University of Zurich[UZH]

The Balgrist

Pivot Calibration Concept for Sensor Attached Mobile C-arms

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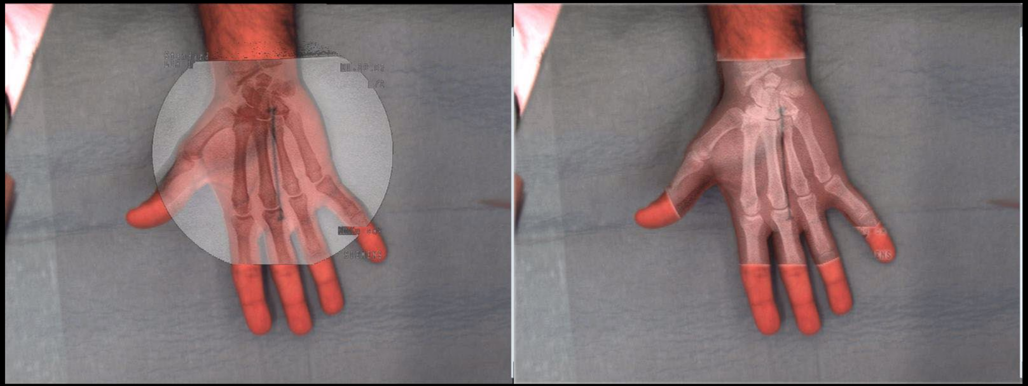
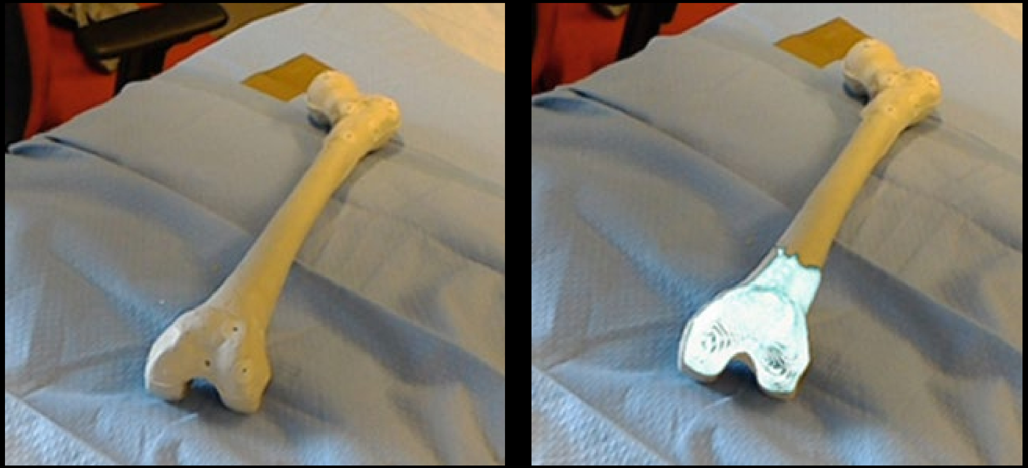
Problems in Surgery

Á la „introduction“

The CAMC system



Overlay of X-Ray and RGB camera frames [1]



Overlay of CBCT volume and real object using a Microsoft HoloLens [2]

- Camera/Tracker rigidly mounted and calibrated to the c-arm
- Real-time augmentation of medical imaging data
  - X-Ray
  - Cone-Beam Computed Tomography (CBCT)

https://www.medicalaugmentedreality.org/camc.html

[1] Supervised classification for customized intraoperative augmented reality visualization, Pauly, Olivier, Katouzian, Amin, Eslami, Abouzar, Fallavollita, Pascal, and Navab, Nassir, In Proceedings of 2012 IEEE International Symposium on Mixed and Augmented Reality (ISMAR), pp 311-312, Atlanta, GA, USA, 2012.

[2] Closing the Calibration Loop: An Inside-Out-Tracking Paradigm for Augmented Reality in Orthopedic Surgery, Jonas Hajek, Mathias Unberath, Javad Fotouhi, Bastian Bier, Sing Chun Lee, Greg Osgood, Andreas Maier, Mehran Armand, Nassir Navab, In Proceedings of International Conference on Medical Image Computing and Computer-Assisted Inverventions, pp 299-306, Granada, Spain, 2018.

CAMC Calibration Methods

- Optical axes alignment and homography transformation [1]
- Iterative-closest-Point (ICP) [2]
- Stereo calibration (Checkerboard, calibration phantom) [3]
- Hand-Eye calibration [4]

Drawbacks:

- Acquisition of corresponcences between X-Ray/CBCT and Camera Images/Poses
  → Emission of ionizing radiation
- Up to 160 pose pairs necessary (Hand-Eye)
- Time-consuming

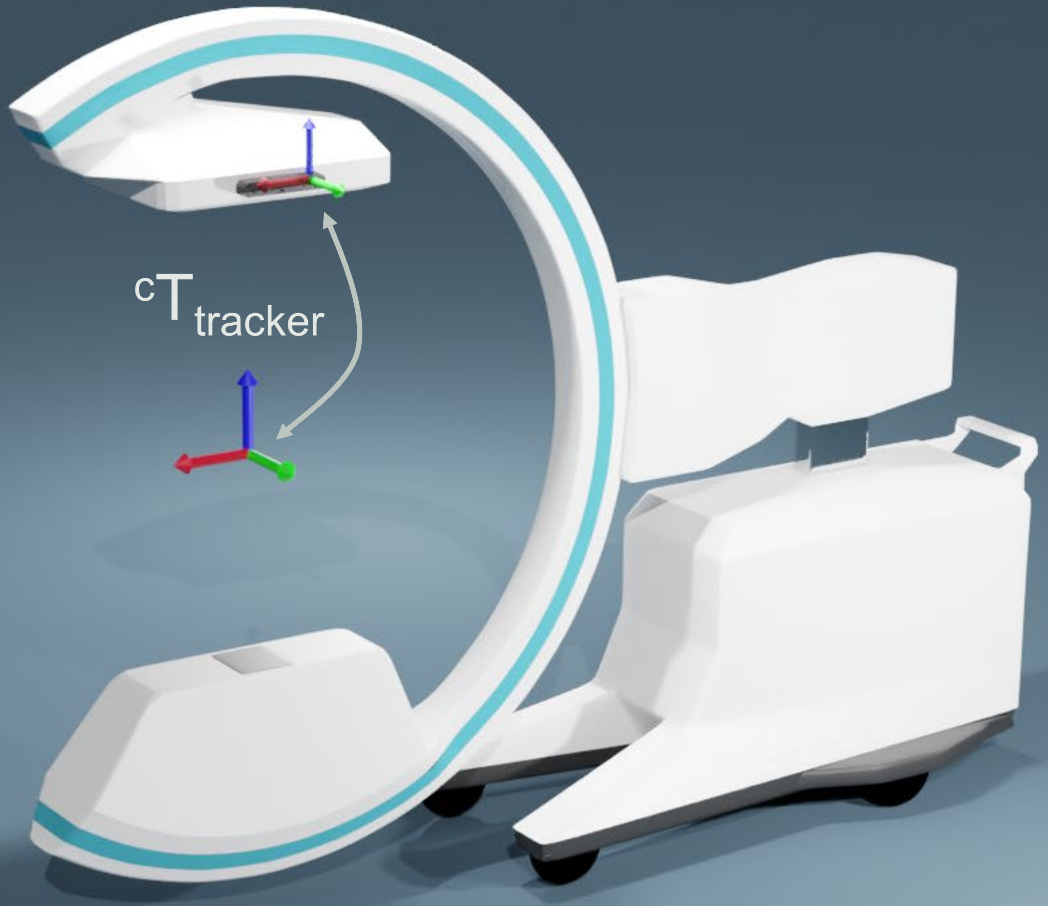
[1] Method for aligning an apparatus for superimposing X-ray and video images, Ali Bani-Hashedmi, Nassir Navab, Matthias Mitschke, US Patent 6,229,873, Sep 30, 1999.

[2] Calibration of RGBD camera and cone-beam CT for 3D intra-operative mixed reality visualization, Sing Chun Lee, Bernhard Fuerst, Javad Fotouhi, Marius Fischer, Greg Osgood, Nassir Navab, International journal of computer assisted radiology and surgery, 11 (6), pp 967-975, 2016.

[3] Augmented reality-based feedback for technician-in-the-loop C-arm repositioning, Unberath, Mathias, Fotouhi, Javad, Hajek, Jonas, Maier, Andreas, Osgood, Greg, Taylor, Russell, Armand, Mehran, and Navab, Nassir, Healthcare technology letters, 5(5), pp 143-147, 2018.

[4] Closing the Calibration Loop: An Inside-Out-Tracking Paradigm for Augmented Reality in Orthopedic Surgery, Jonas Hajek, Mathias Unberath, Javad Fotouhi, Bastian Bier, Sing Chun Lee, Greg Osgood, Andreas Maier, Mehran Armand, Nassir Navab, In Proceedings of International Conference on Medical Image Computing and Computer-Assisted Inverventions, pp 299-306, Granada, Spain, 2018.

What do we want to recover?



Analyzing the Geometry

- Sensor trackable and rigidly attached to the gantry
- Rotation around two axes (X- and Y-Rotation)
- Base plate movement remains fixed

Question:
Can we recover the the transformation from sonsor coordinates to the rotation center of the c-arm gantry ${}^{c}T_{tracker}$ and thereby solve the calibration problem?

Advantage:
Simple, robust and radiation-free method to calibrate a sensor to an imaging system

C-arm Pivot Calibration

Input: Observed poses of the rigidly attached sensor during C-arm movements T_i, where i is the number of observed poses.

Problem: Can we recover the offset t of the sensor to the pivot point c_c and the pivot locus (x-circle)?

Output: The locus of c_c (the x-circle) and the offset t.

Possible solution:
Fit the shape using the parametric form of the spindle torus.

Problem:
We need to recover not only the offset and locus, but also the orientation of the shape

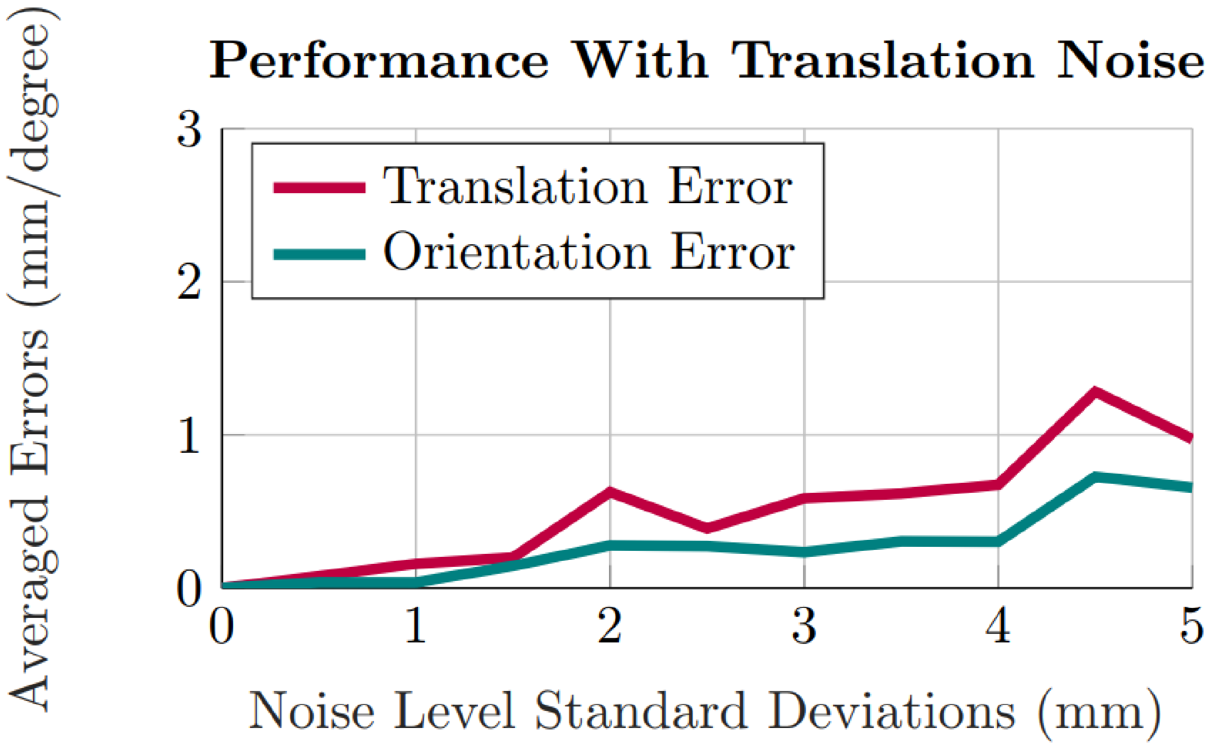
C-arm pivot calibration reformulated

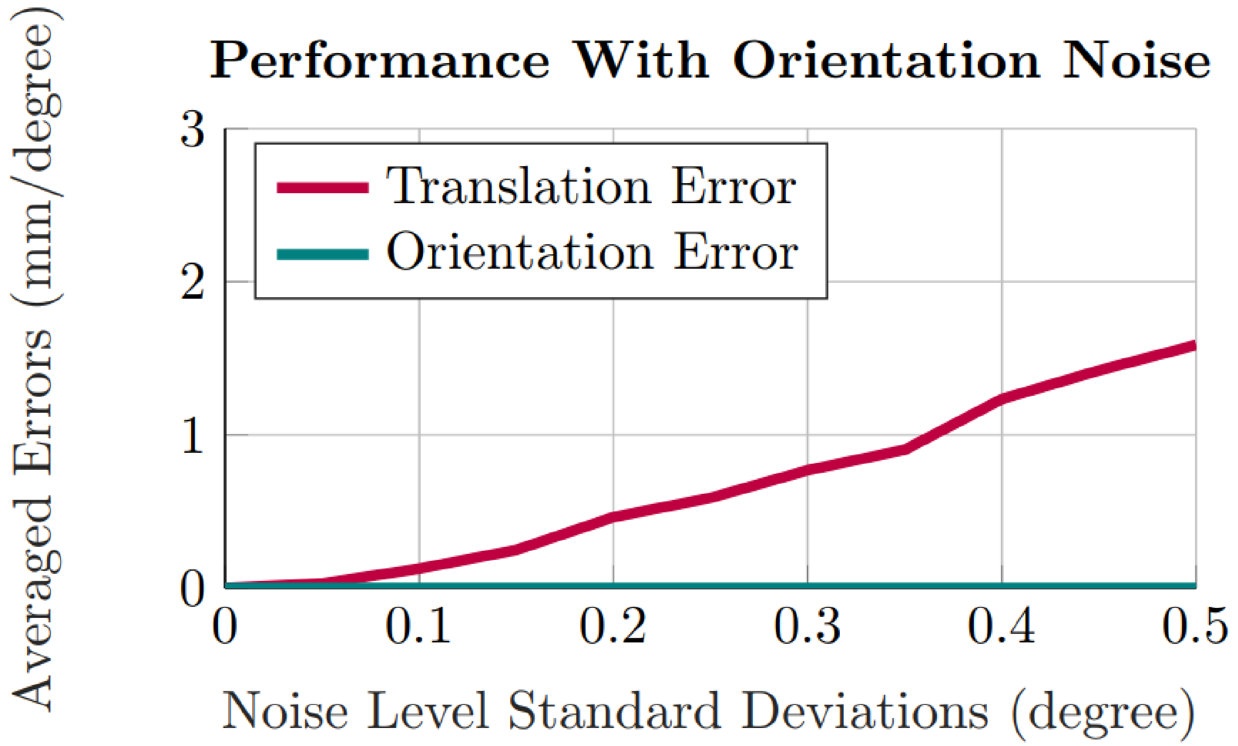
Input: Observed poses of the rigidly attached sensor during c-arm-axis movements $\{T_n^x\}_m$ and x-axis movements $\{T_i^x\}_j$, where i, n and j, m are the number of observed poses and observed sets.

Problem: Can we recover the offset t of the sensor to the pivot point c_c, the pivot locus (x-circle) and the orientation of the rotation center by fitting shapes in 2D instead of 3D?

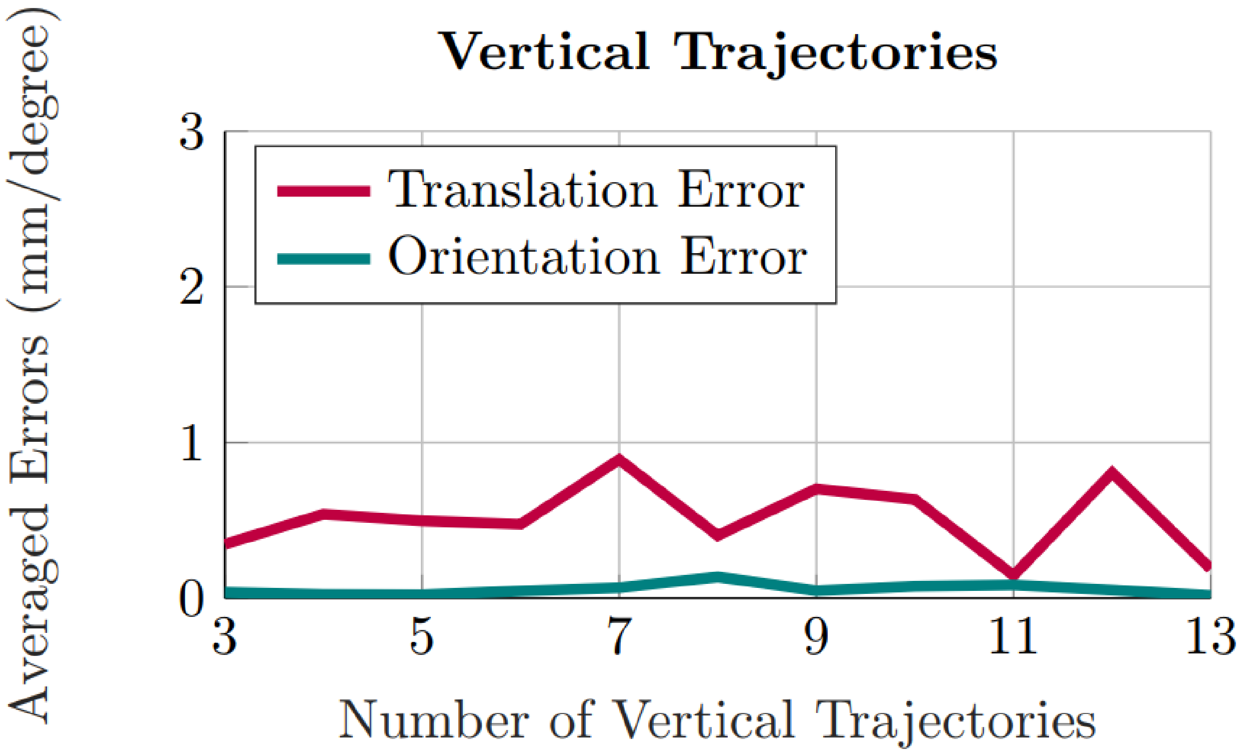
Output: The locus of c_c (the x-circle), the offset t and the orientation R.

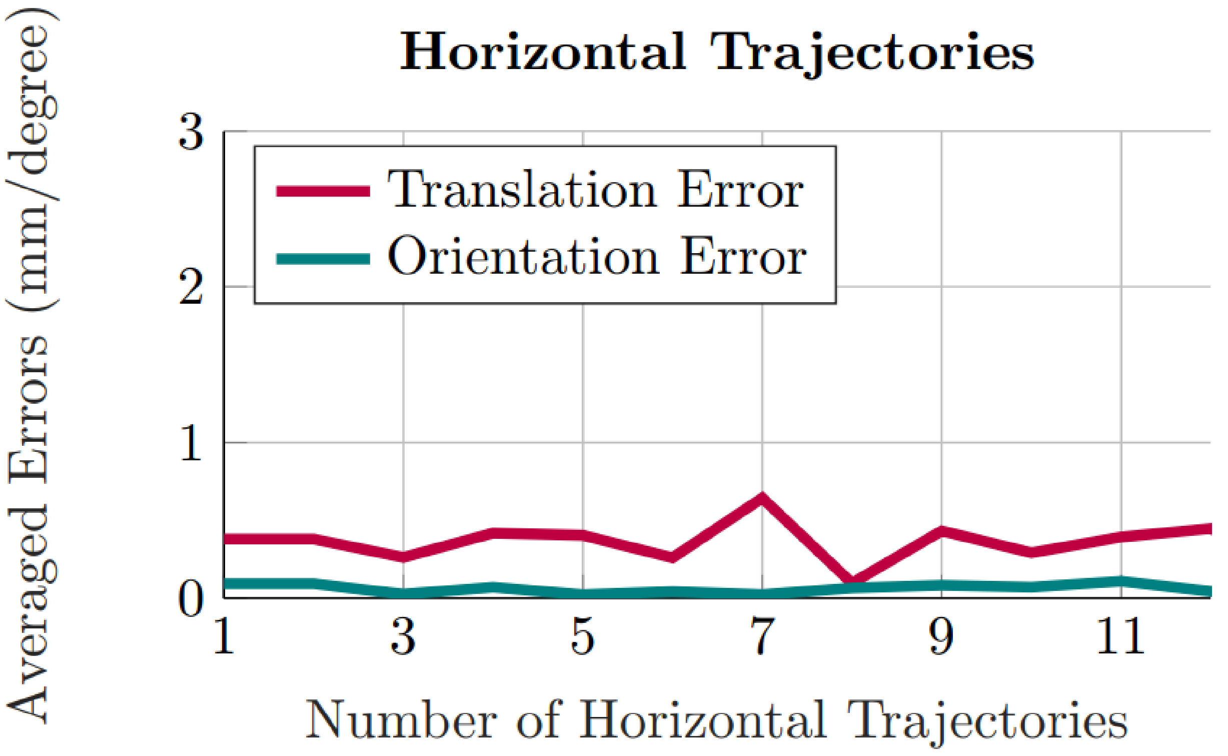
Results – robustness to noise



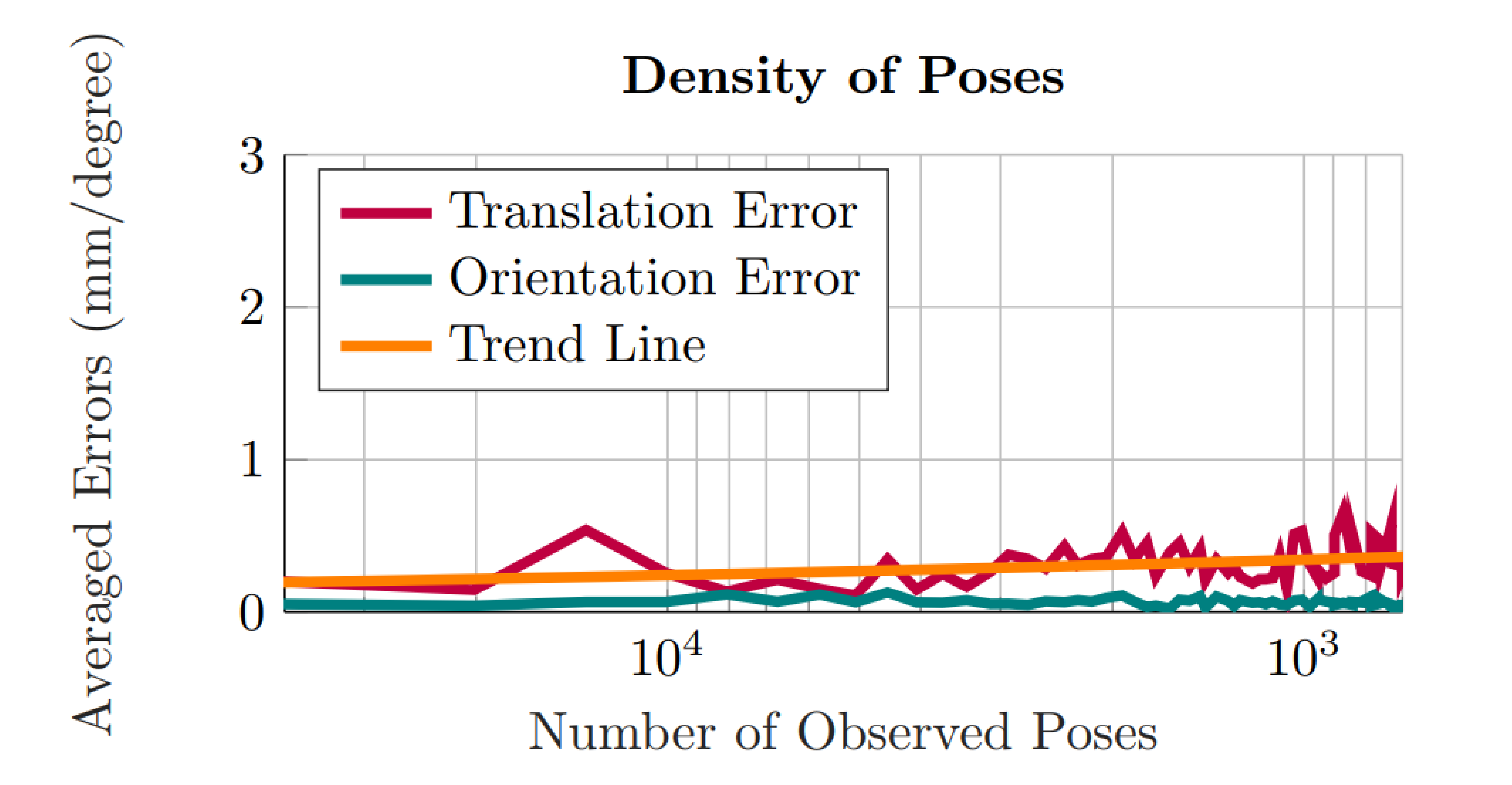


Results – number of observed trajectories





Results – number of observed poses



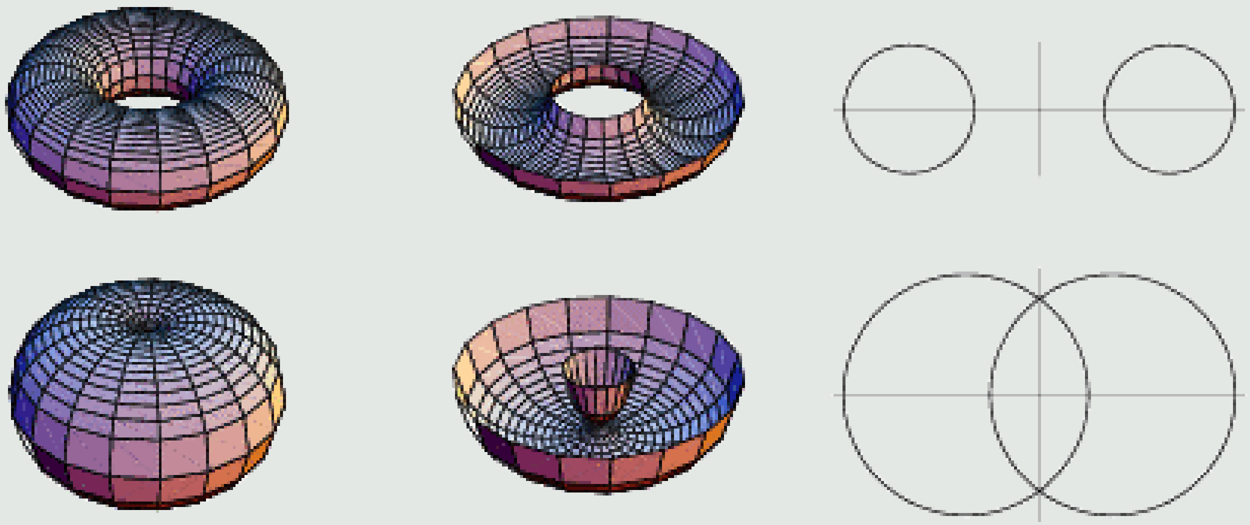
THANK YOU!

Resulting shape

Full view | Cutaway | Cross-section

Ring torus

Spindle torus



Adapted from: http://mathworld.wolfram.com/Torus.html, retrieved 01/28/2020

Solution #1:

Solve the 3D circle fitting energy for the pivot locus

$$\underset{c,n,rmaj,t}{\arg\min} \sum_i (||Ti(t) - c\,|| - rmaj)^2 + \langle Ti(t) - c, n\rangle^2 \; subject\ to\ \|n\| = 1$$

Or fit the Torus in its parametric form of the spindle torus.

Parametric form of the spindle-torus-like shape for c-arm movement

$$g(\alpha,\beta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix} \begin{bmatrix} t_x \\ t_y \\ r + t_z \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ R \end{bmatrix}$$

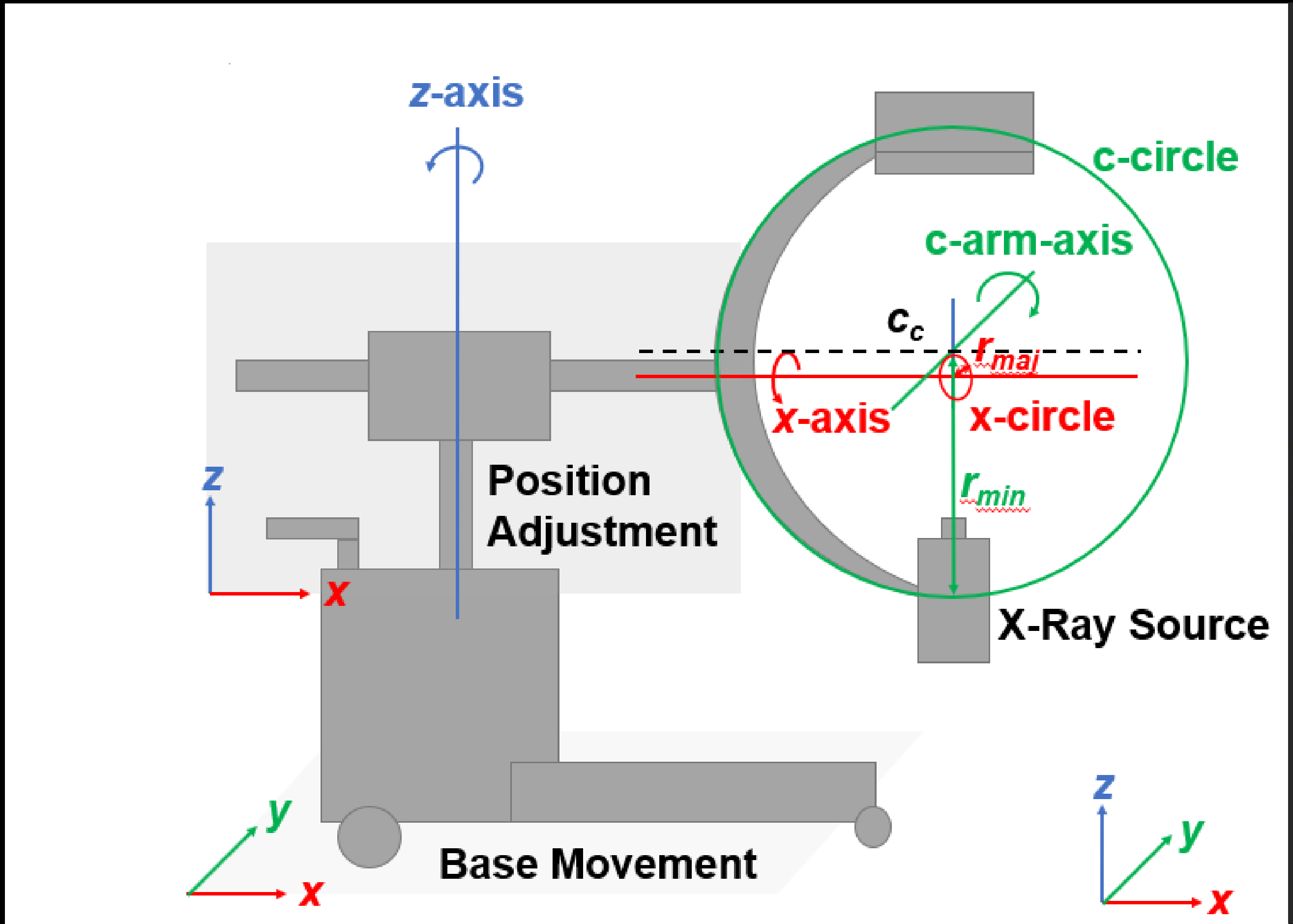
$$= \begin{bmatrix} (r+t_z)\sin\beta + t_x\cos\beta \\ t_y\cos\alpha - ((r+t_z)\cos\beta - t_x\sin\beta + R)\sin\alpha \\ t_y\sin\alpha + ((r+t_z)\cos\beta - t_x\sin\beta + R)\cos\alpha \end{bmatrix}$$

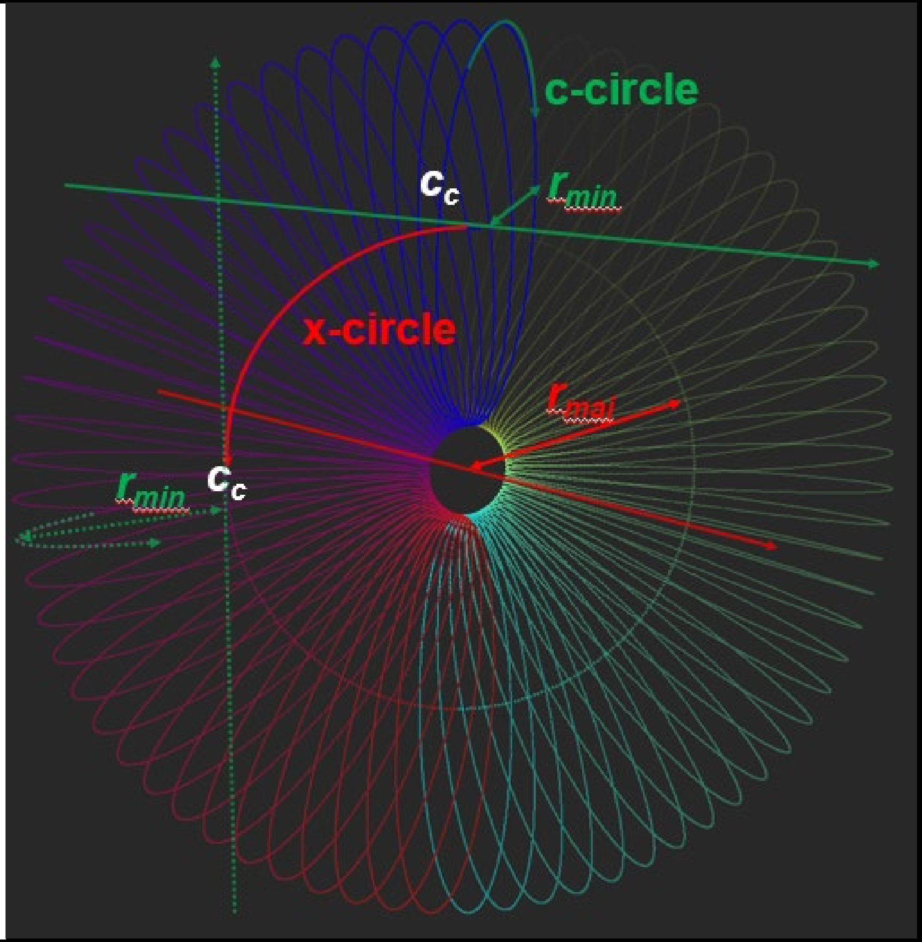
$$g(\alpha,\beta) = \begin{bmatrix} b\sin(\beta+\gamma) & (b\cos(\beta+\gamma)+R)\csc\delta\cos(\alpha+\delta) & (b\cos(\beta+\gamma)+R)\csc\delta\sin(\alpha+\delta) \end{bmatrix}^T$$

where $b = \sqrt{(r+t_z)^2 + t_x^2}$, $\gamma = \tan^{-1}\frac{t_x}{r+t_z}$, and $\delta = \tan^{-1}\frac{b\cos\beta+\gamma+R}{t_y}$.

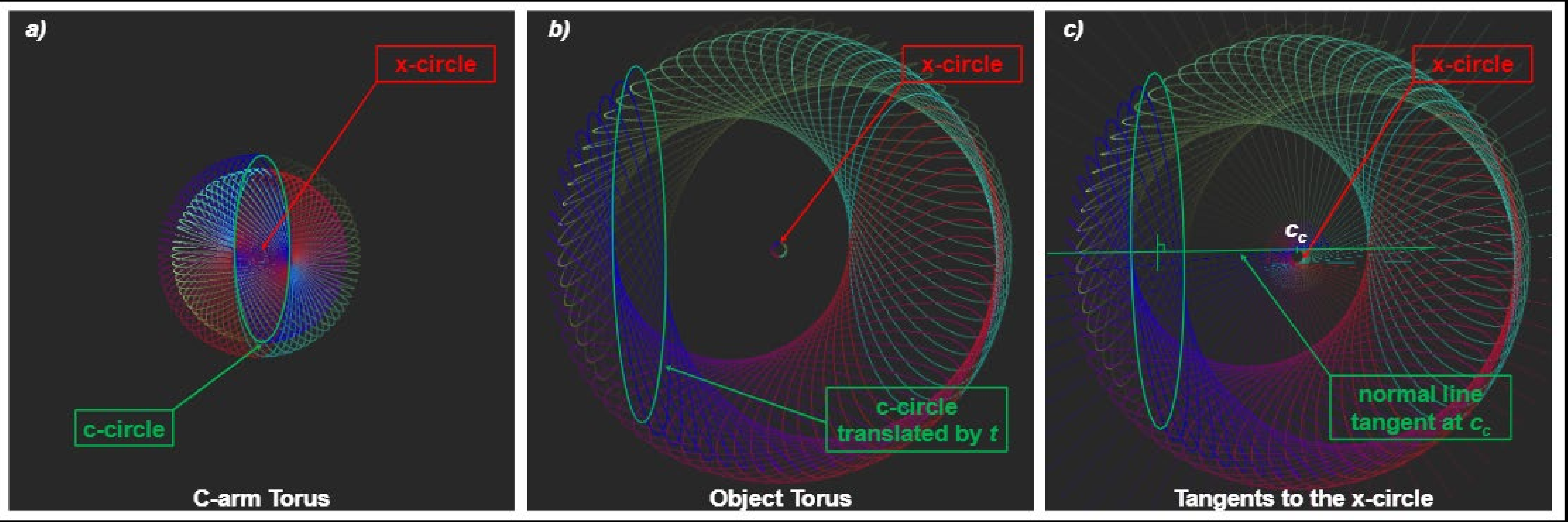
The equation shows that the sensor movement describes a generalized Torus.

Problem Formulation

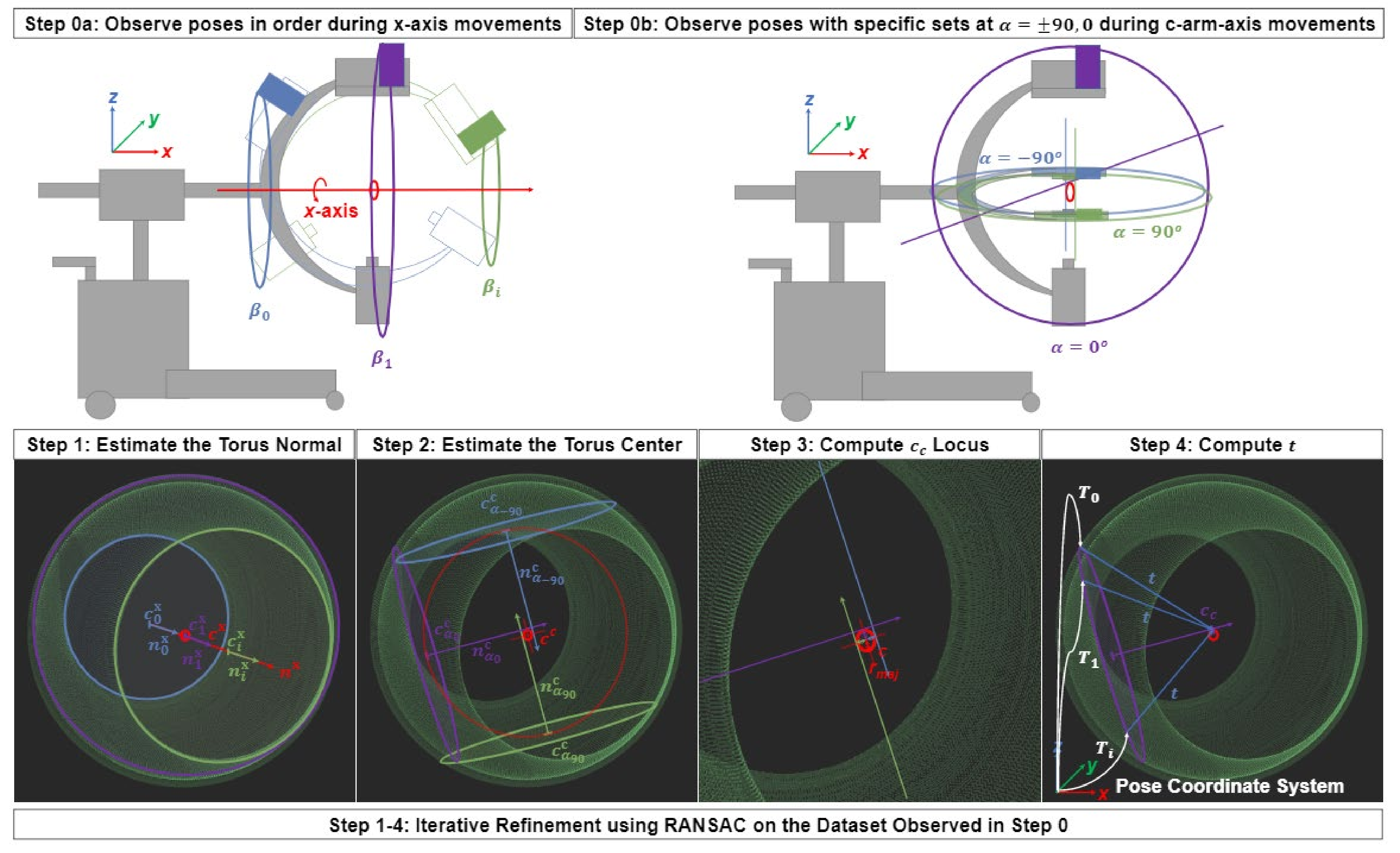




Trajectory of an object attached to the gantry



Algorithm



Step 0a: Observe poses in order during x-axis movements
Step 0b: Observe poses with specific sets at $\alpha = \pm 90, 0$ during c-arm-axis movements
z
y
x
x-axis
β_0
β_1
β_i
$\alpha = -90^o$
$\alpha = 90^o$
$\alpha = 0^o$
Step 1: Estimate the Torus Normal
Step 2: Estimate the Torus Center
Step 3: Compute c_c Locus
Step 4: Compute t
T_0
T_1
T_i
t
c_c
Pose Coordinate System
Step 1-4: Iterative Refinement using RANSAC on the Dataset Observed in Step 0