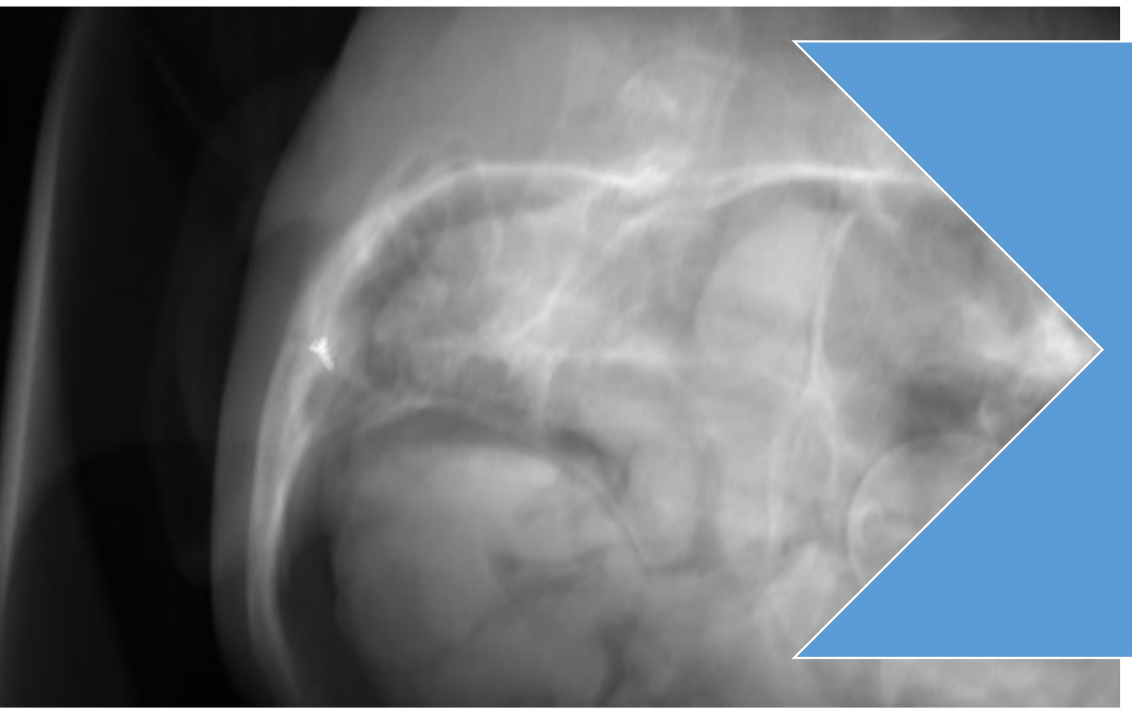
[Krumb et al., IJCARS 2020]

[Kügler et al., WBIR 2018] i3PosNet, IPCAI2020

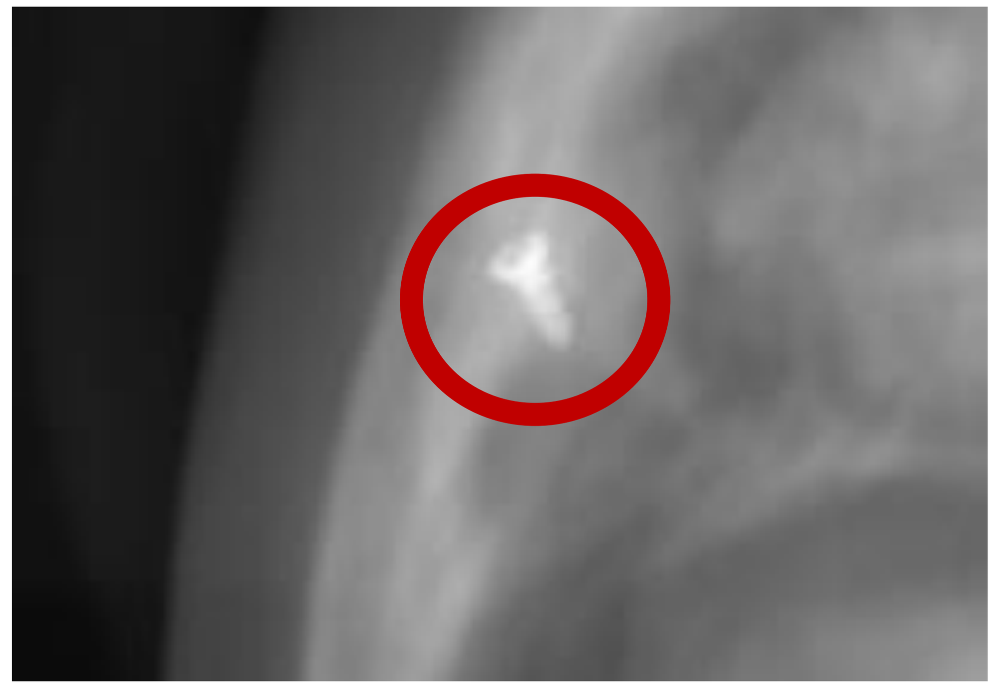
Appearance Normalization

Images/Annotation - **Augmentation** - Problem Design

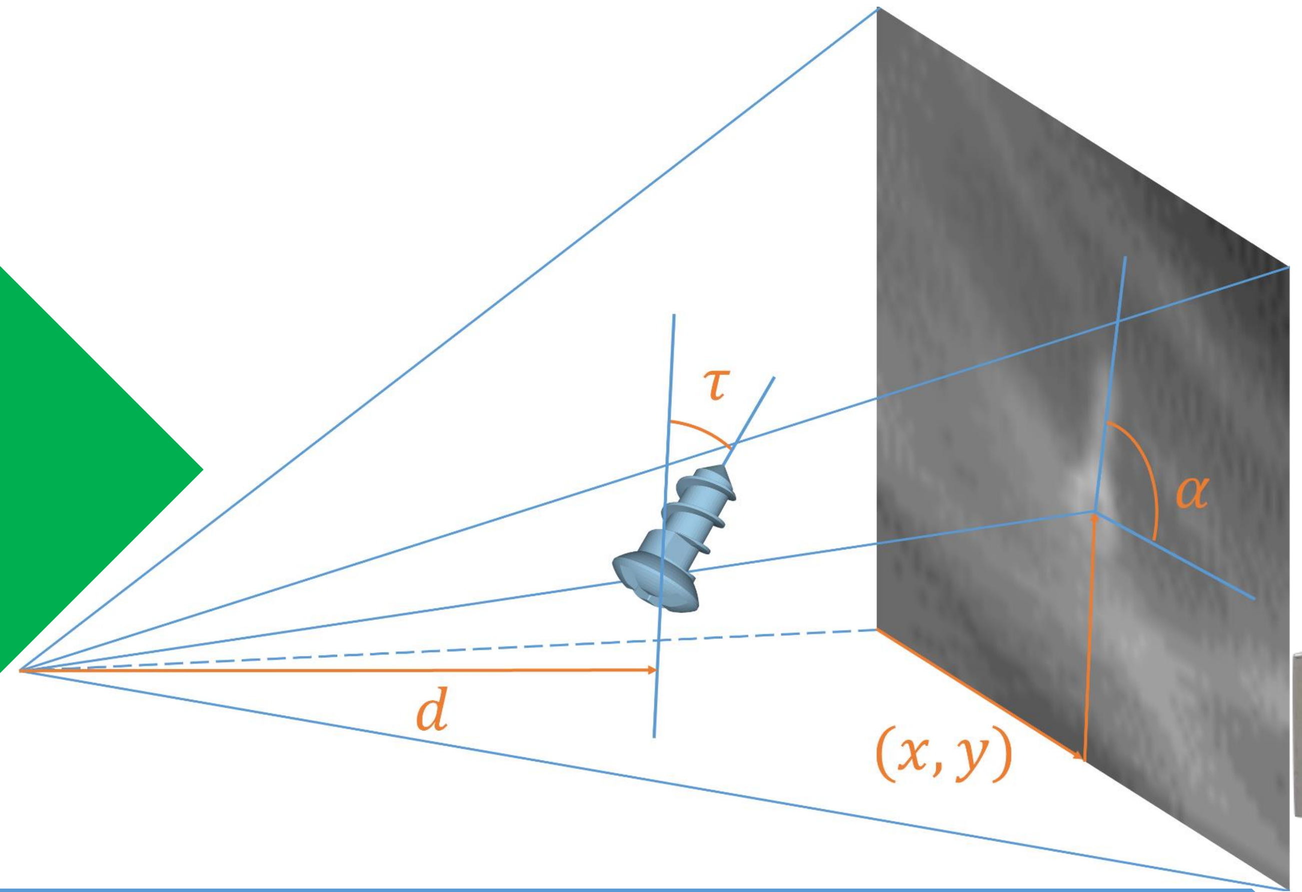
Fluoroscopy-Guided Tracking



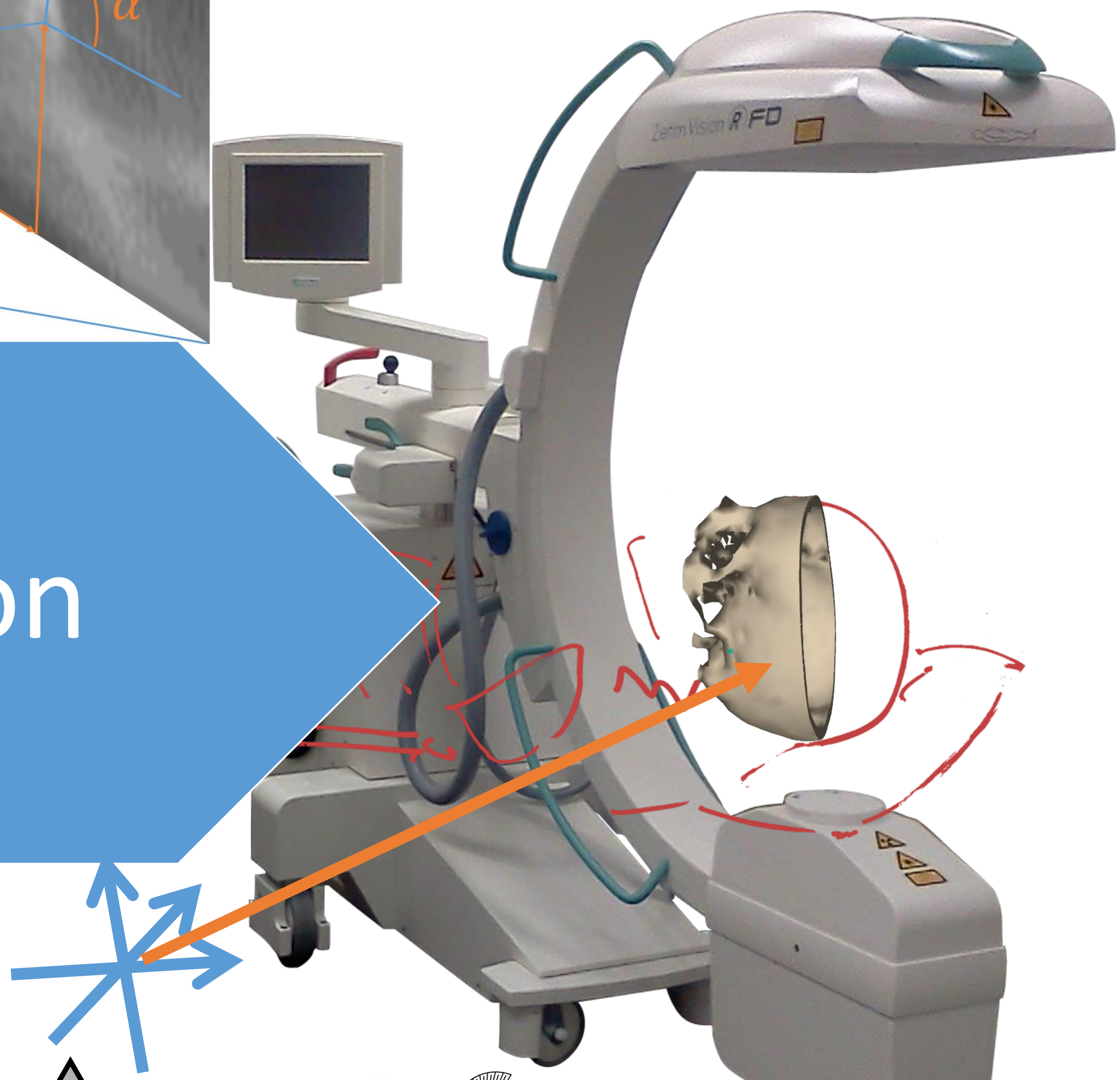
Localization



i3PosNet



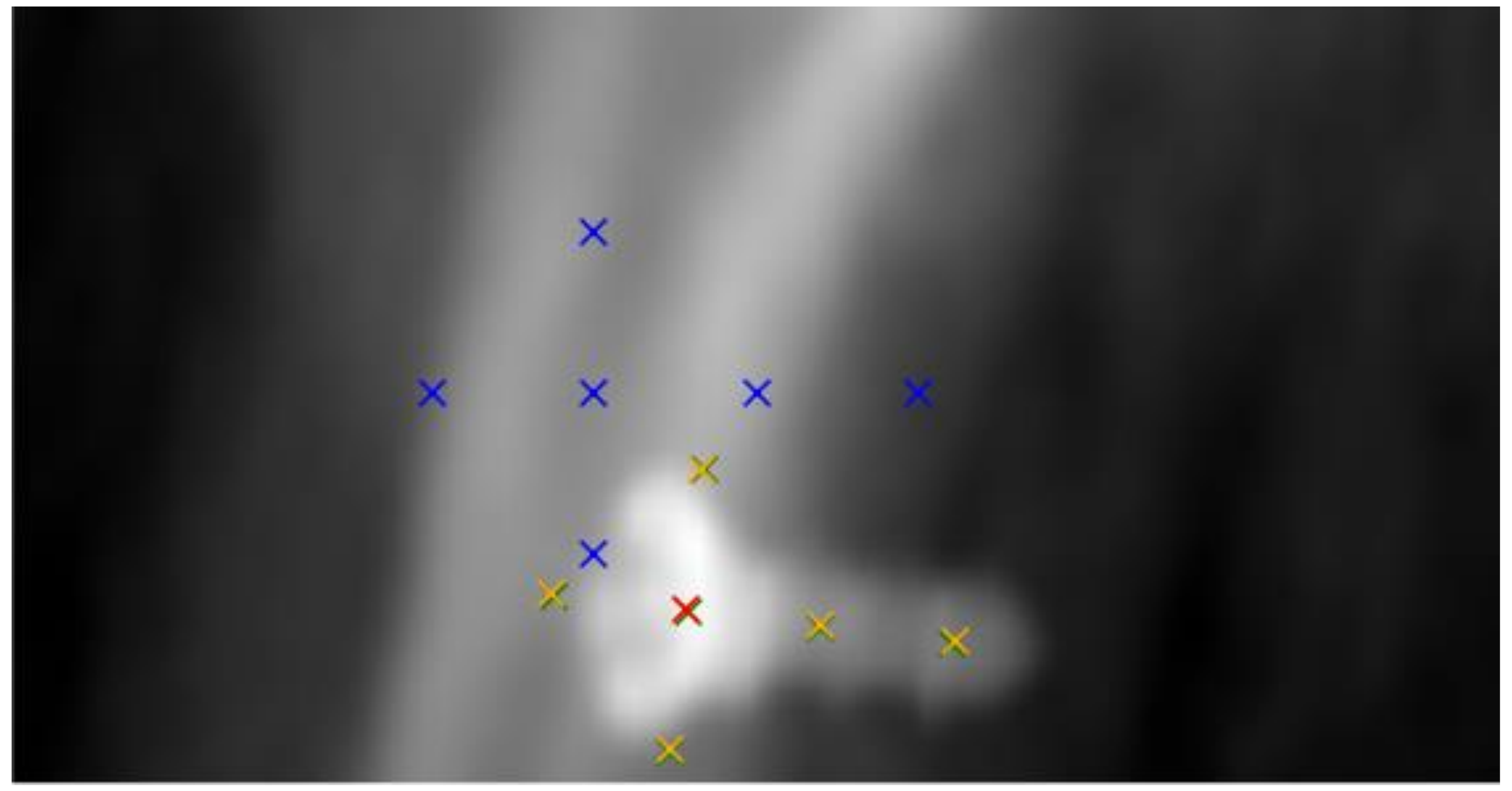
Reprojection



Method

Initial pose estimate

CROP



RECON

Iteration 1 pose estimate

Appearance Normalization Pipeline

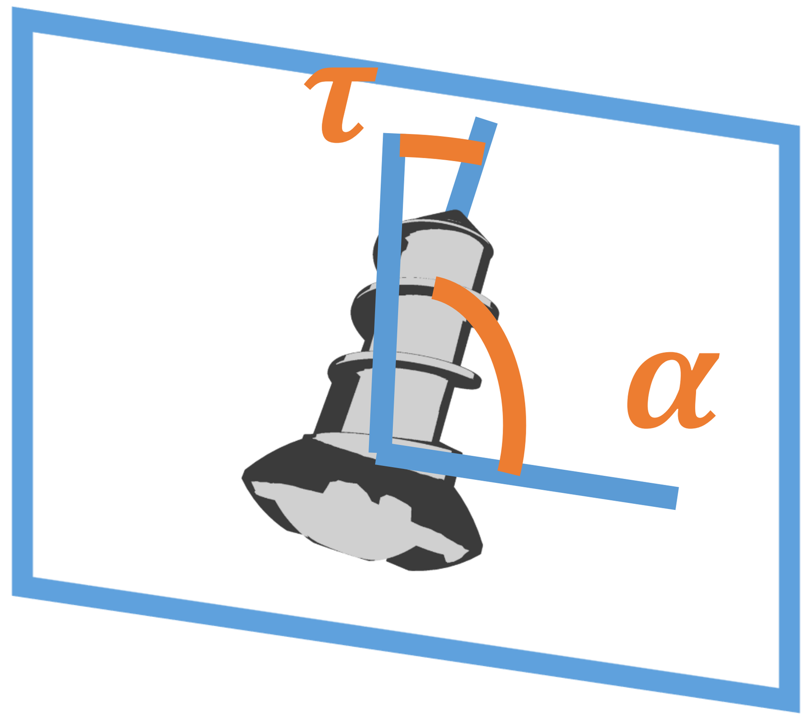
Normalization of
- Intensity
- Annotation

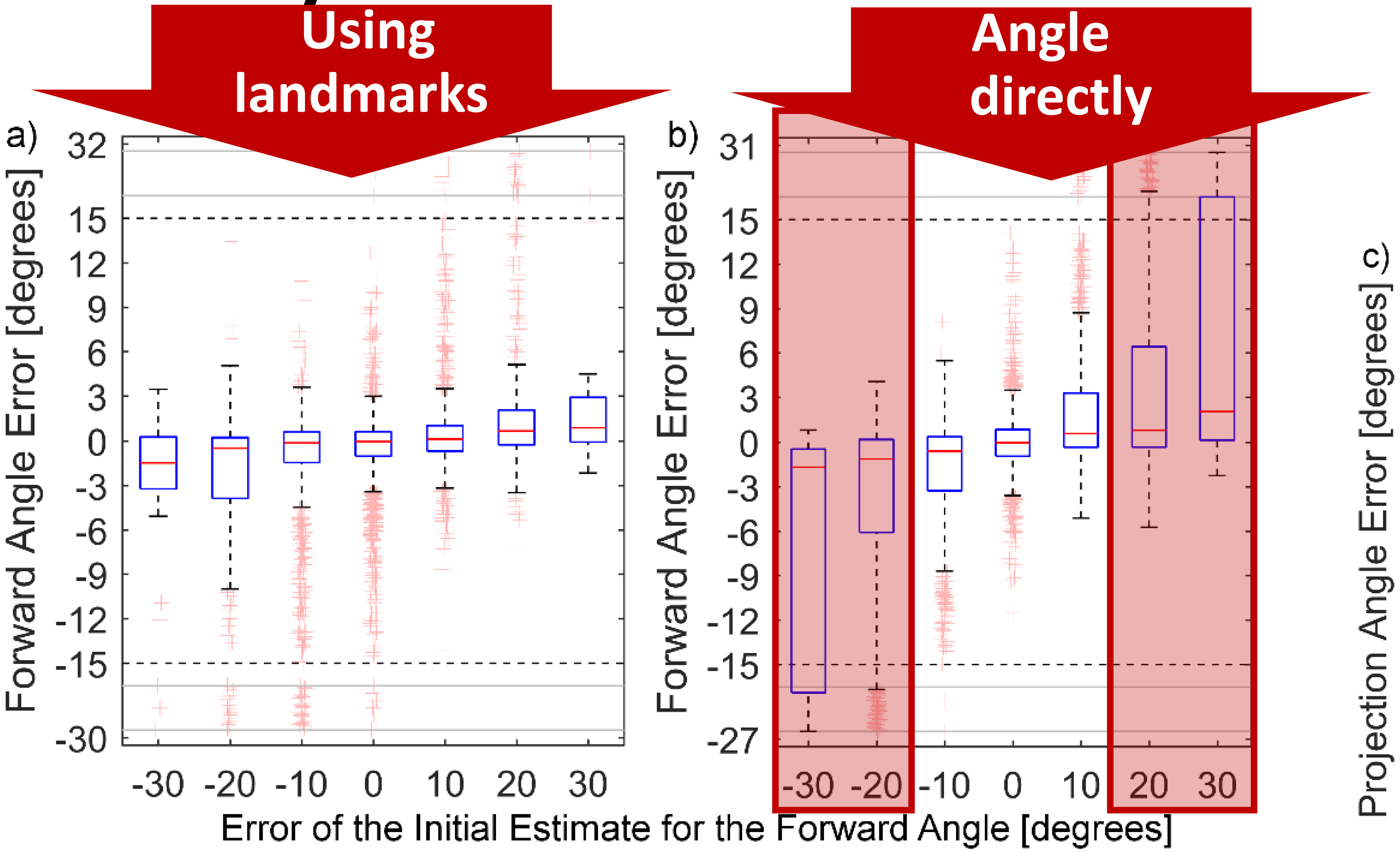
Distribution of
- Annotation

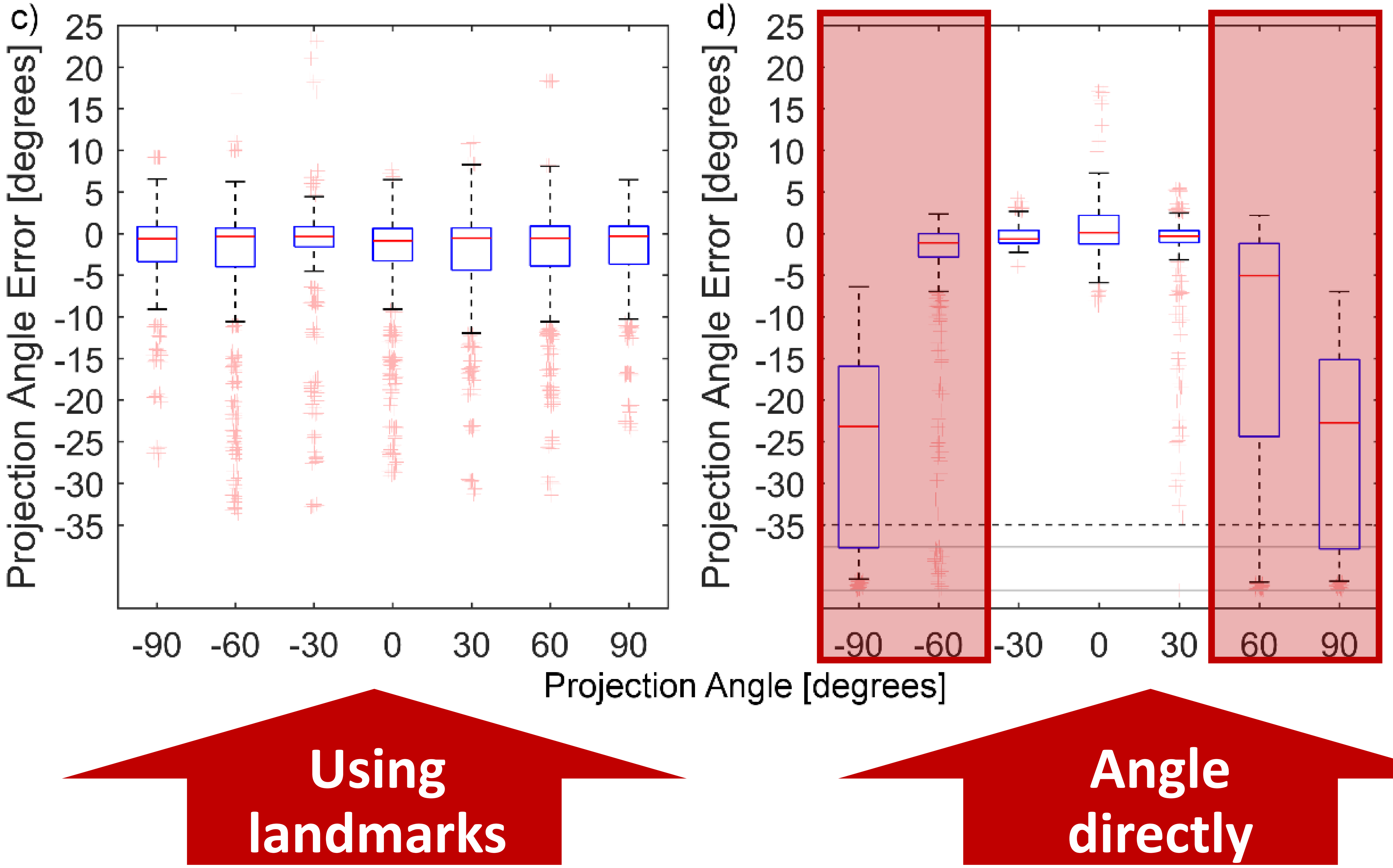
Not learning end-to-end

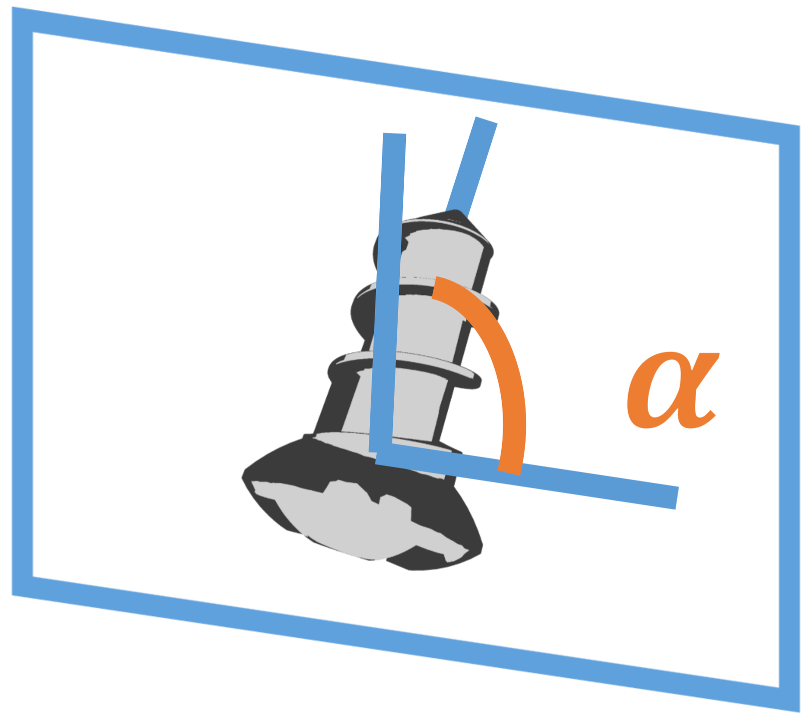
Images/Annotation - Augmentation - **Problem Design**

Why landmarks?









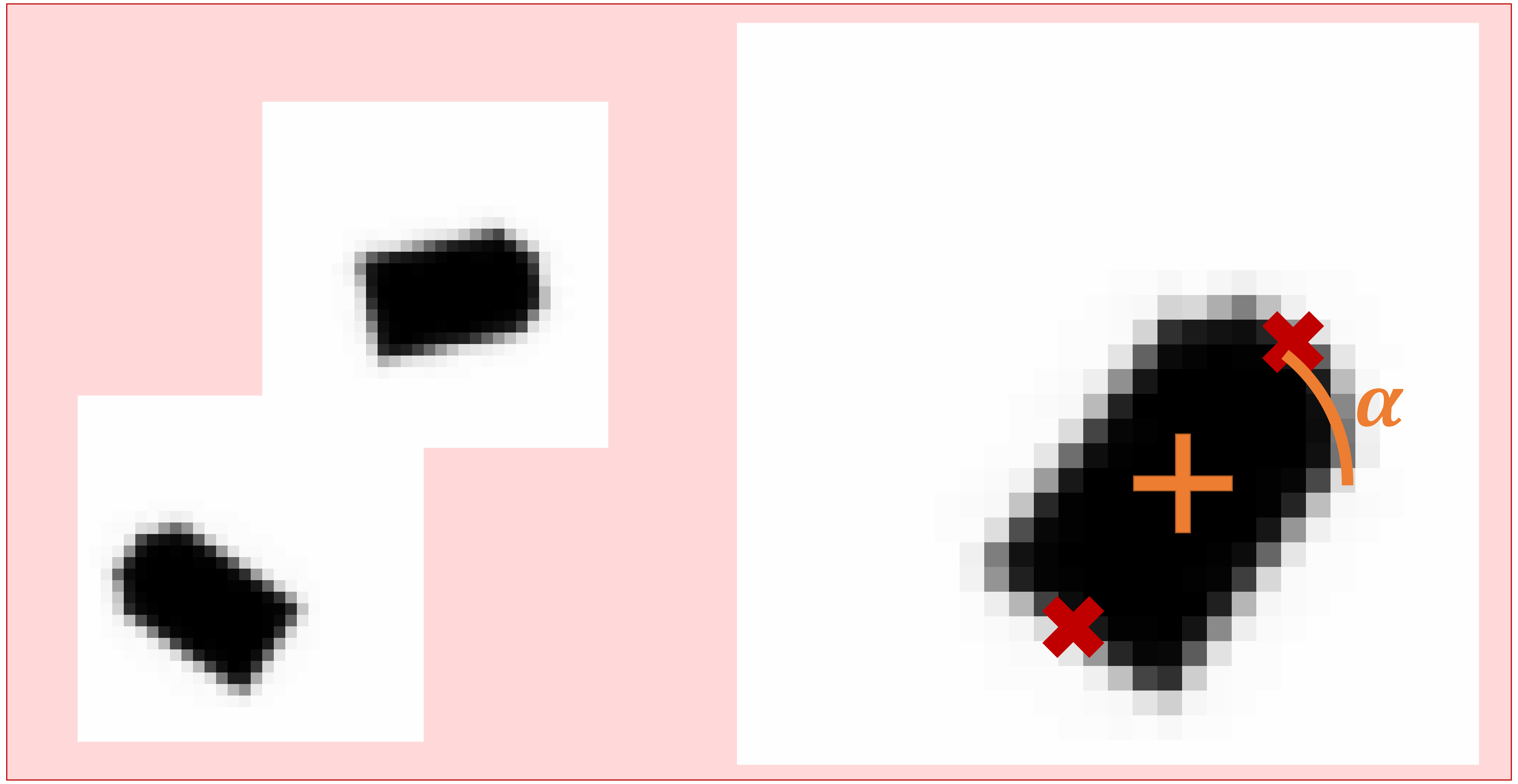
Exploration on a toy dataset

Toy Dataset

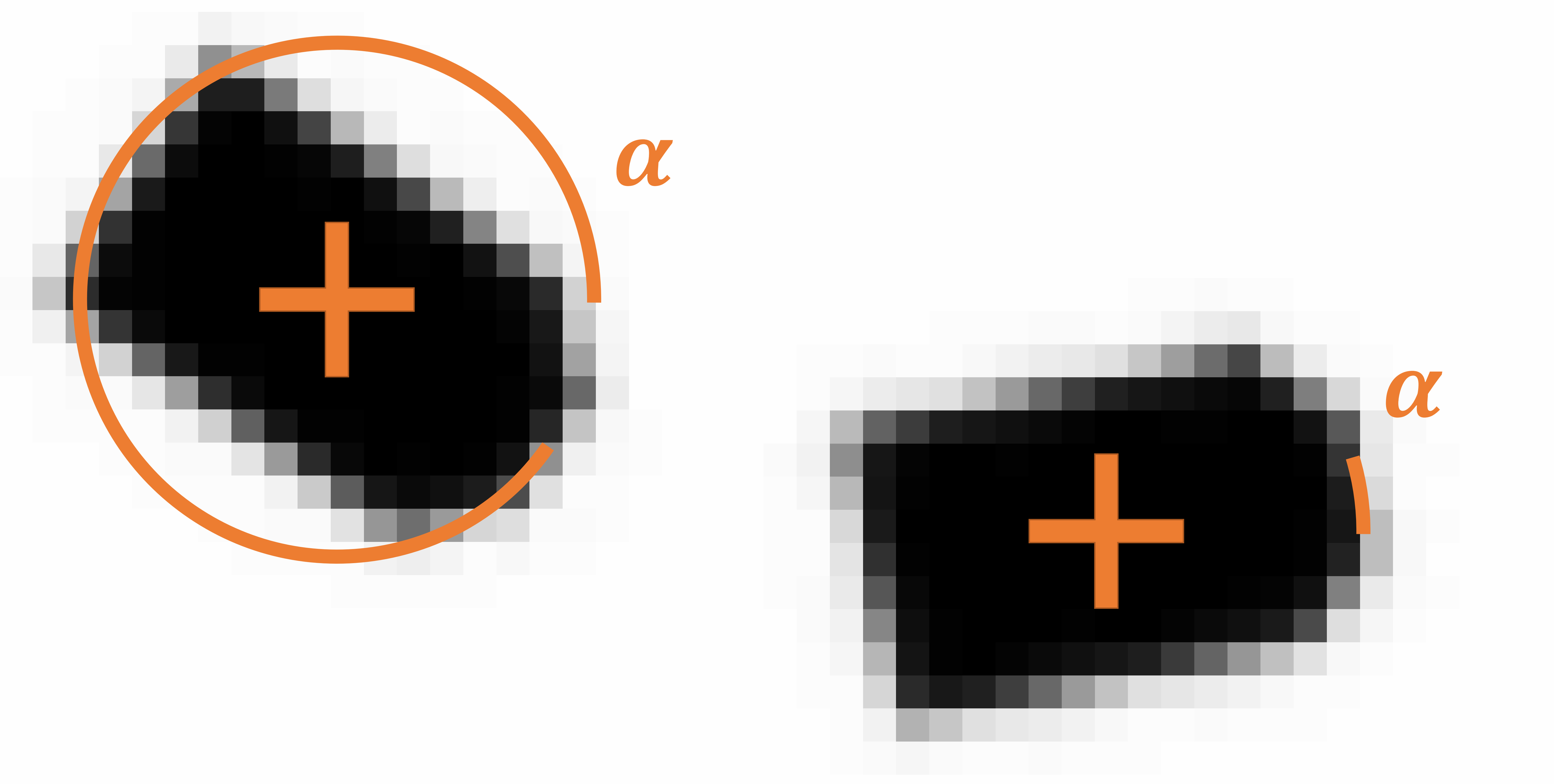
- Rectangle
  (one side rounded corners)
- Random position
- Random „forward angle“ α

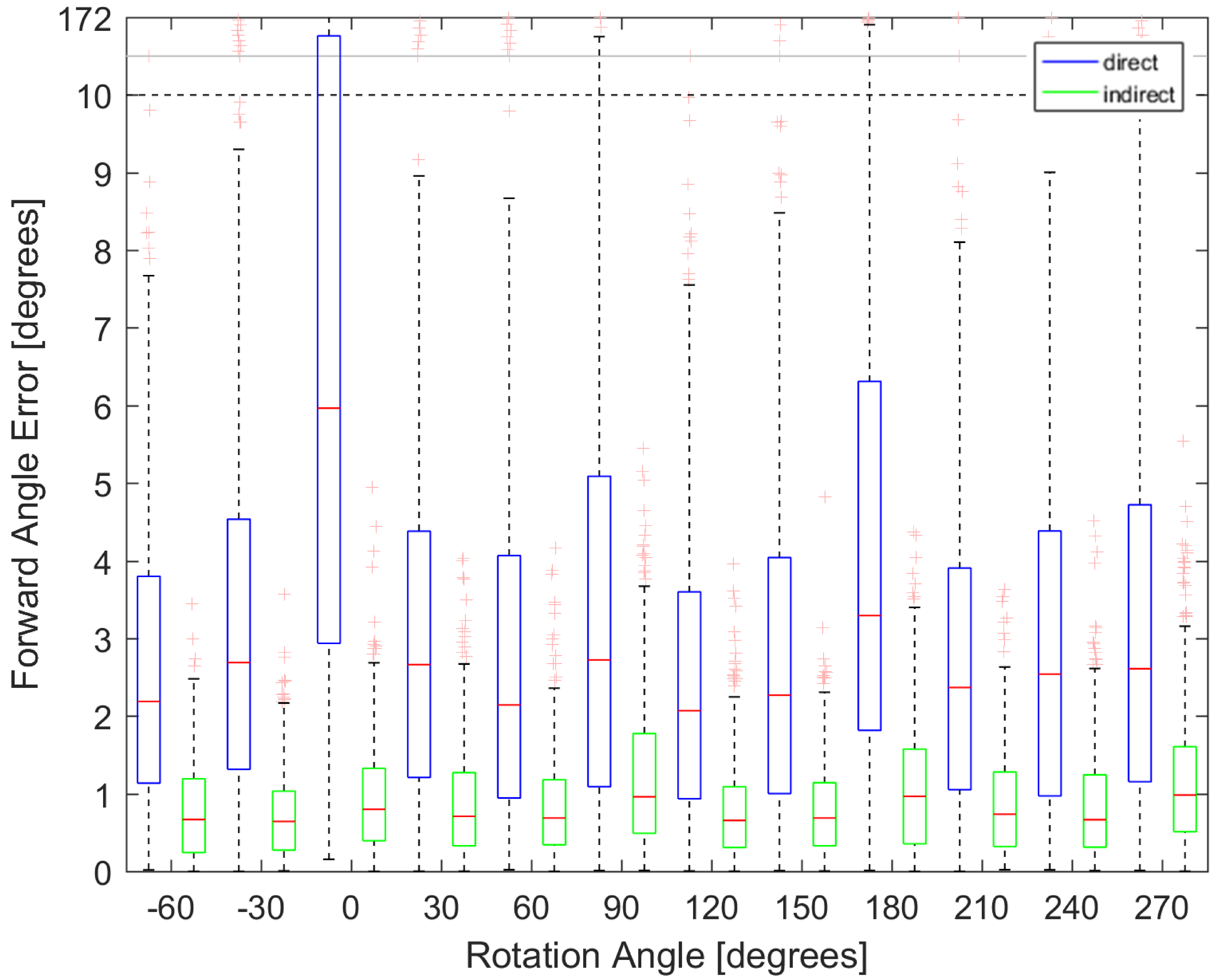
Task: Predict α

landmarks vs. angle (indirect vs. direct)

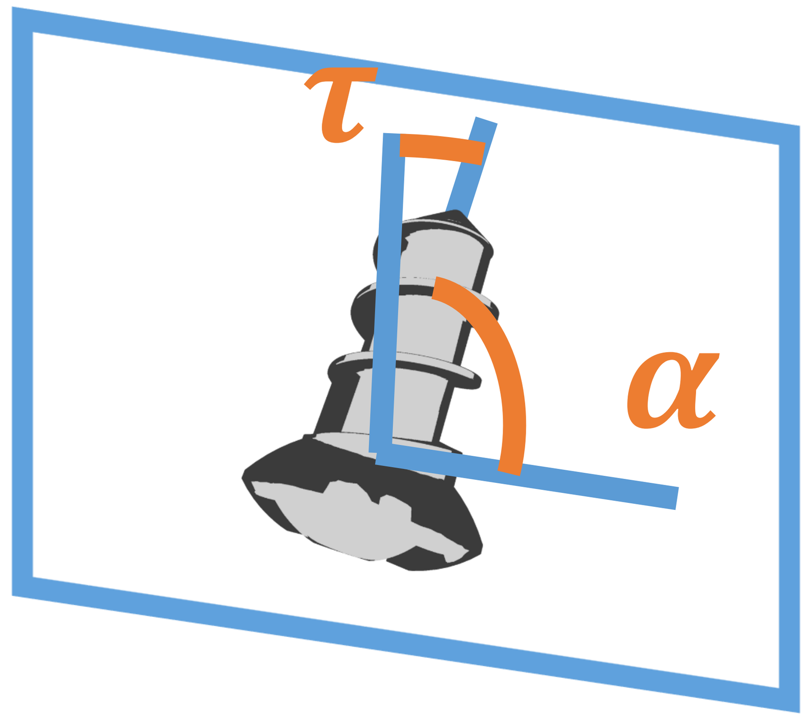


Exploration on a toy dataset



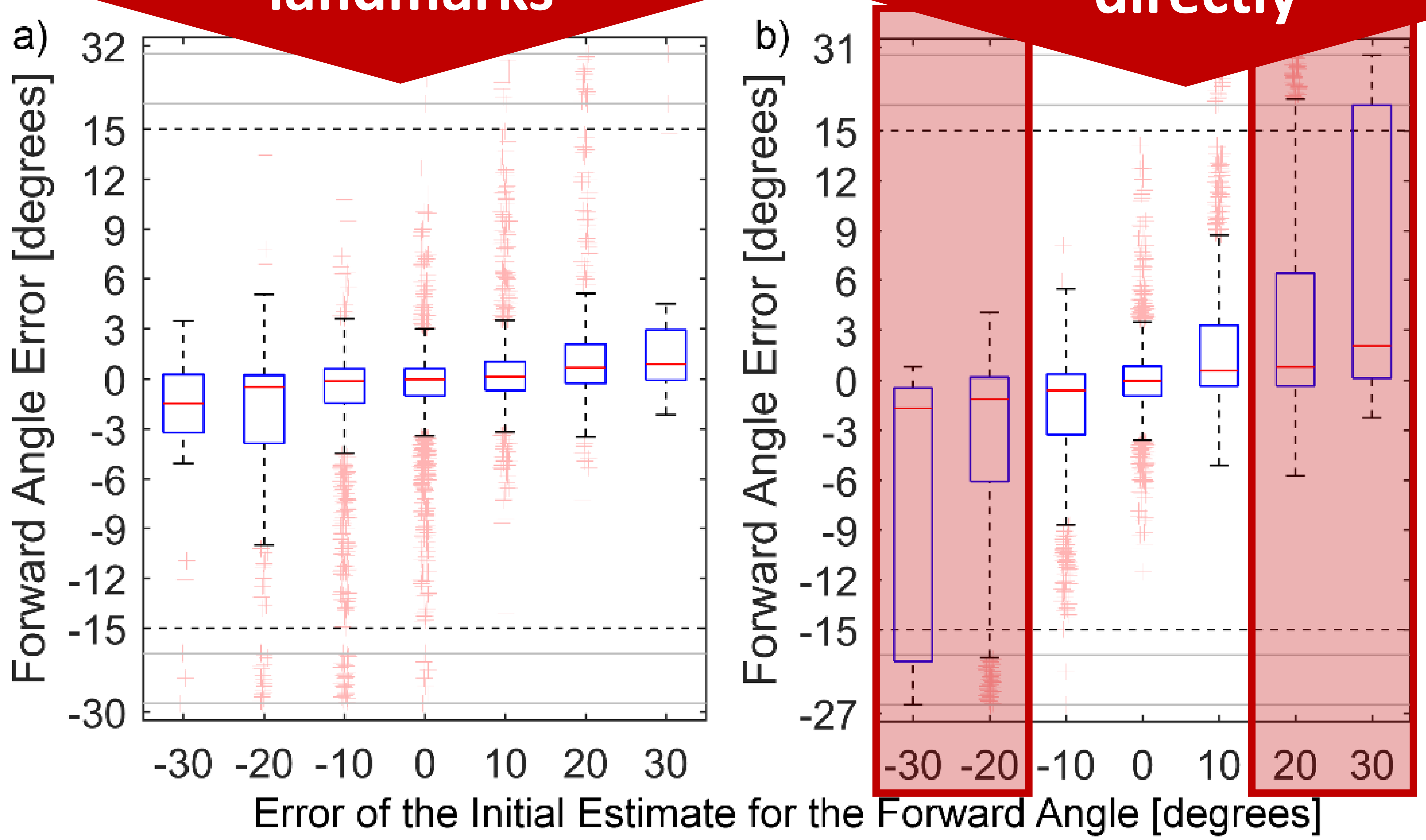


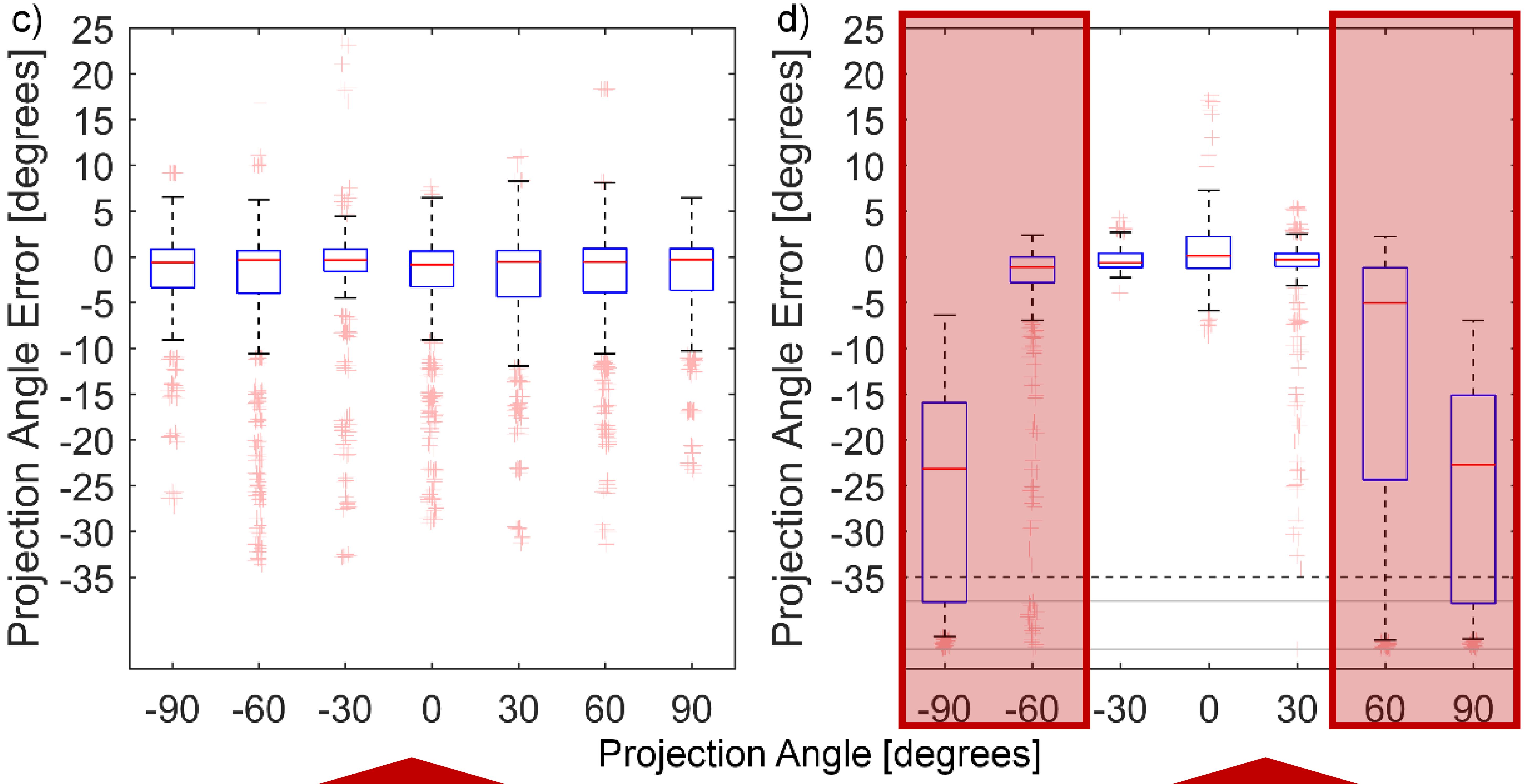
Why landmarks?



Using landmarks

Angle directly





Using landmarks

Angle directly

AI-readiness of CAI

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Summary

@kueglerd @anirbanakash

AI-readiness of
Instrument pose estimation

- Images/Augmentation
- Augmentation
- Problem Design

Limitations

- Projection angle
- Transfer from synthetic to real x-rays

Future Work

- Improved deep learning
- Multi-instrument

https://i3posnet.david-kuegler.de