EUROPEAN
SPALLATION
SOURCE

Robotised Change Process for Lightweight Samples – a First Approach

Outline

- Task Description
- Definition of a Cryostat
- Cryostat Model Development
- Laboratory Equipment/Setup
- Implementation including Camera Calibration and Image Evaluation
- Results and Outlook

Definition of the Task

- Simulate exemplary the Sample Change Process on a Cryostat of a Neutron Instrument

- **Goal of the Thesis**: Develop and implement the process of **inserting a slim, lightweight Sample Stick** (330 mm long, weight <10 g) assembled with three equally spaced (dL≈ 100 mm) thin disk-shaped plates (baffles with outer **Ø 9 mm**) into a **Sample Tube** with inner **Ø 10 mm**, utilizing a **Robotic Arm**

- Coaxial alignment of both cylinder axes as precise as 0.1 mm

- Robot manipulates **Sample Stick** in a final move into **Sample Tube** as fast as possible (≈ 50 mm/s)

Cryostat

- Keyword: Sample Environment on Neutron Instruments
- Apparatus or fluid container maintaining very low temperatures* for an object or sample under study
- Induce a sample in a state (physical/chemical) of particular interest, during a neutron scattering experiment
- Wide temperature range: T = 50 mK – 2100 K**, Variable magnetic fields: up to B = 15 Tesla**
- Equipped with Supporting Systems (valves, heater, thermometry sensor, electrical + mechanical interfaces)

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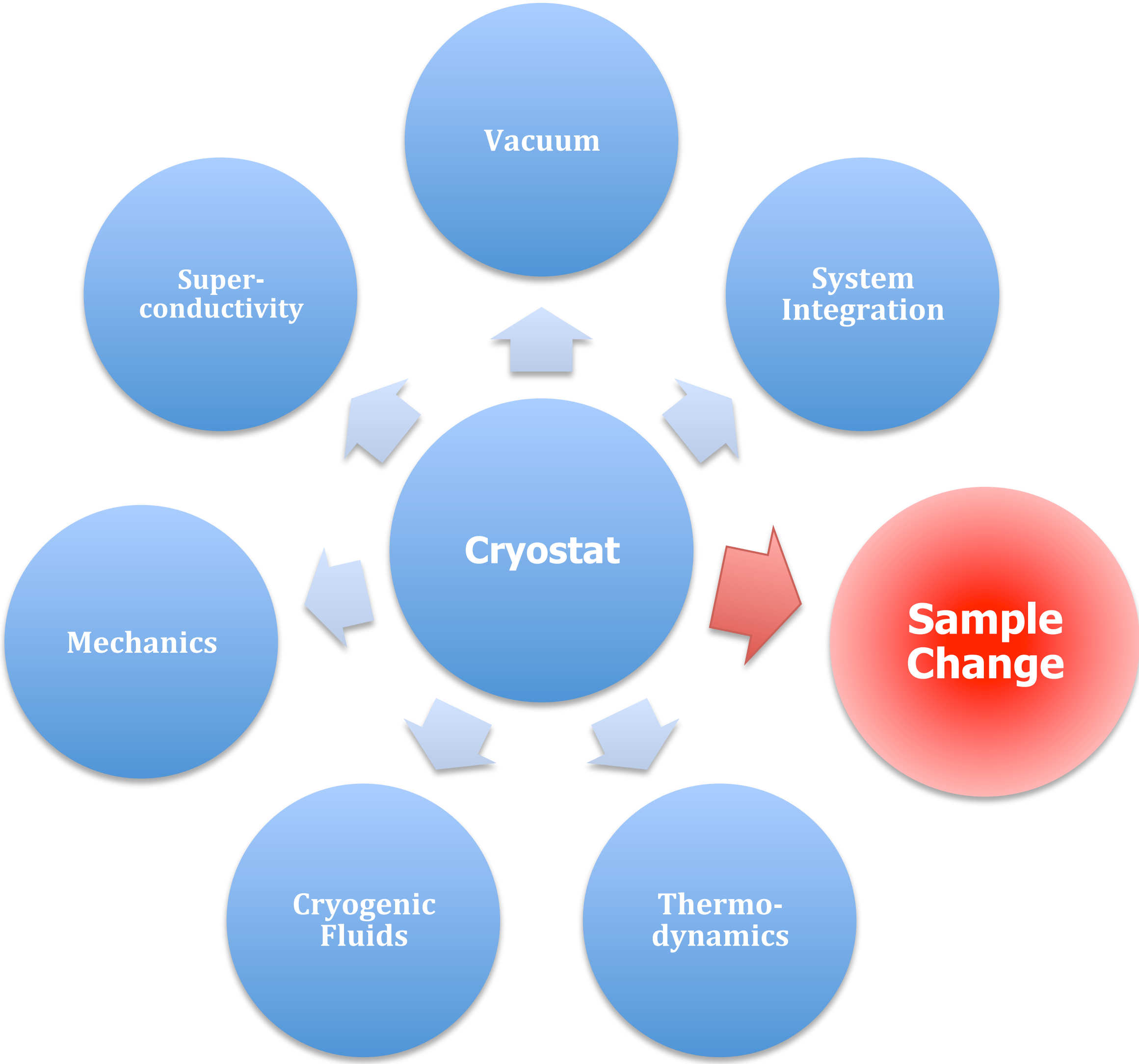
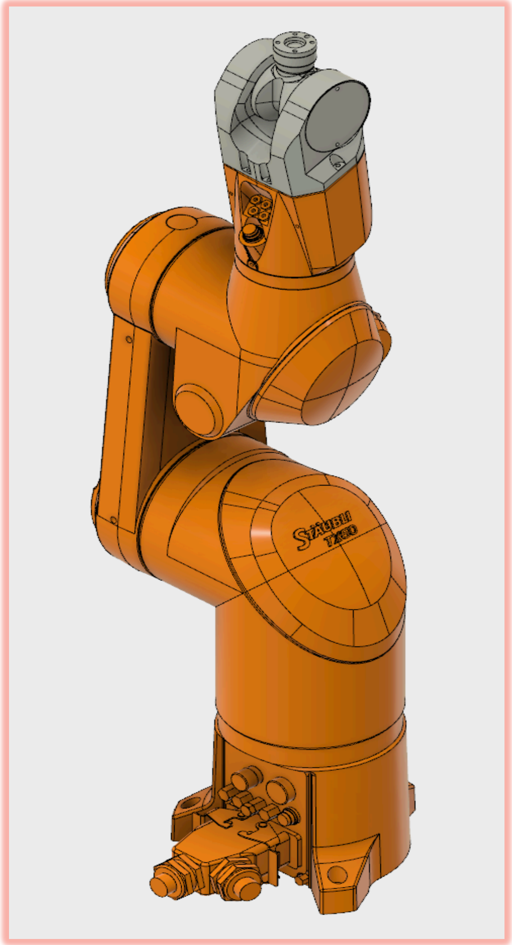
*) cryogenic temperatures, typically below 120 K
**) in combination with Dilution Refrigerator Sticks

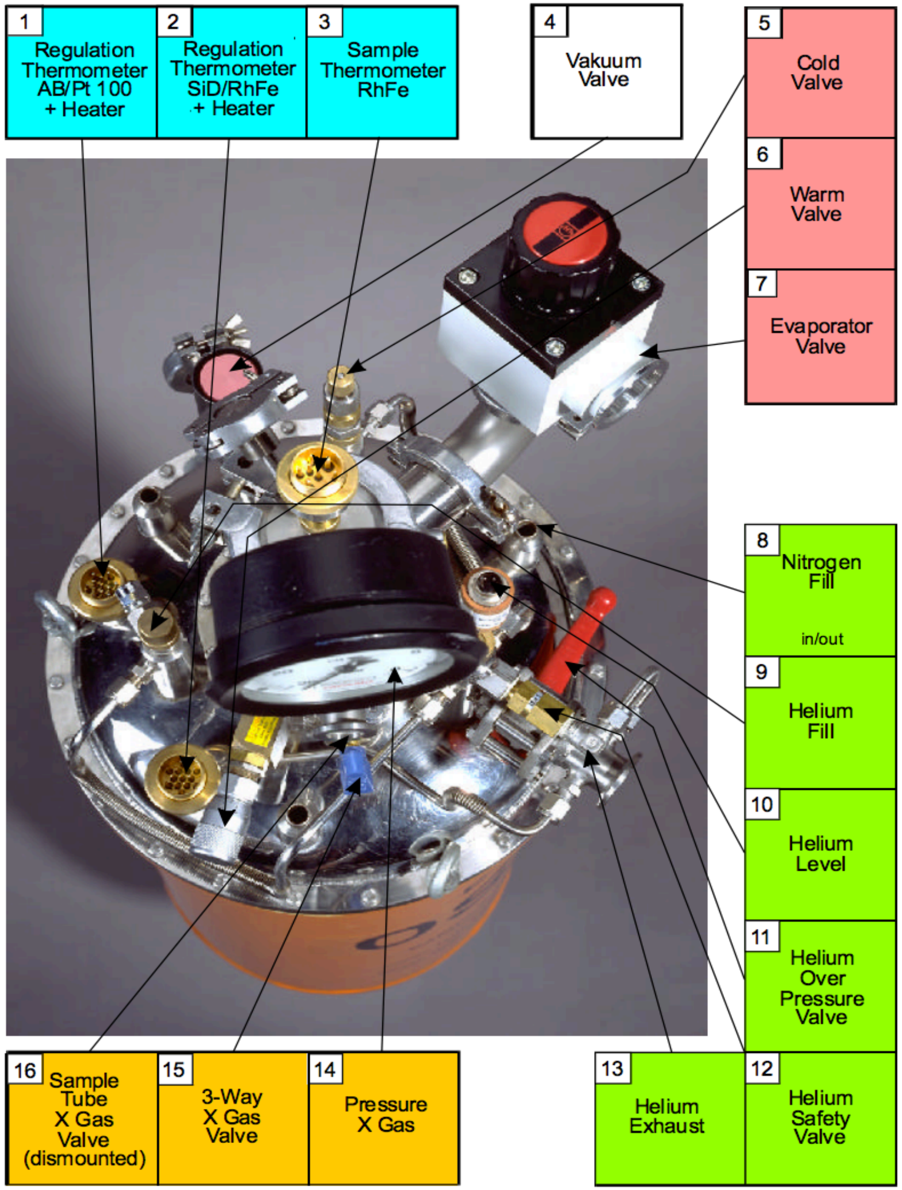
Cryostat – Interacting Engineering Disciplines



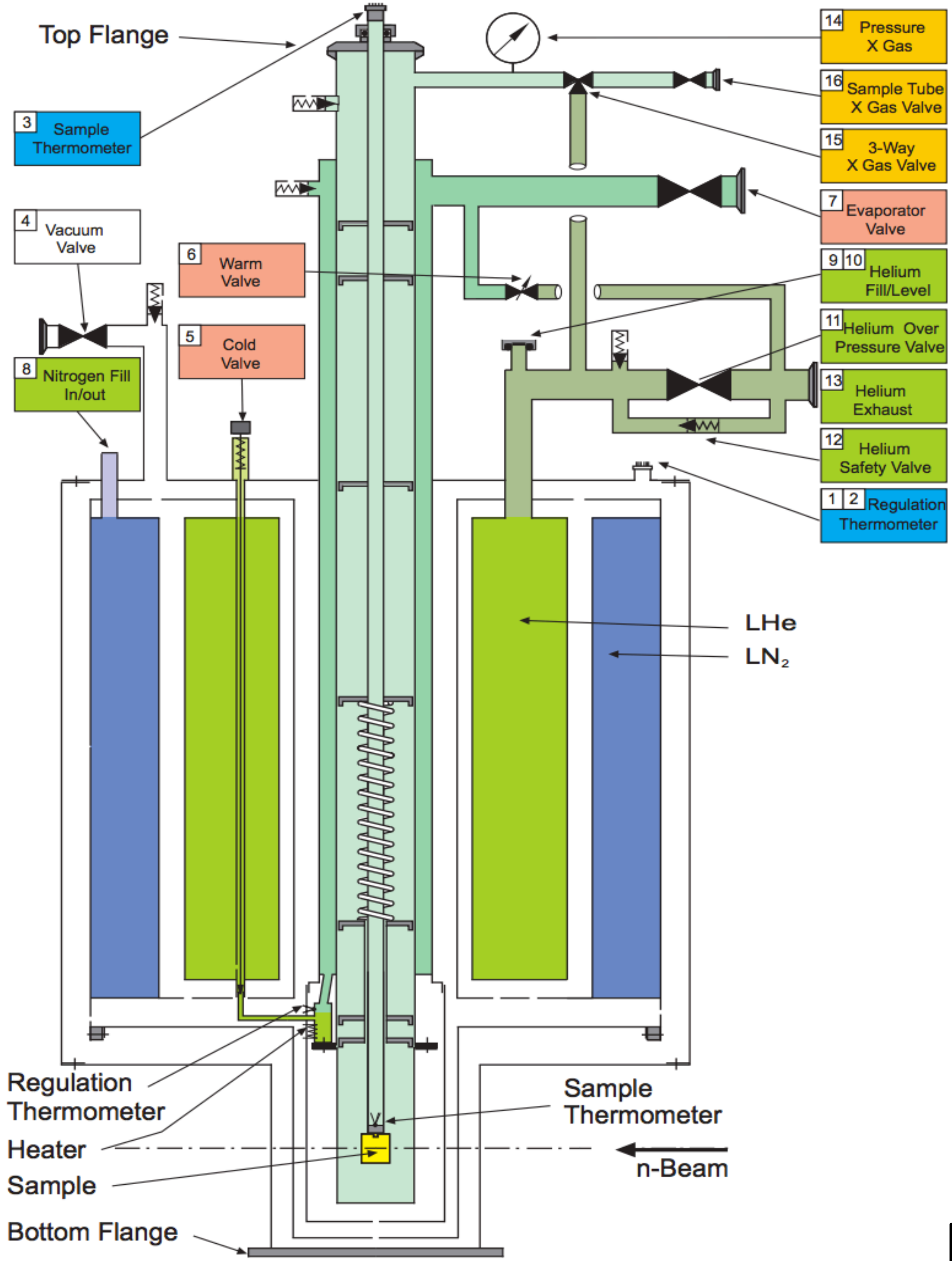
Robotics



Cryostat



1 Regulation Thermometer AB/Pt 100 + Heater
2 Regulation Thermometer SiD/RhFe + Heater
3 Sample Thermometer RhFe
4 Vakuum Valve
5 Cold Valve
6 Warm Valve
7 Evaporator Valve
8 Nitrogen Fill in/out
9 Helium Fill
10 Helium Level
11 Helium Over Pressure Valve
12 Helium Safety Valve
13 Helium Exhaust
14 Pressure X Gas
15 3-Way X Gas Valve
16 Sample Tube X Gas Valve (dismounted)



Top Flange
3 Sample Thermometer
4 Vacuum Valve
8 Nitrogen Fill In/out
6 Warm Valve
5 Cold Valve
14 Pressure X Gas
16 Sample Tube X Gas Valve
15 3-Way X Gas Valve
7 Evaporator Valve
9 10 Helium Fill/Level
11 Helium Over Pressure Valve
13 Helium Exhaust
12 Helium Safety Valve
1 2 Regulation Thermometer
LHe
LN₂
Regulation Thermometer
Heater
Sample
Bottom Flange
Sample Thermometer
n-Beam

[2]

Cryostat Model Development

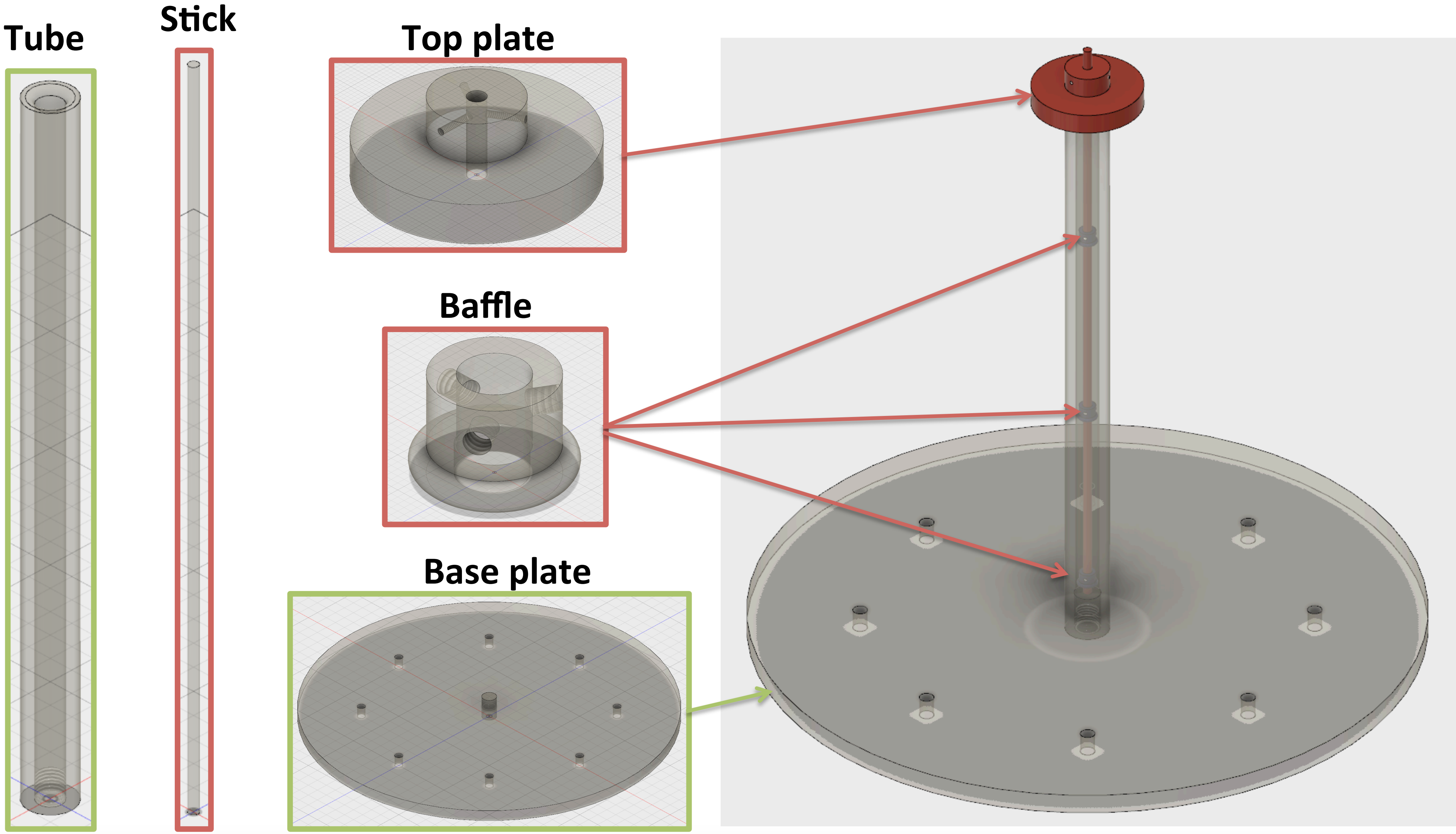
Requirements

- User-selectable sequencing
- Sample identification and sequence monitoring/recording
- High sample throughput within reasonable times
- No significant influence of cryostat performance, e.g. regarding temperature changes
- Unattended operation cycle with application-specific amount of appropriated samples
- Potential of increasing the sample throughput
- Accuracy and reliability of sample change mechanics
- Flexibility in terms of ensuring location-independent mobility

Laboratory Conditions – Most relevant Differences

- No Cryogenic Environment, instead Room Temperature Conditions
- Use of different Materials/Dimensioning compared to a real Cryostat
- Focus on Sample Change Procedure only

Cryostat Model Development



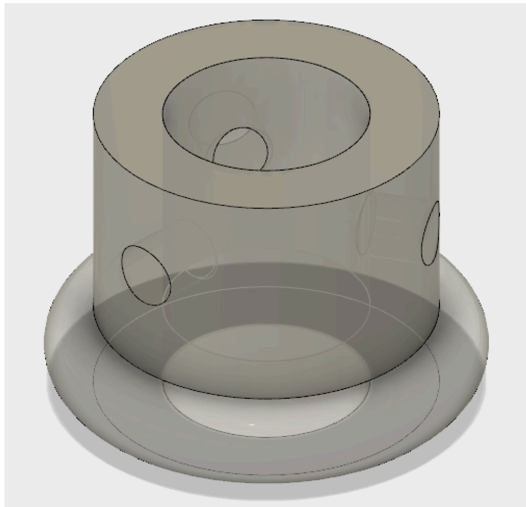
Top Plate & Baffle – Redesign update

Top plate

- 3D-printed
- Cavity inside to save weight
- Holes on top to remove redundant powder
- Small notch near the bottom for QR-code stamp
- Conical bottom part to centralize stick while inserting into tube
- Fixation holes not threaded

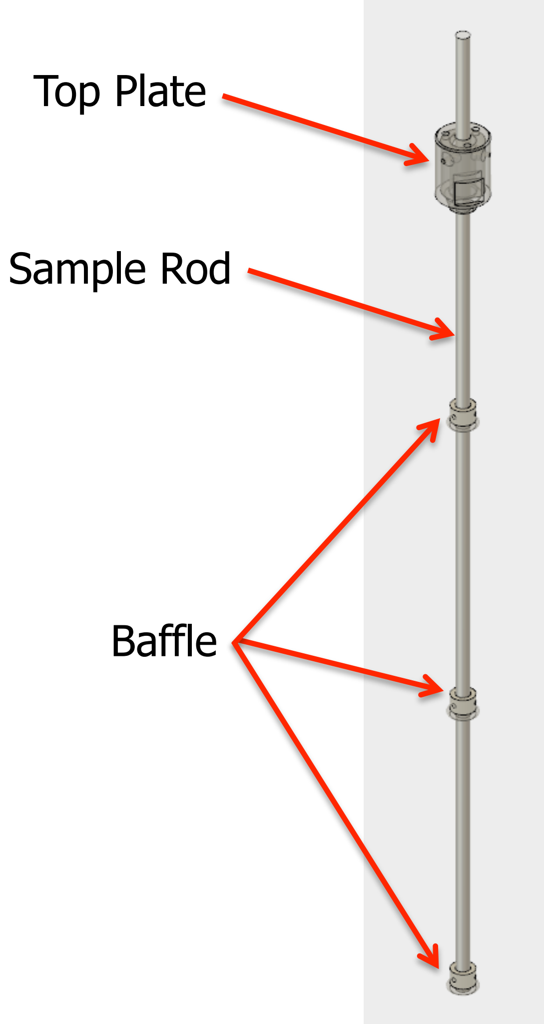
Baffle – distance disk

- 3D-printed
- Fixation holes not threaded

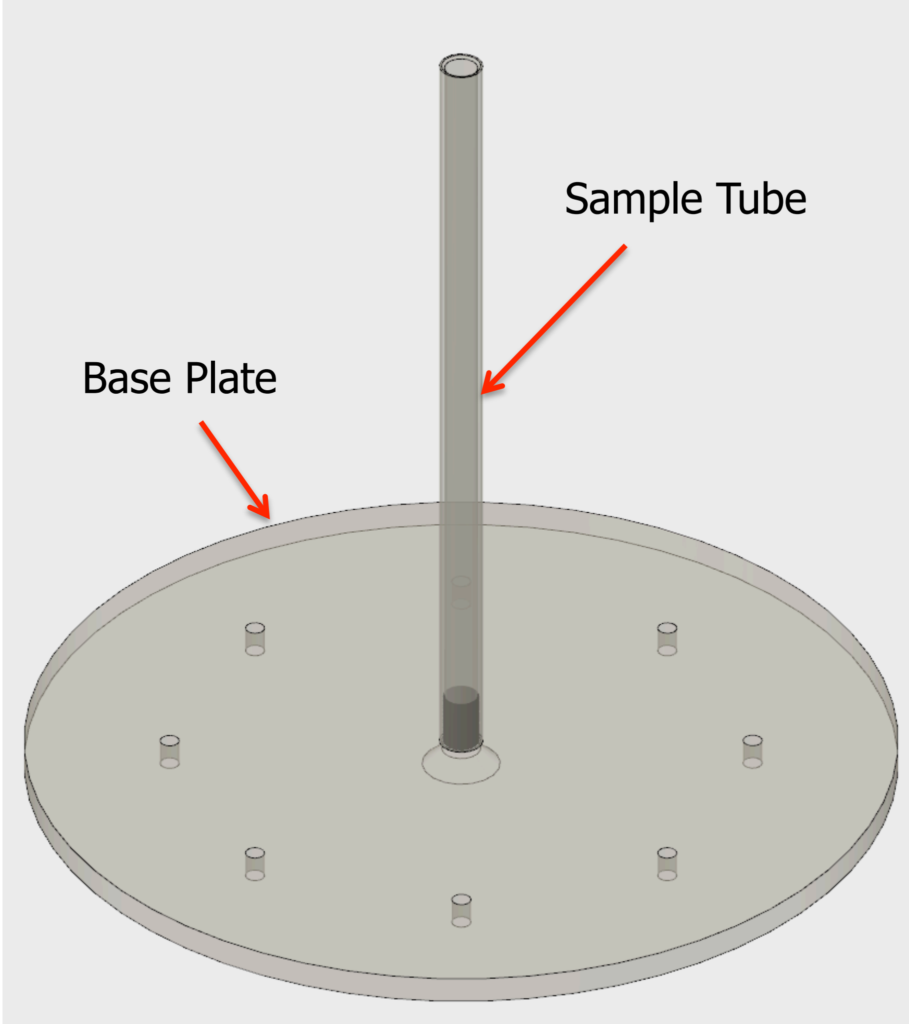


Laboratory Setup – Cryostat Model

Sample Stick



Cryostat Model



Laboratory Setup – Cryostat Model

Sample Stick + Cryostat Model

Sample Magazine fully equipped with Sample Sticks

Laboratory Setup – Gripper Fingers

2-finger Parallel Gripper from Schunk, Pneumatic, Model: JGP 80-1 gripper

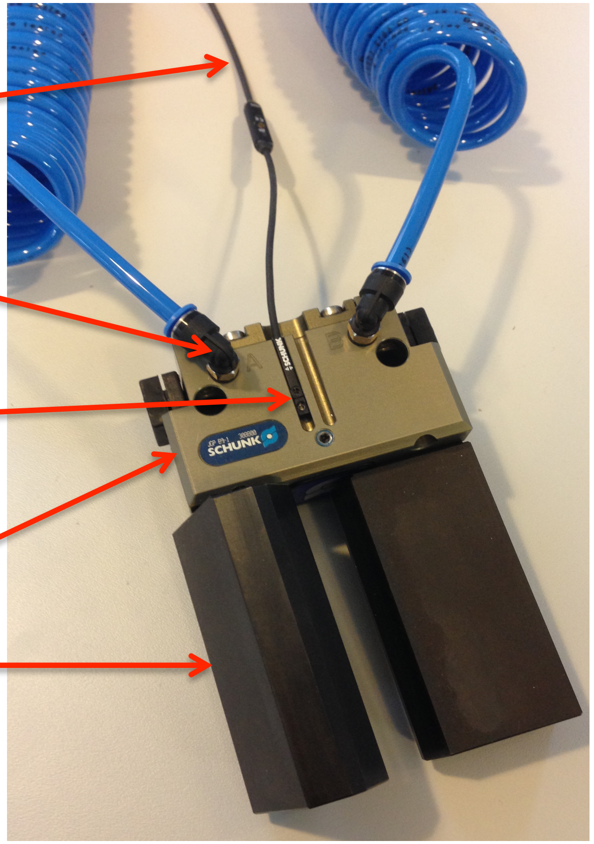
Electric connection

Pneumatic connection

Position sensor

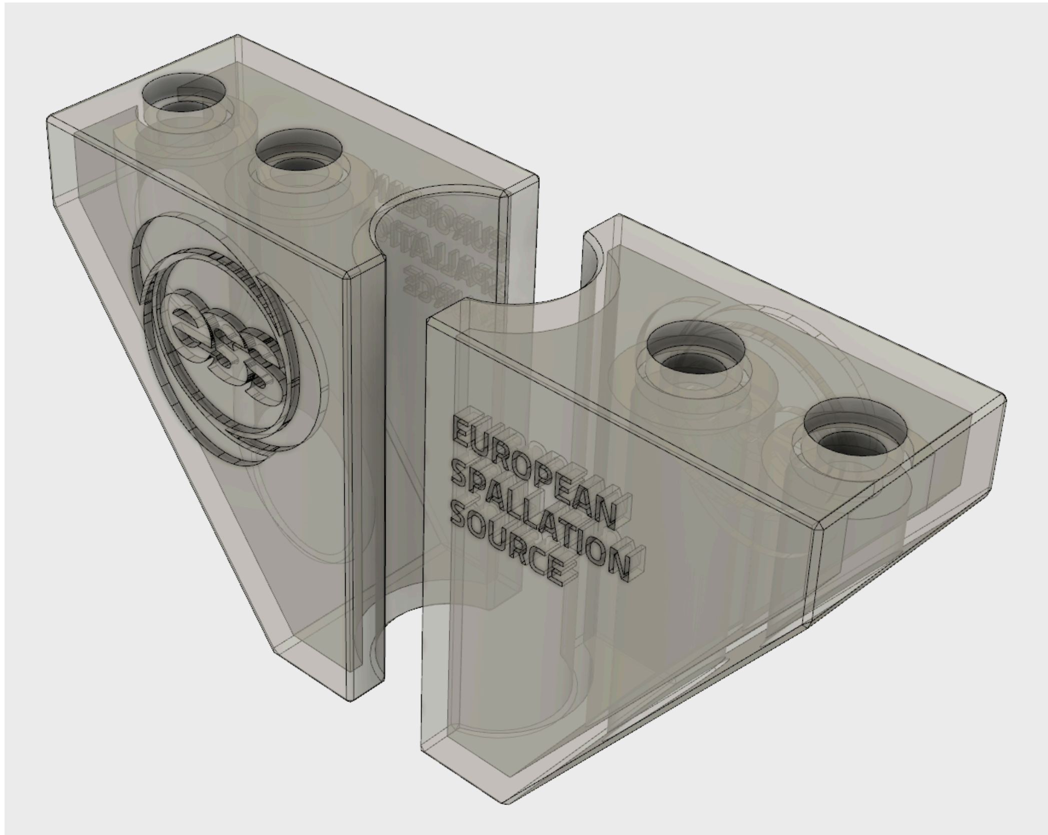
Gripper mechanics

Finger blanks



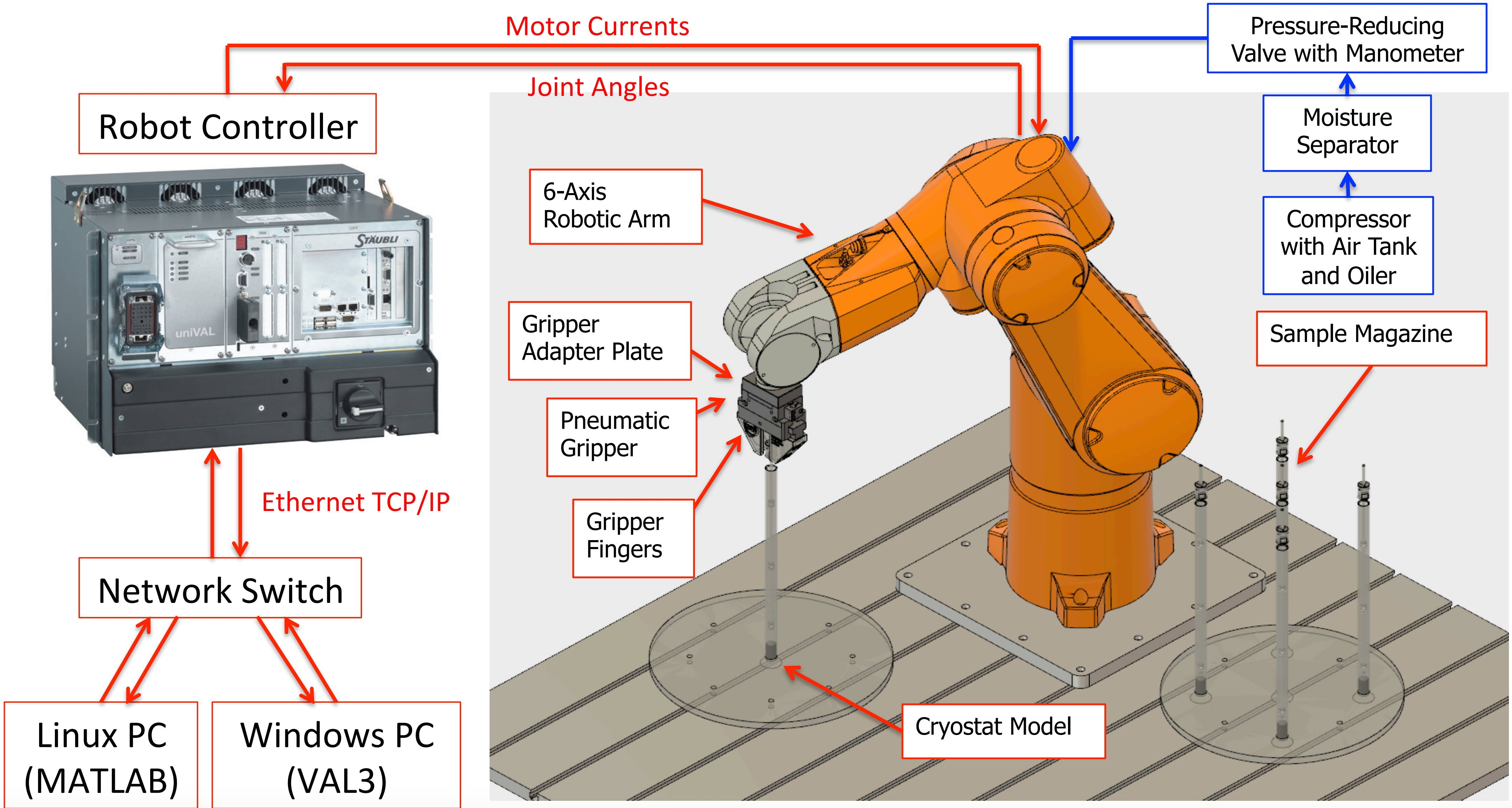
876 g (43,5%)

Custom-made Gripper Fingers, with Semi-Circular Notch matching Top Plate Dimension of the Sample Stick, 3D-printed



28 g (0,9 %)

Laboratory Setup – Robot Cell



Visual feedback - Cameras

2 x Basler GigE Cameras with Lenses and Illumination

- CMOS Sensor Type, 1/2.5 inch Sensor Size
- 2592 x 1944 (5 MP) Resolution
- Image area 35 x 47 mm (Portrait Format, 4:3)
- 14.6 Frames per Second
- Working distance ≈0.15 m
- Monochrome, Software Trigger
- C-Mount Telephoto Lens (25.12°), 16 mm, f/1.4 - f/16, MOD 0,1 m

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Image Evaluation & Communication with Robot Controller

- Software: Matlab + Toolboxes
- TCP/IP Connection
- Object Identification + Alignment using Image Processing Algorithms

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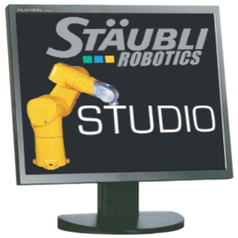

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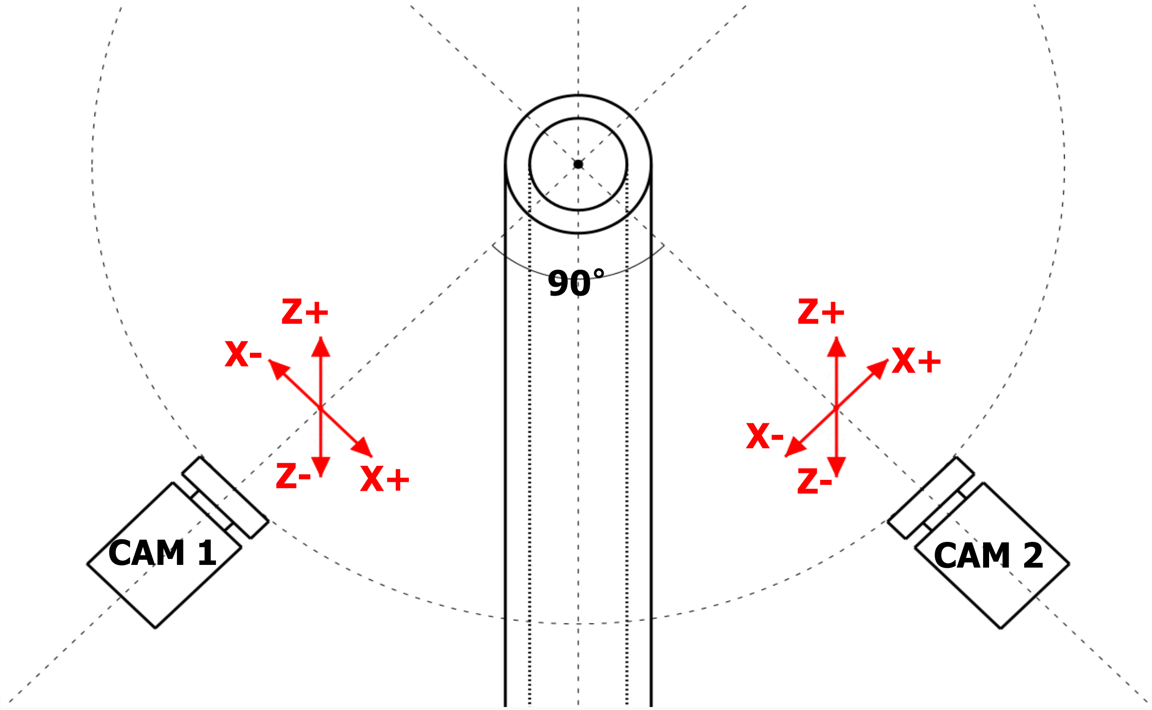
Construction Aspects – Camera Mounting

- Both Cameras on the same Height, keeping the same Distance to the Sample Tube
- Optical Axes 90° displaced (perpendicular) to each other, radiant from the Sample Tube Centreline
- Same Image Format
- Horizontal + Vertical Adjustment referred to Optical Axes
- Consider Geometric Constraints given by Experimental Table
- Stability, Cost-Effectiveness, Economic-Efficiency



Construction Aspects – Camera Mounting

Design A

- Distance
- Optical Axes Intersection

Design B

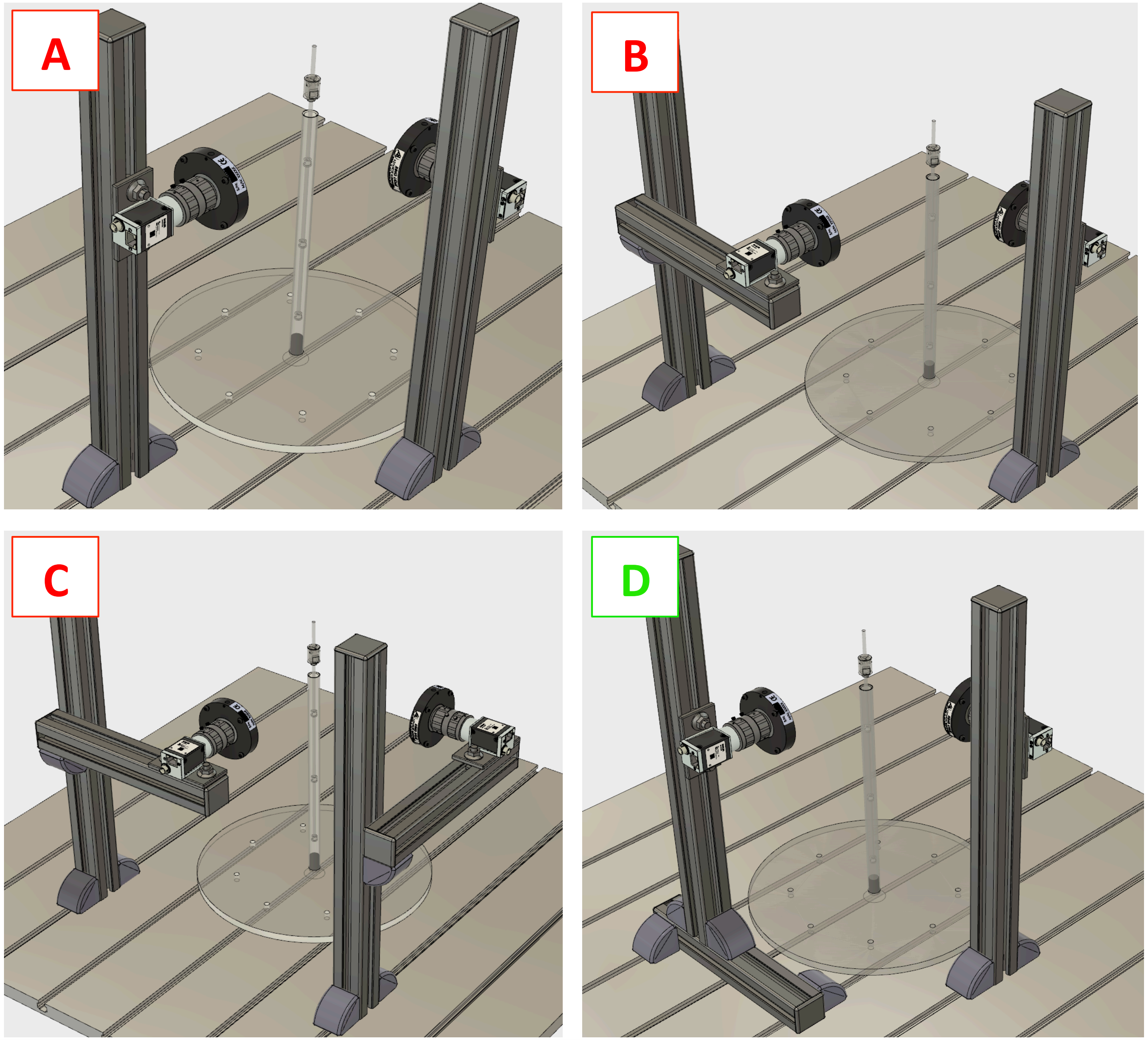
- Diverging Image Format
- Design Aspects

Design C

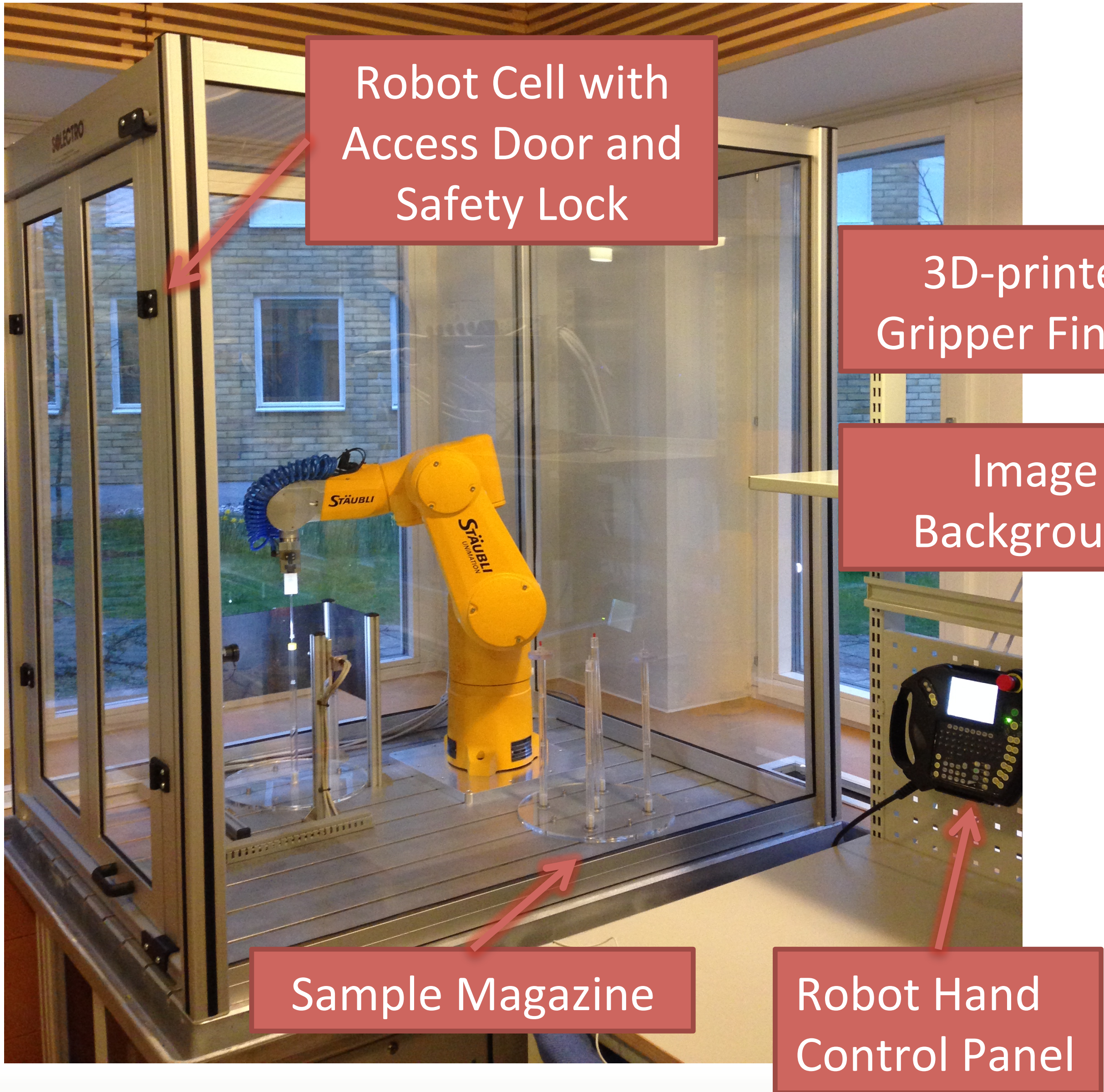
- Landscape Image Orientation
- Design Aspects

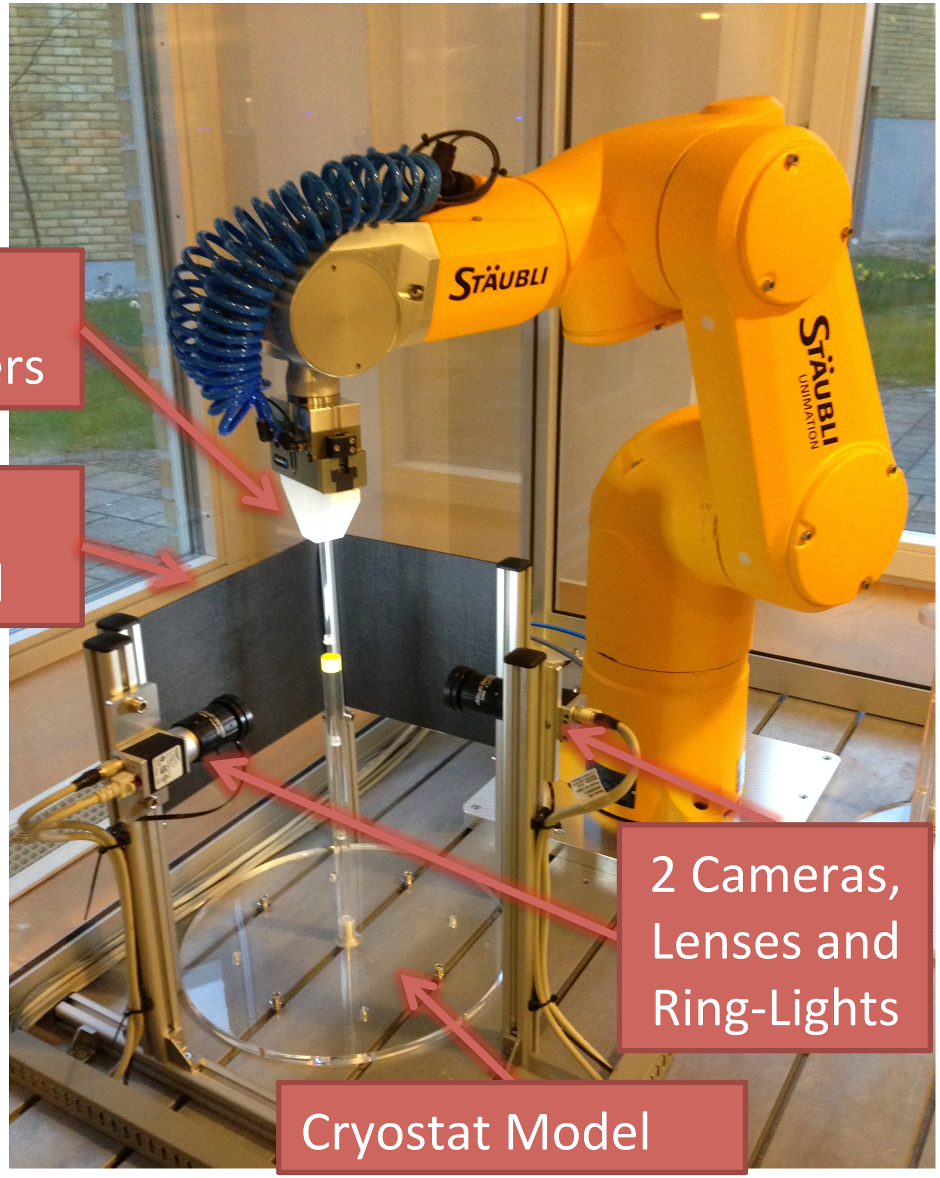
Design D

✓



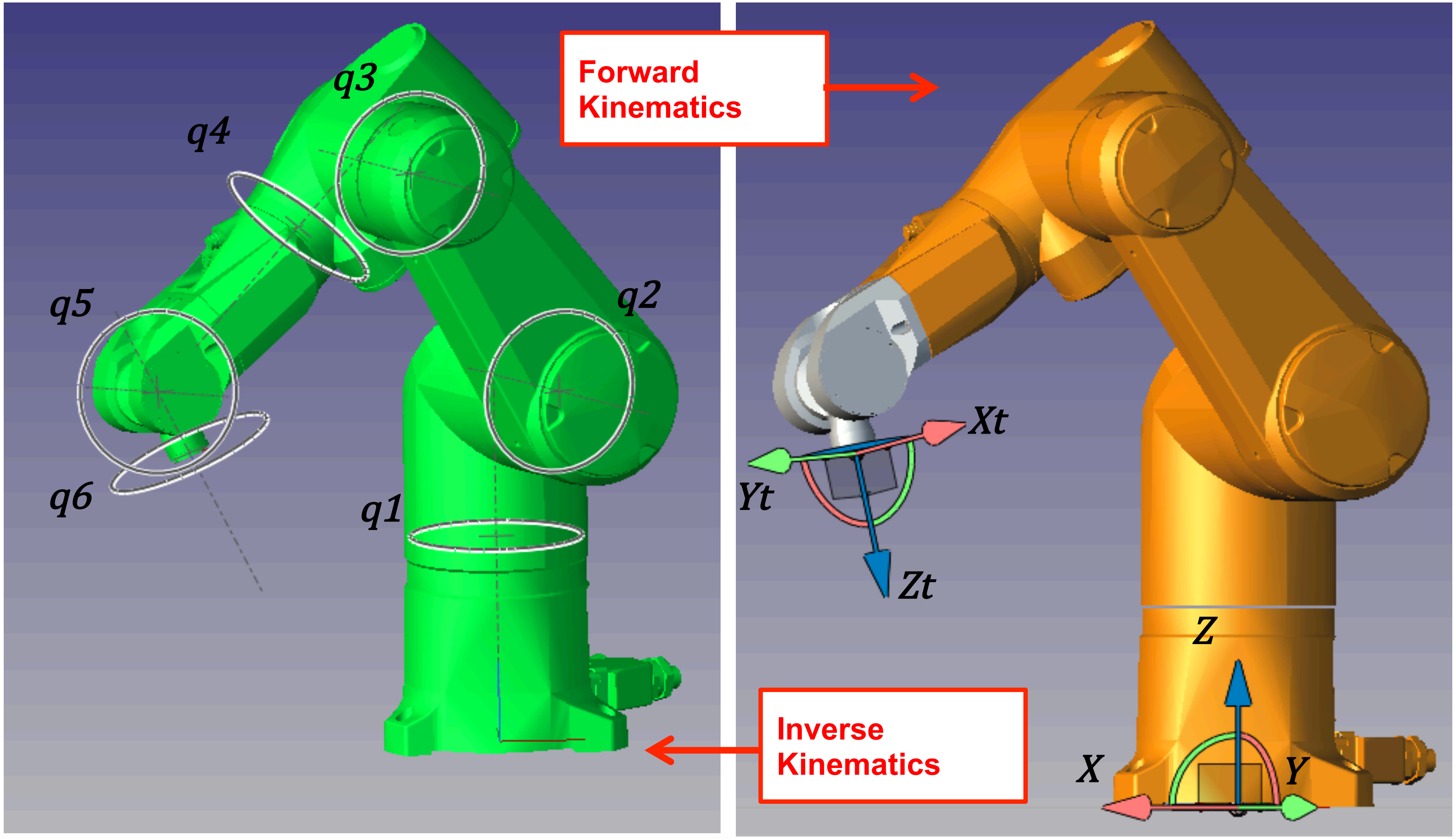
Laboratory Setup – Robot Cell





Implementation – Robot Positioning

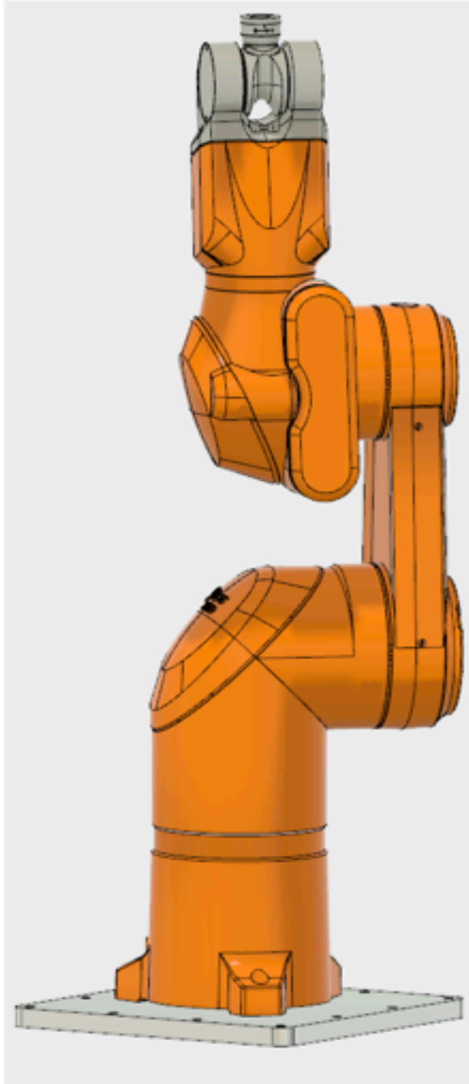
Joint Angle Coordinate System | **Cartesian Coordinate System**

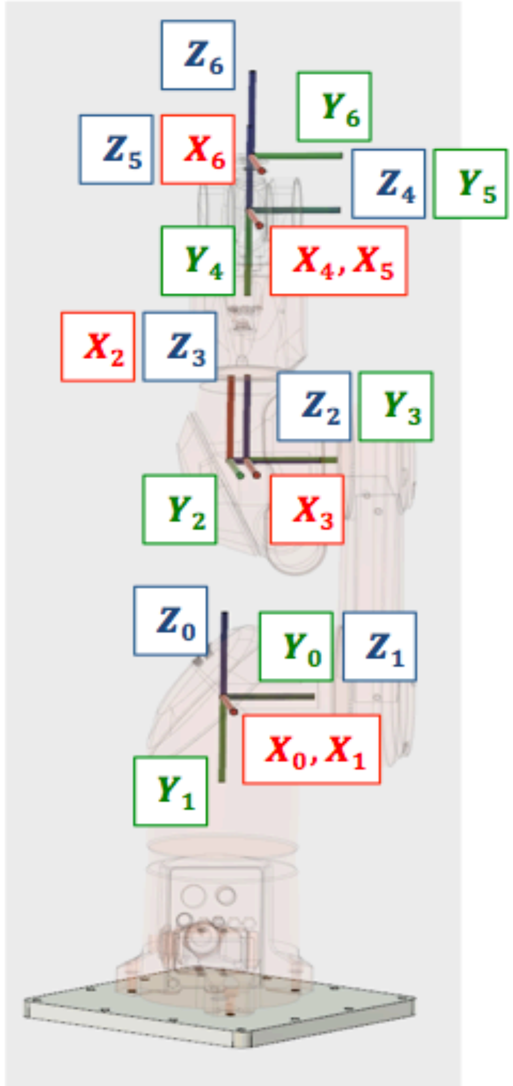


Implementation – Stäubli TX60 Forward Kinematics

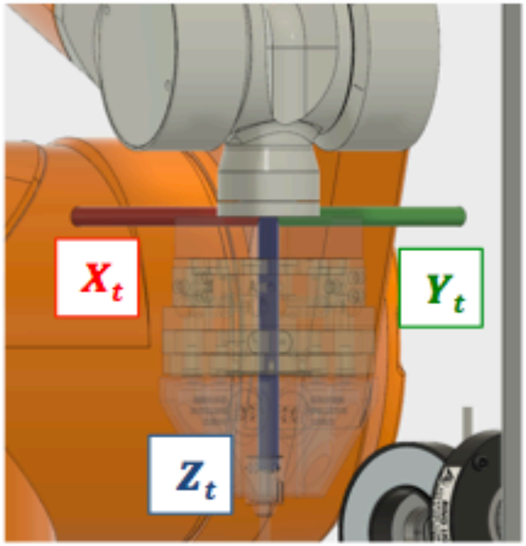
Apply Denavit-Hartenberg Theorem

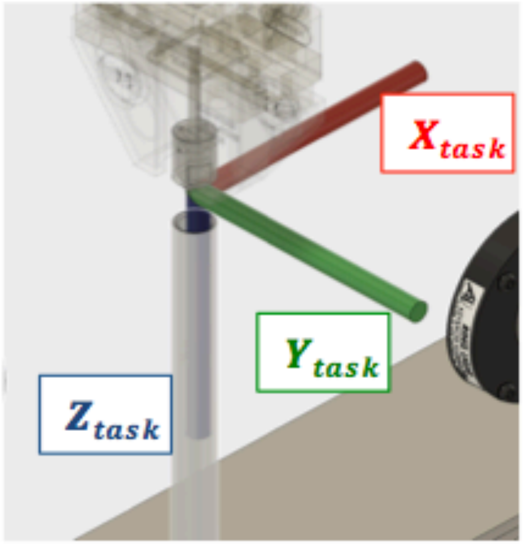
1. Define coordinate systems in each joint of the robot according to the rules from DH
2. Identify DH-parameter and tabularize them
3. Calculate DH-transformation matrices
4. Multiply DH-matrices in the right order
5. Consider additional new reference coordinate system, e.g. for an application-specific tool mounted on the end-effector

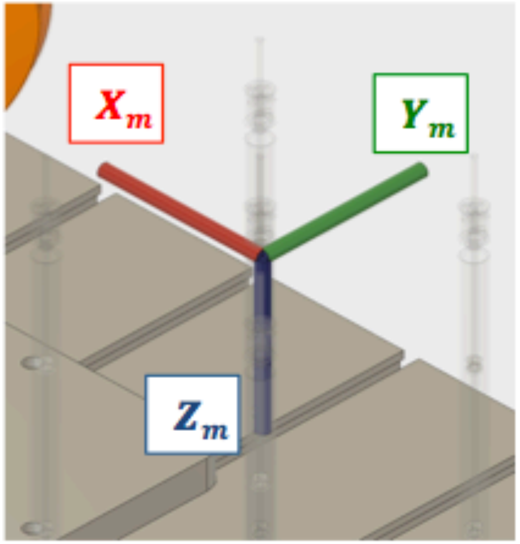


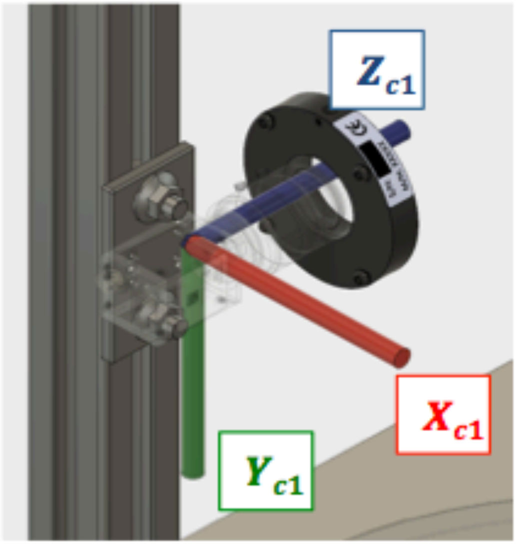


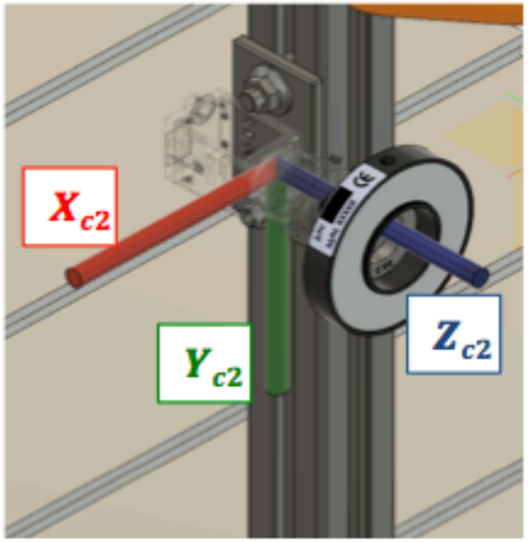
Implementation – Definition of Coordinate Systems

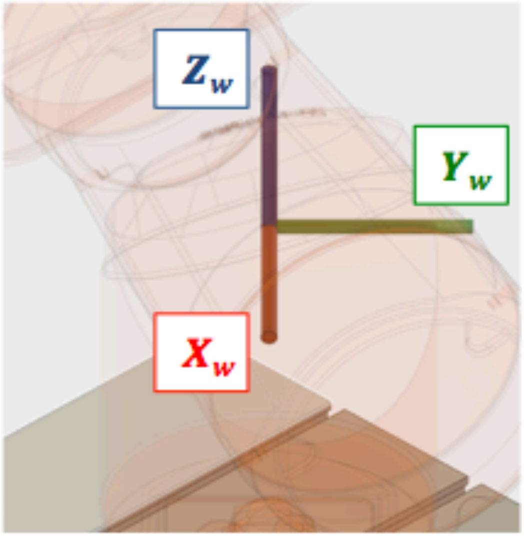












Implementation

- Starting point of the robot → home position $\vec{q} = (0,0,0,0,0,0)^T$
- Fully equipped Sample Magazine
- No Sample Stick inserted in Cryostat Model

Gripping Process

- Sample stick position and orientation taught to the robot
- User selectable sequencing
- Ensure safe gripping of the Sample Stick

→

Trajectory Planning

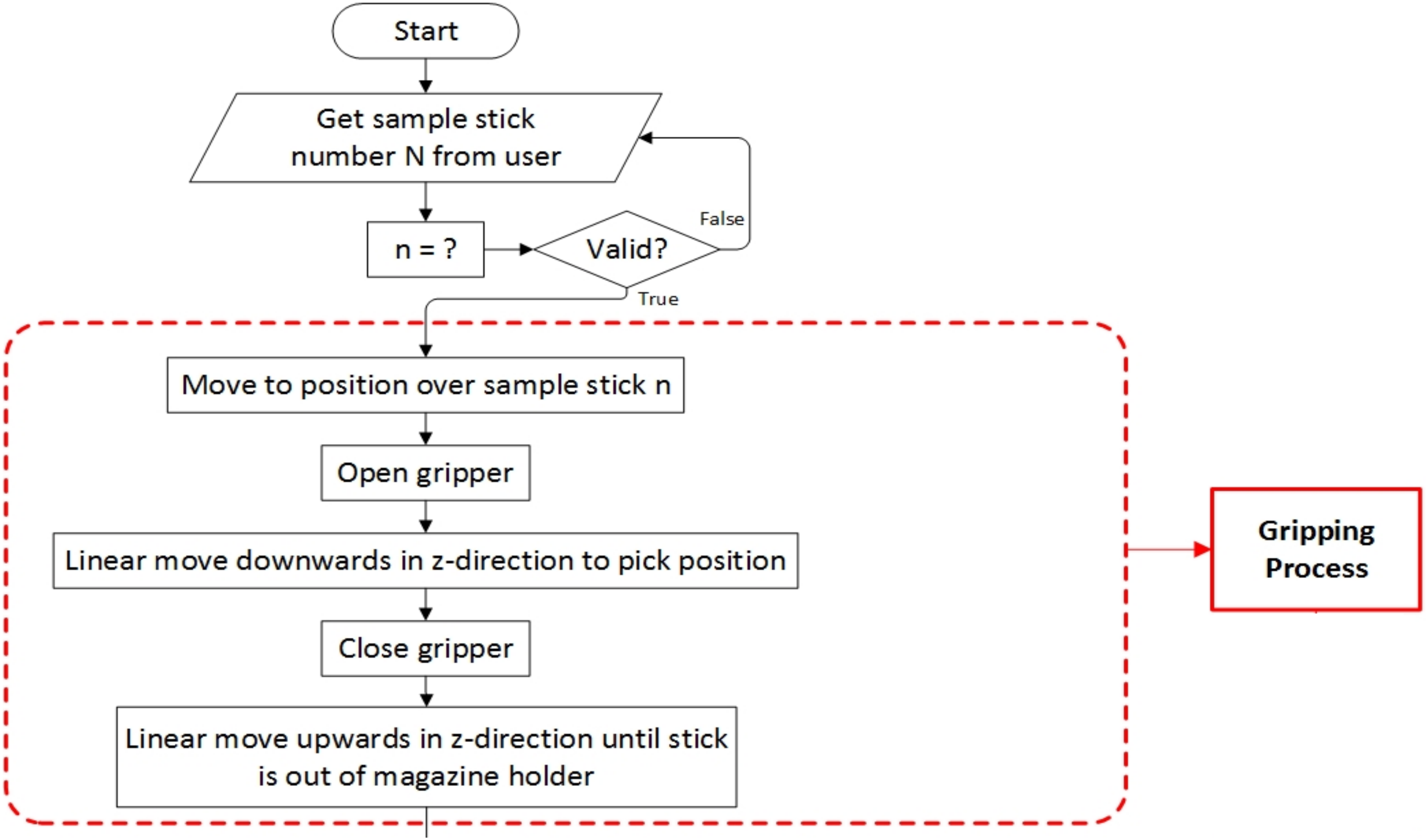
- Smooth transfer of Sample Stick avoiding collisions
- Preferably no interruption of the movement
- Position Sample Stick within Image Area of the Cameras

→

Placement Process

- Camera Initialization
- **Camera Calibration**
- **Image Evaluation**
- **Position-based Visual Servoing**
- QR-Code reading to identify Sample

Implementation – Gripping Process



Implementation – Gripping Process

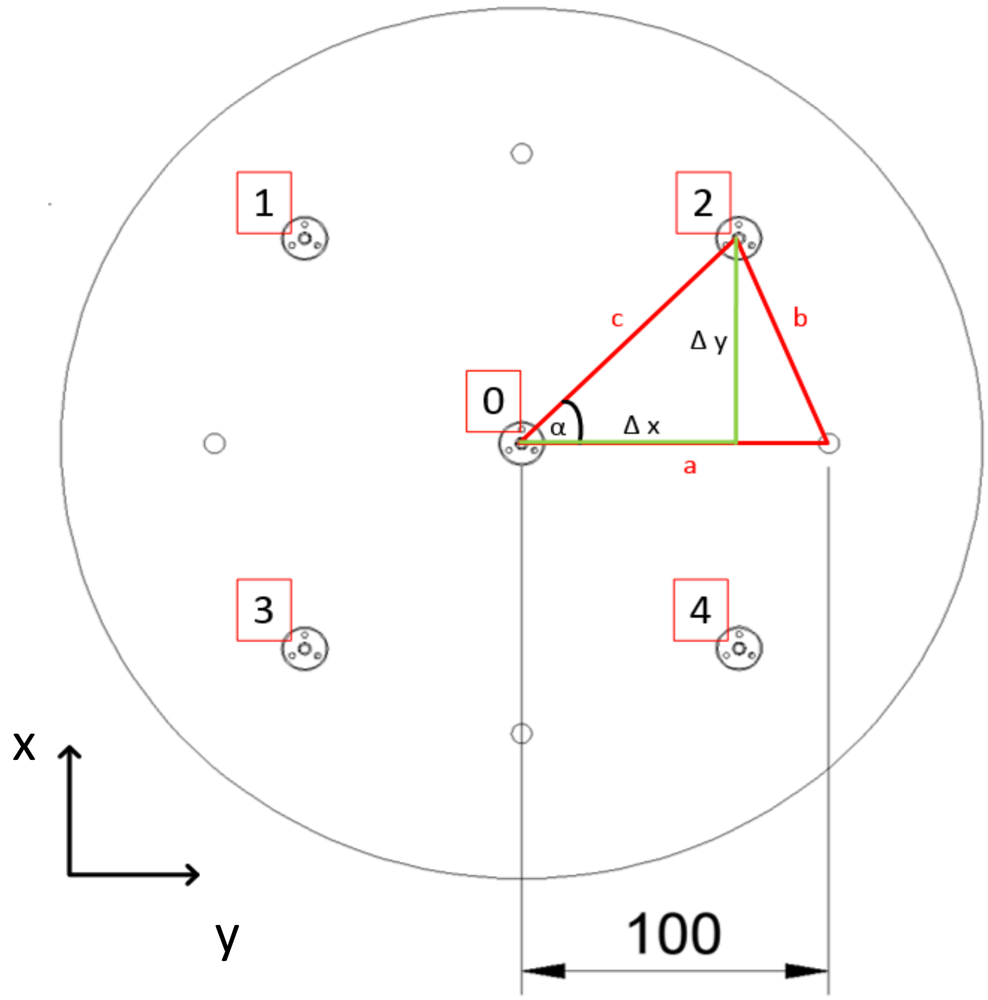
Sample Magazine Top View

$$\Delta x = \cos\alpha * c \qquad \Delta y = \sin\alpha * c$$

$$a = c = 100\,mm \text{ and } \alpha = 45°$$

$$\Delta x = \Delta y = \frac{100\,mm}{\sqrt{2}} \approx 70.71\,mm$$

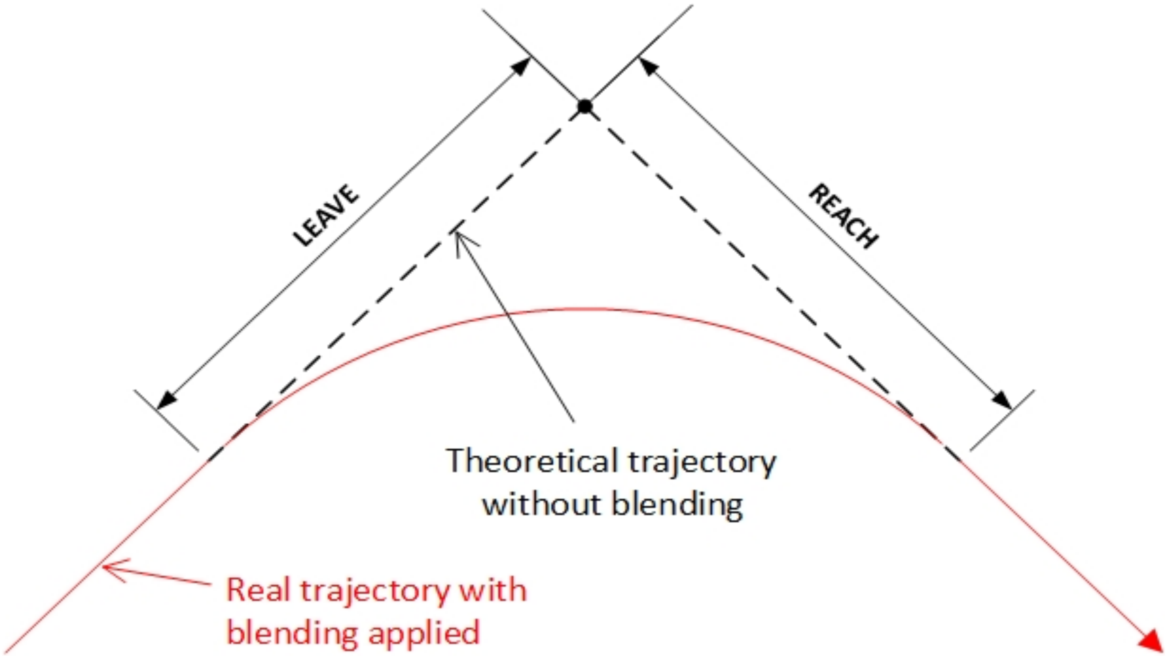
Sample stick number	Position
0	$\vec{p}_0(x,y,z)$ → Manually taught to the robot, represents origin of (X_m, Y_m, Z_m) with x-y-plane parallel to experimental table
1	$\vec{p}_1(x,y,z) = \vec{p}_1(\vec{p}_0(x) - \Delta x, \vec{p}_0(y) + \Delta y, \vec{p}_0(z))$
2	$\vec{p}_2(x,y,z) = \vec{p}_2(\vec{p}_0(x) + \Delta x, \vec{p}_0(y) + \Delta y, \vec{p}_0(z))$
3	$\vec{p}_3(x,y,z) = \vec{p}_3(\vec{p}_0(x) - \Delta x, \vec{p}_0(y) - \Delta y, \vec{p}_0(z))$
4	$\vec{p}_4(x,y,z) = \vec{p}_4(\vec{p}_0(x) + \Delta x, \vec{p}_0(y) - \Delta y, \vec{p}_0(z))$



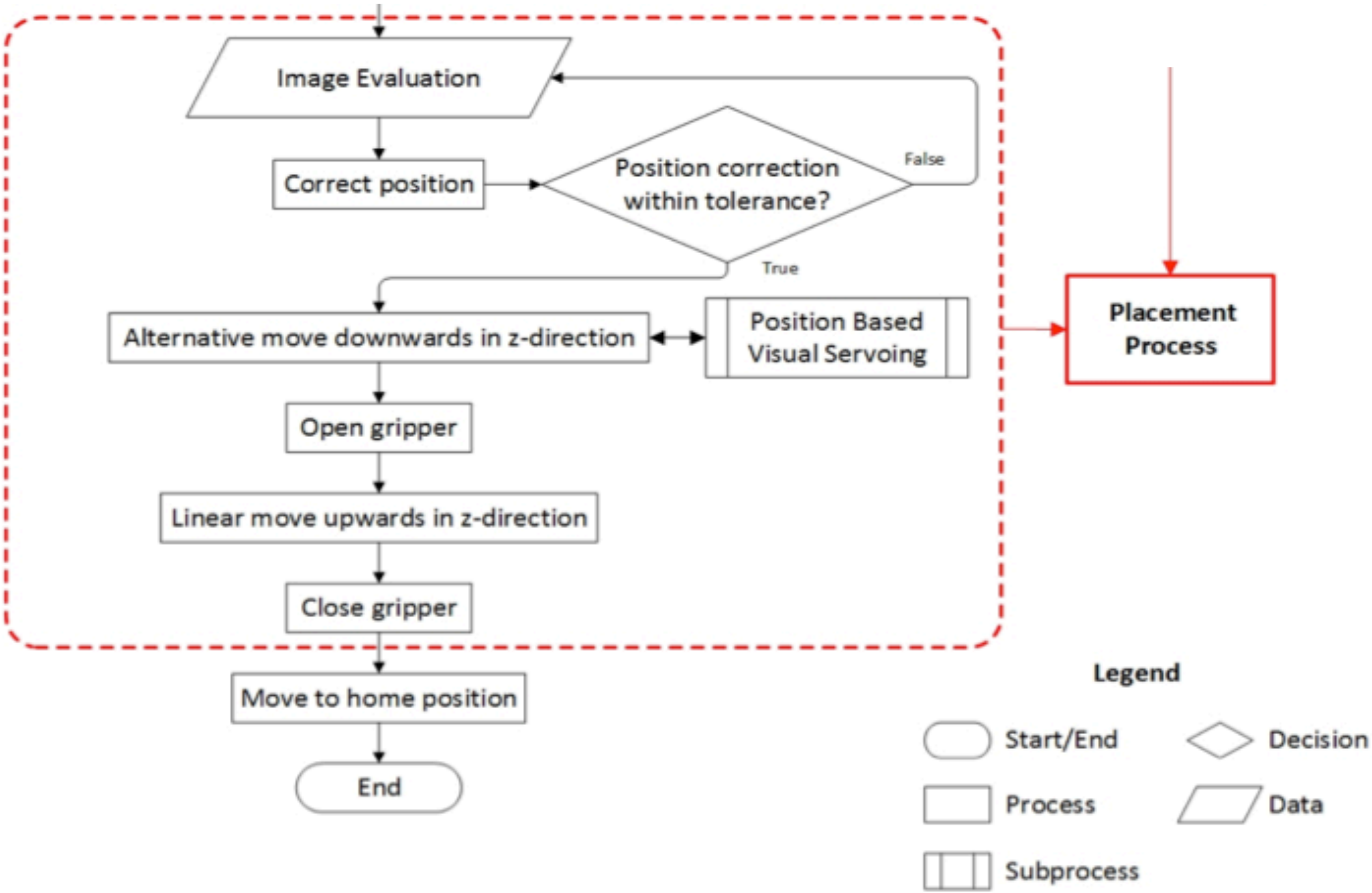
→ Only one position taught to the robot

Implementation – Trajectory Planning

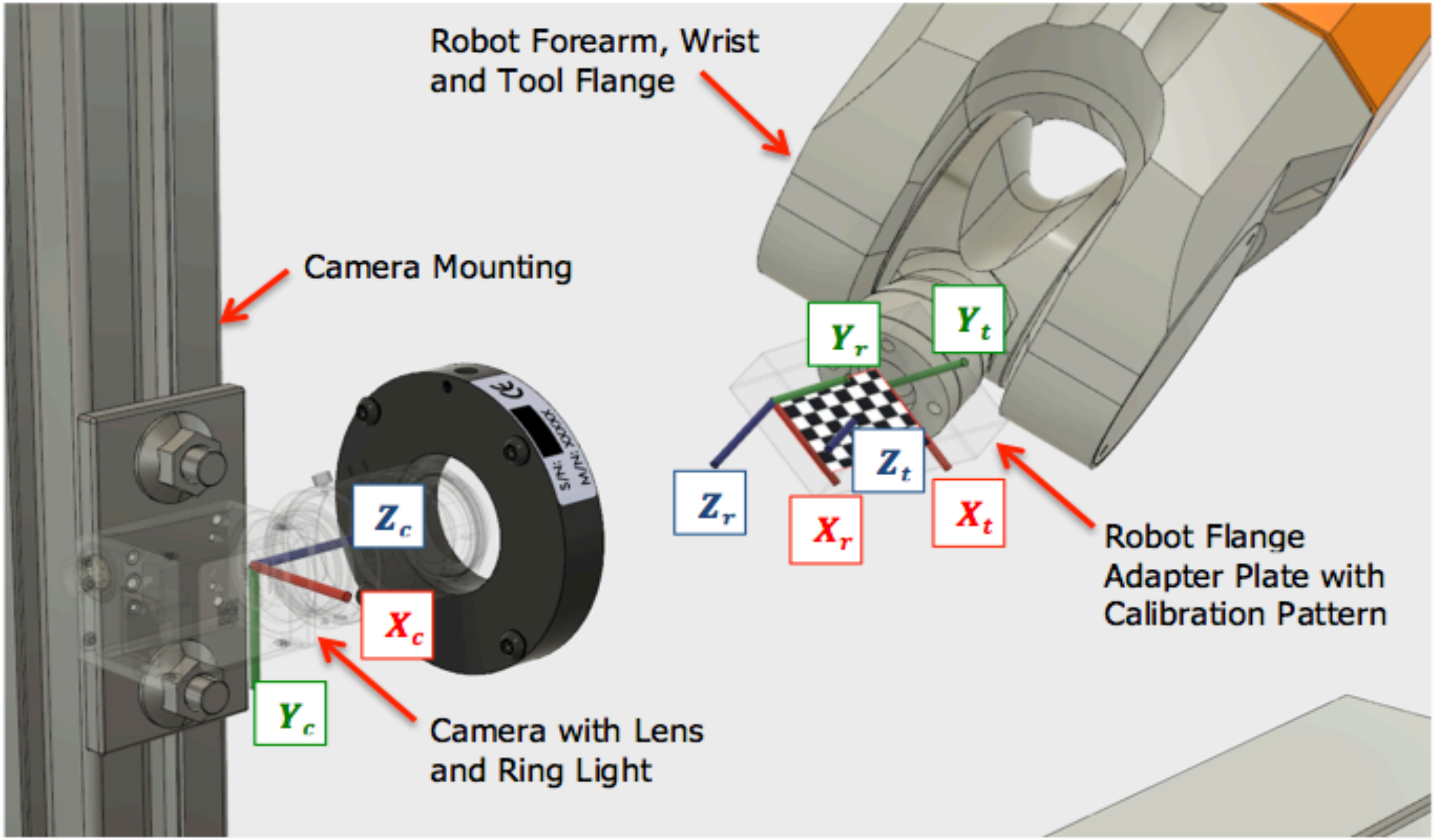
- Definition of an Intermediate Point between Sample Magazine and Cryostat Model
- Linear Move from Sample Magazine to Intermediate Point
- Second Linear Move from Intermediate Point to Cryostat Model
- Apply Blending to ensure smooth movement without interruption on Intermediate Point



Implementation – Placement Process



Implementation – Camera Calibration



Camera Calibration – I+E Camera Parameters

Calibration results after optimization (with uncertainties):

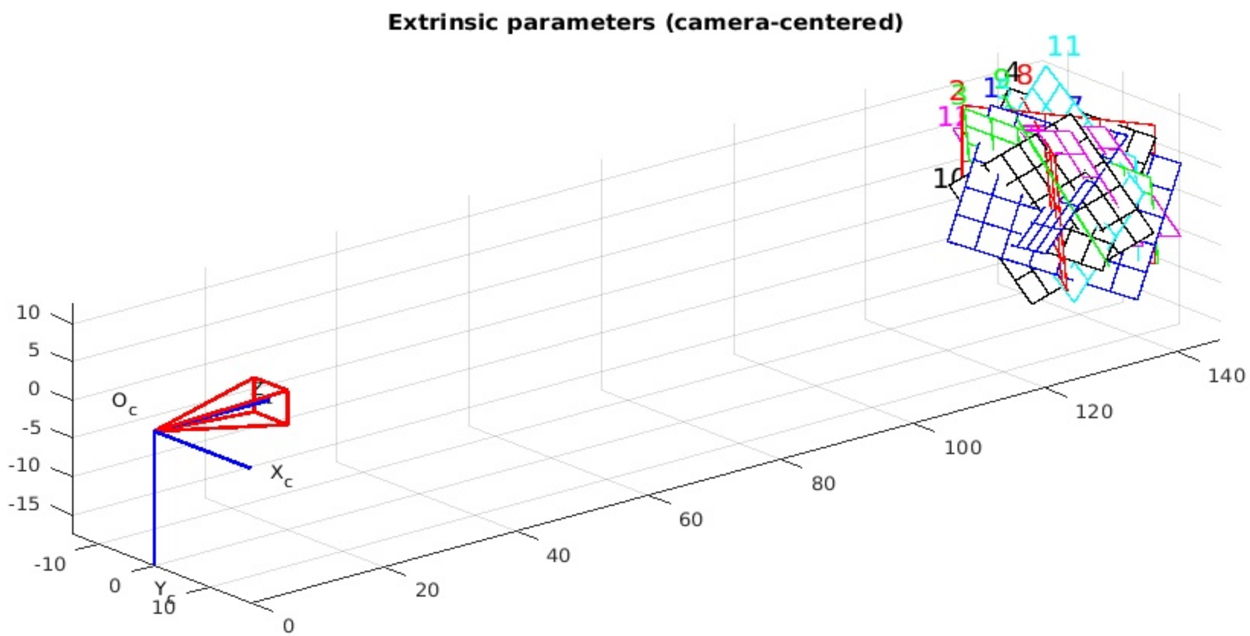
Focal Length: fc = [7581.35626 7583.28538] +/- [112.40203 112.53063]

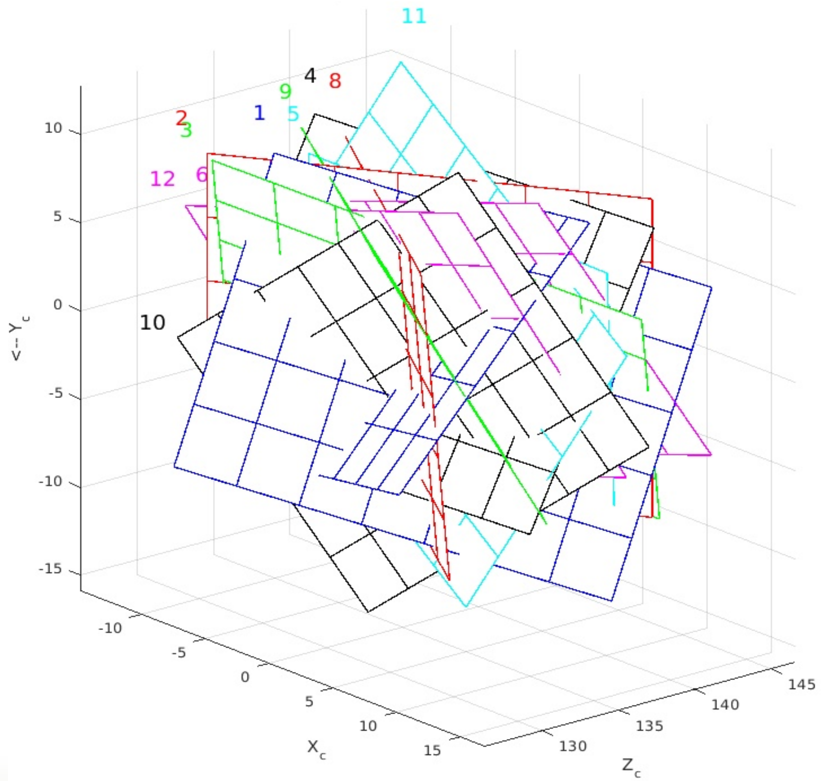
Principal point: cc = [1234.98797 920.95125] +/- [153.64122 133.11030]

Skew: alpha_c = [0.00000] +/- [0.00000] => angle of pixel axes = 90°

Distortion: kc = [-0.15226 -9.71375 -0.00135 -0.00103 0.00000] +/- [0.38611 25.17468 0.00333 0.00259 0.00000]

Pixel error: err = [1.17303 1.43216]

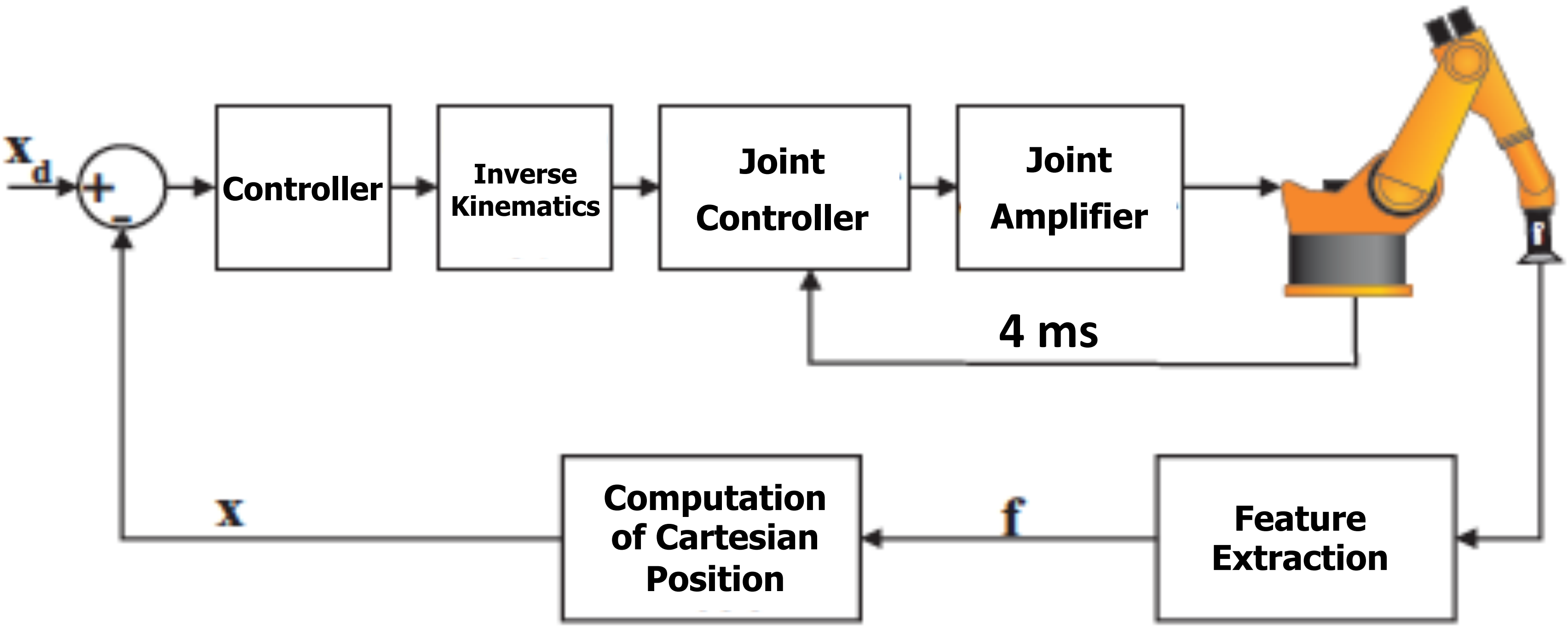




Implementation – Placement Process

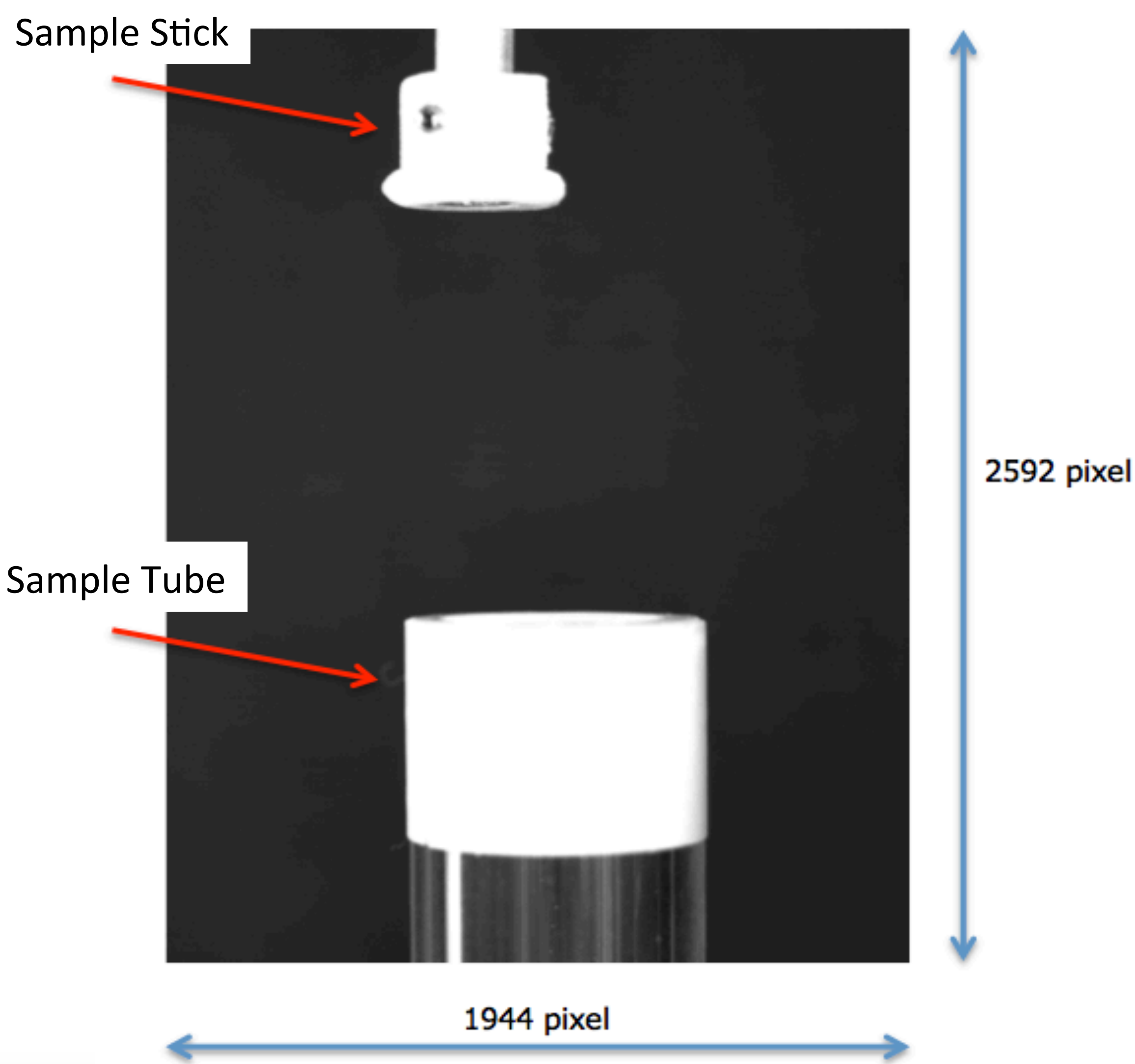
Control Loop – Position-based Visual Servoing

- Feature Detection from Image Evaluation converted into 3D-dimensional Feature
- Camera Calibration necessary → determination of extrinsic and intrinsic Camera Parameters
- Set point as 3D-dimensional Feature transferred to Robot Controller
- Dynamic Look-and-Move Principle applies → closed loop not directly closed over Feature Extraction, but also over internal Joint Controller (subordinate control loop)

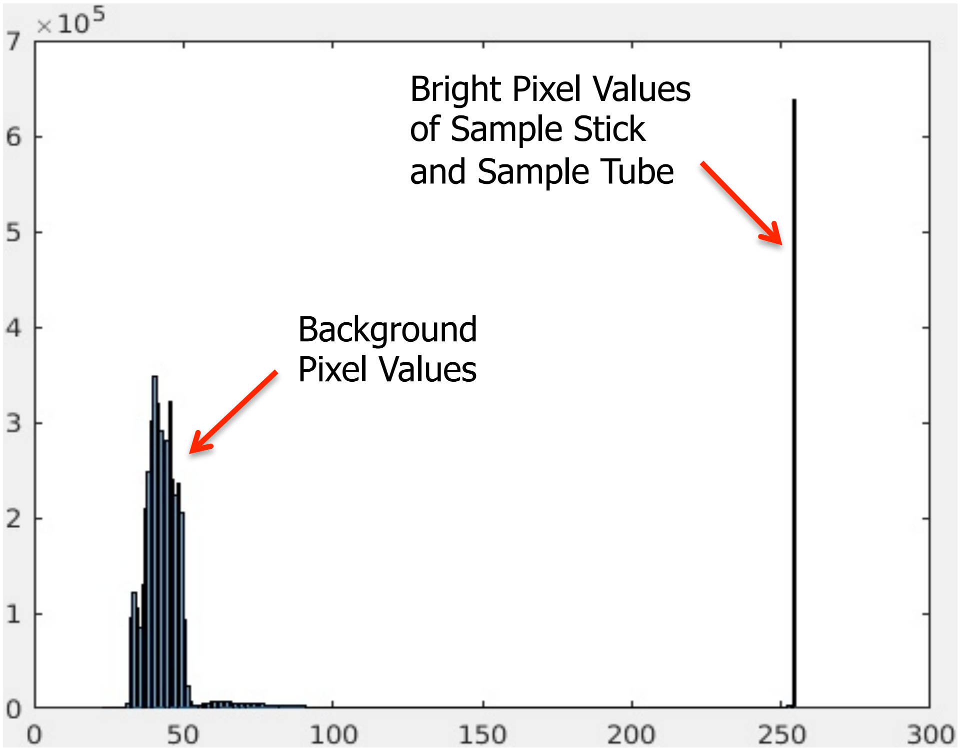


Implementation – Image Evaluation

Typical Example Image



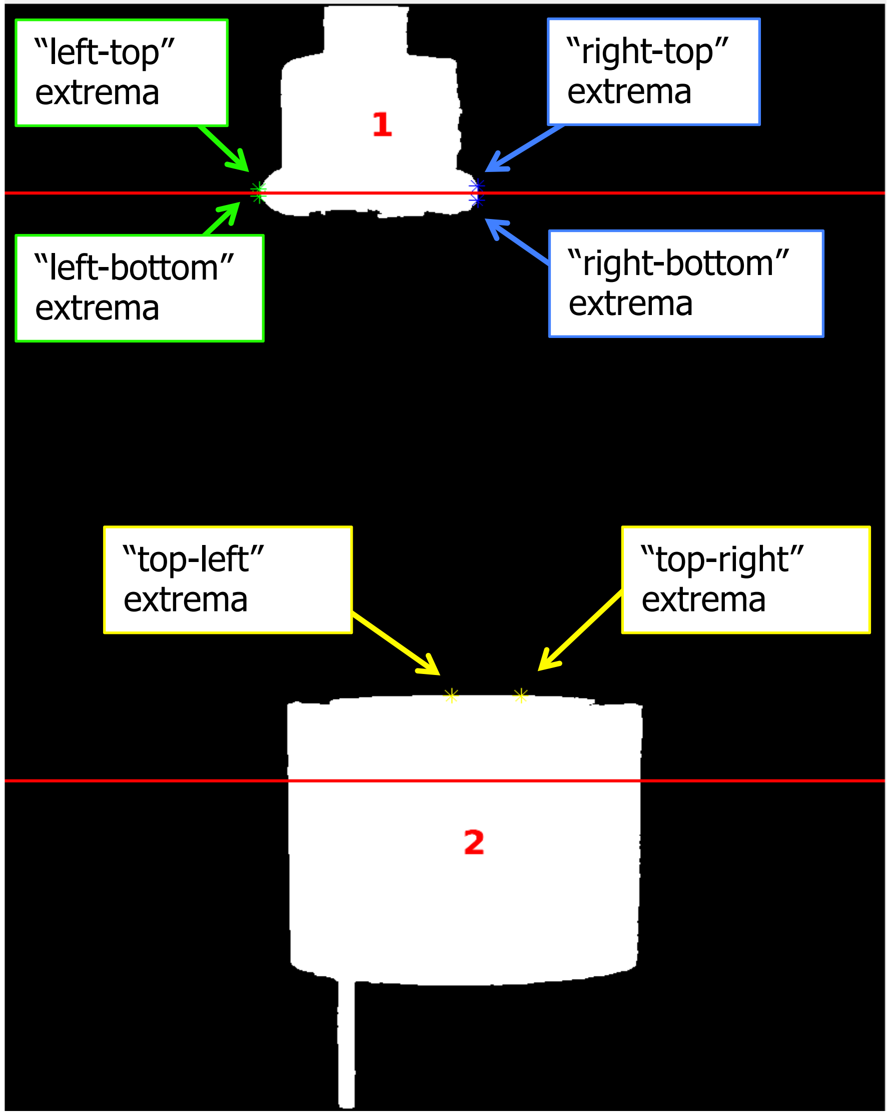
Corresponding Histogram



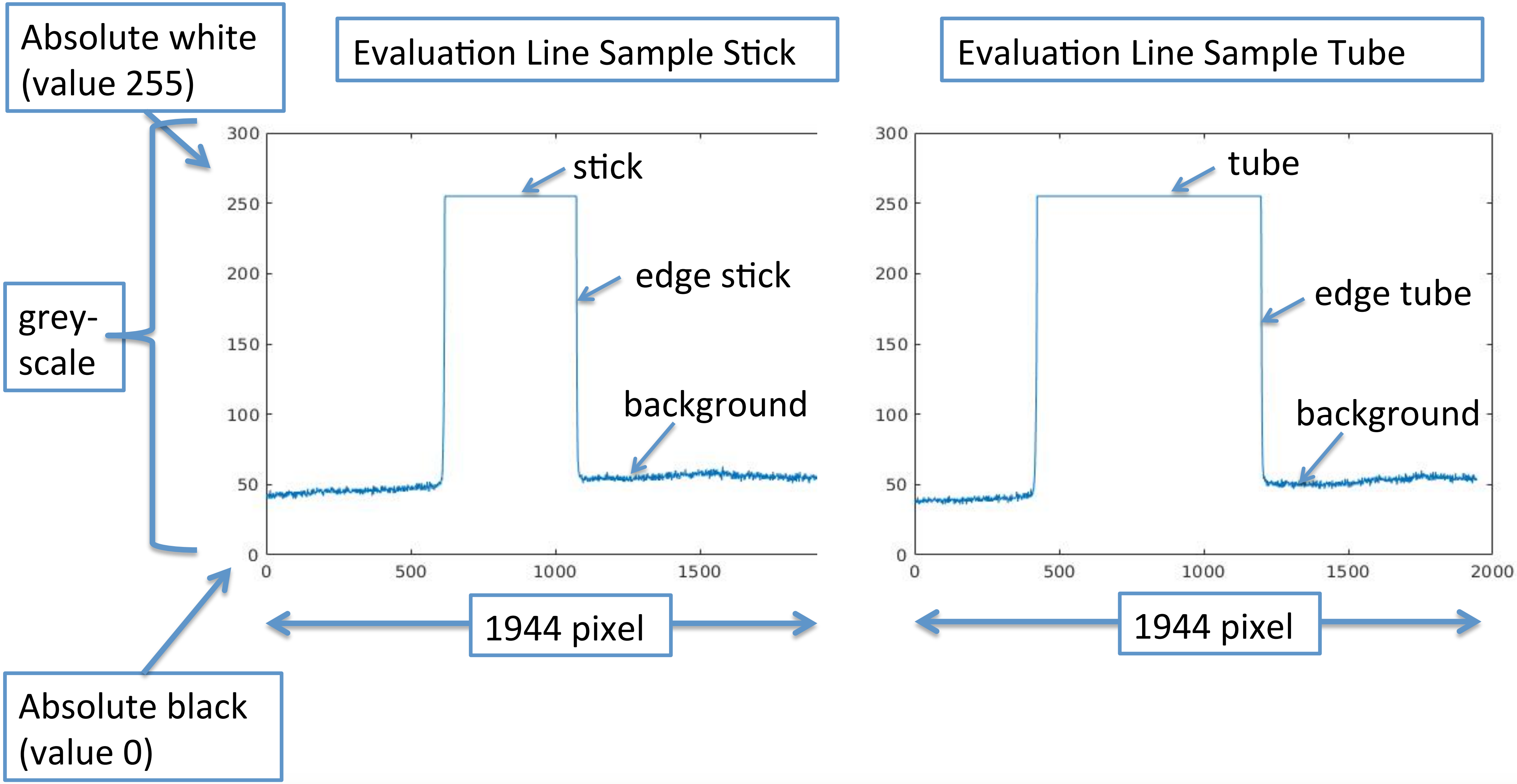
Implementation – Image Evaluation

Approach of finding Evaluation Lines

- Binary Image by Threshold to separate Background from Objects (refer to Histogram)
- Edge Detection based on Canny Algorithm
- Morphology Operations – Erosion and Dilatation to obtain closed Edge Lines around Objects (Boundary)
- Fill Holes (Boundary Line of Objects) to get Sample Stick and Sample Tube as separate Objects
- Compute Extrema Values of both Objects
- Define Position of Evaluation Lines within Image (Pixel Row) by Averaging the Results of Extrema Value Detection



Implementation- Image evaluation



Implementation - Gaussian Curve Fitting

- Gaussian Function serves as non-linear Model Curve to approximate Pixel Intensity Data
- Goal is to find Gaussian Function with dedicated Parameters, representing and thus approximating the measured pixel values best possible

$$f_{\mu,\sigma}(u) = \frac{1}{\sqrt{2 * \pi * \sigma}} * e^{-\frac{1}{2} * \left(\frac{u-\mu}{\sigma}\right)^2}$$

- Apply method of Non-Linear Least Squares based on Gauss-Newton-Algorithm

$$GN(\mu,\sigma) = \sum_{i=1}^{n} \left(p_i - f_{\mu,\sigma}(u_i)\right)^2 = \|\vec{f} - \vec{p}\|_2^2 \rightarrow min!$$

- To minimize calculate partial derivations of residual function $r = p_i - f_{\mu,\sigma}(u_i)$

$$r'_1 = \frac{\partial r}{\partial \mu} \quad and \quad r'_2 = \frac{\partial r}{\partial \sigma}$$

→ Jacobian Matrix of residuum derivations

$$J_i = (r'_1 \quad r'_2) \quad and \quad \vec{a} = \begin{pmatrix} \mu \\ \sigma \end{pmatrix}$$

- Determine vector $\vec{a}$ by iterations based on the matrix equation:

$$a_{i+1} = a_i - (J_i^T * J_i)^{-1} * J_i^T * r$$

Implementation - Gaussian Curve Fitting

- Improve Curve Fitting by more advanced Method (→ higher chance of convergence)
- Apply method of Non-Linear Least Squares based on Levenberg-Marquardt-Algorithm

$f_{\mu,\sigma}(u_i) = f(u_i, \vec{a})$ $\vec{a}$ is replaced by $\vec{a} + \delta$ $f(u_i, \vec{a} + \delta) \approx f(u_i, \vec{a}) + J_i * \delta$

$$LM(\vec{a} + \delta) \approx \sum_{i=1}^{n} \left(p_i - \left(f(u_i, \vec{a}) + J_i * \delta\right)\right)^2 \approx \left\|\vec{p} - \vec{f}(u_i, \vec{a}) - J_i * \delta\right\|_2^2 \to min!$$

- To minimize calculate derivative of $LM(\vec{a} + \delta)$

$$(J^T * J) * \delta = J^T \left(\vec{p} - \vec{f}(u_i, \vec{a})\right) \quad \to \quad \delta = (J^T * J)^{-1} * J^T \left(\vec{p} - \vec{f}(u_i, \vec{a})\right)$$

- Contribution of Levenberg → introduction of an additional non-negative damping factor λ
- Small damping factors → GN-method → decrease λ after iteration
- Large damping factors → closer to gradient descent direction → increase λ after iteration

$$(J^T * J + \lambda * I) * \delta = J^T * \left(\vec{p} - \vec{f}(u_i, \vec{a})\right)$$

- Contribution of Marquardt → scaling each component of the gradient
- Larger parameter changing in the direction where the gradient is smaller

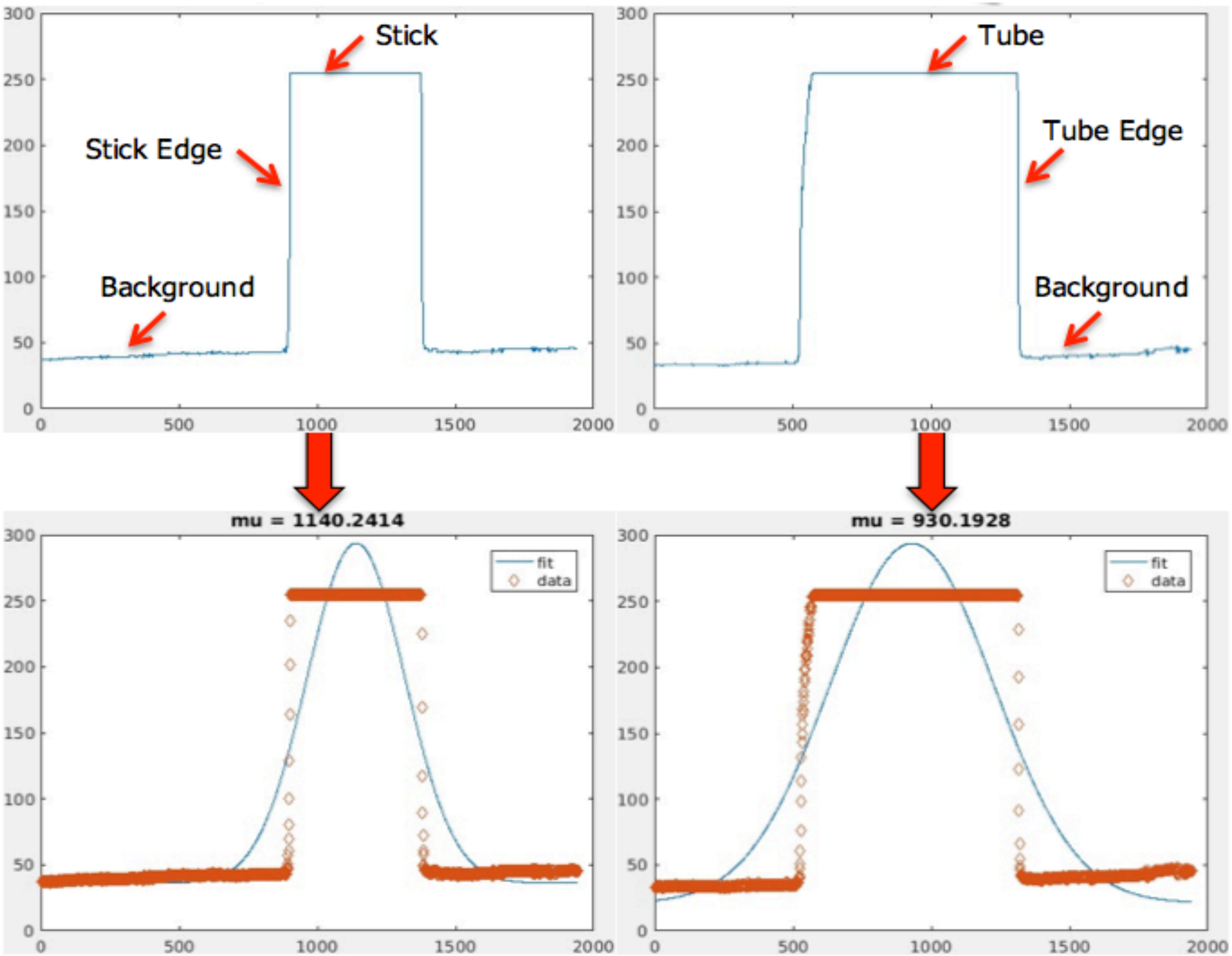
$$(J^T * J + \lambda * diag(J^T * J)) * \delta = J^T * \left(\vec{p} - \vec{f}(u_i, \vec{a})\right)$$

Implementation - Gaussian Curve Fitting

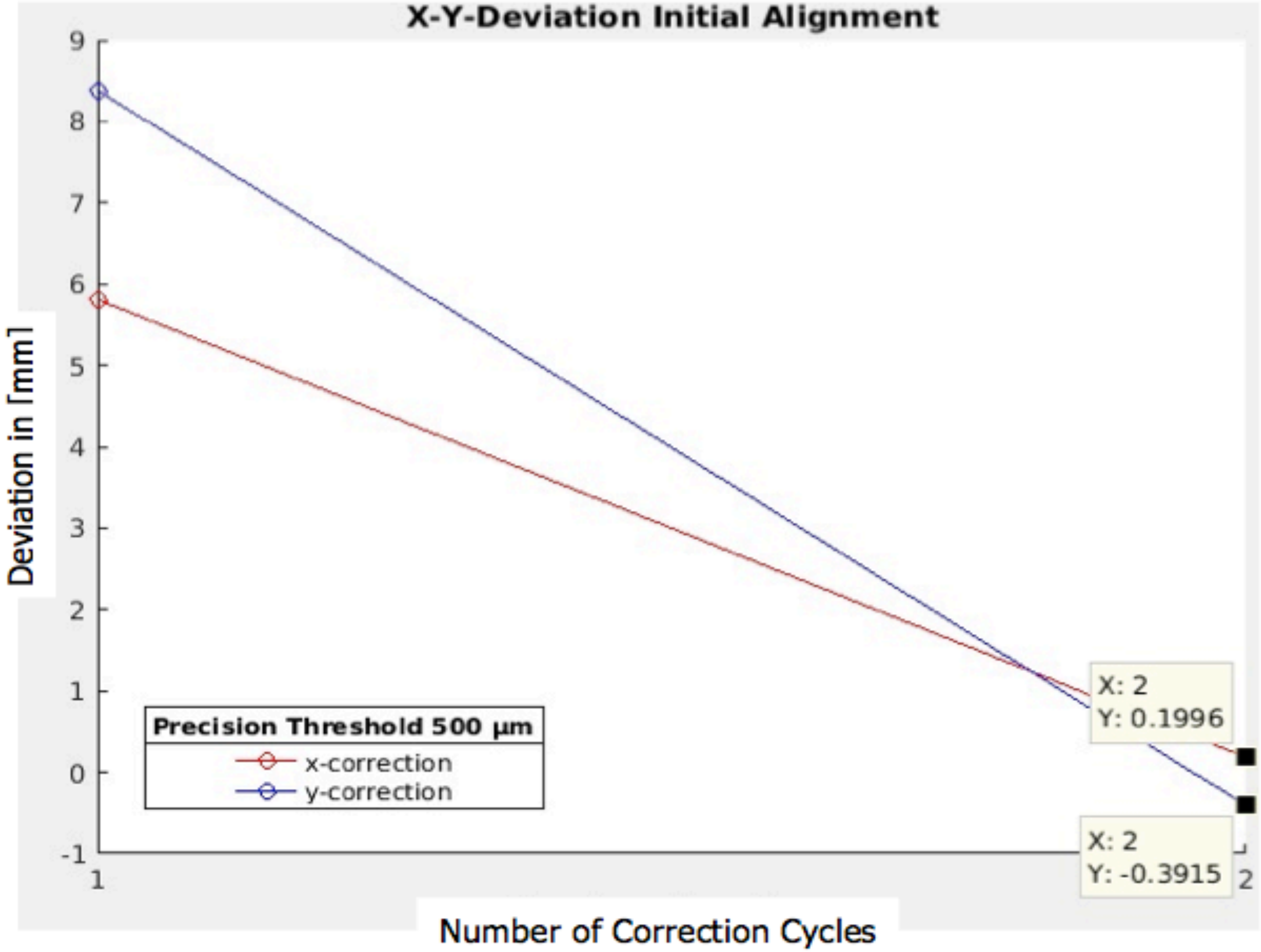
Misalignment between Sample Stick and Sample Tube:

$$p_{p\_corr} = \mu_{stick} - \mu_{tube}$$

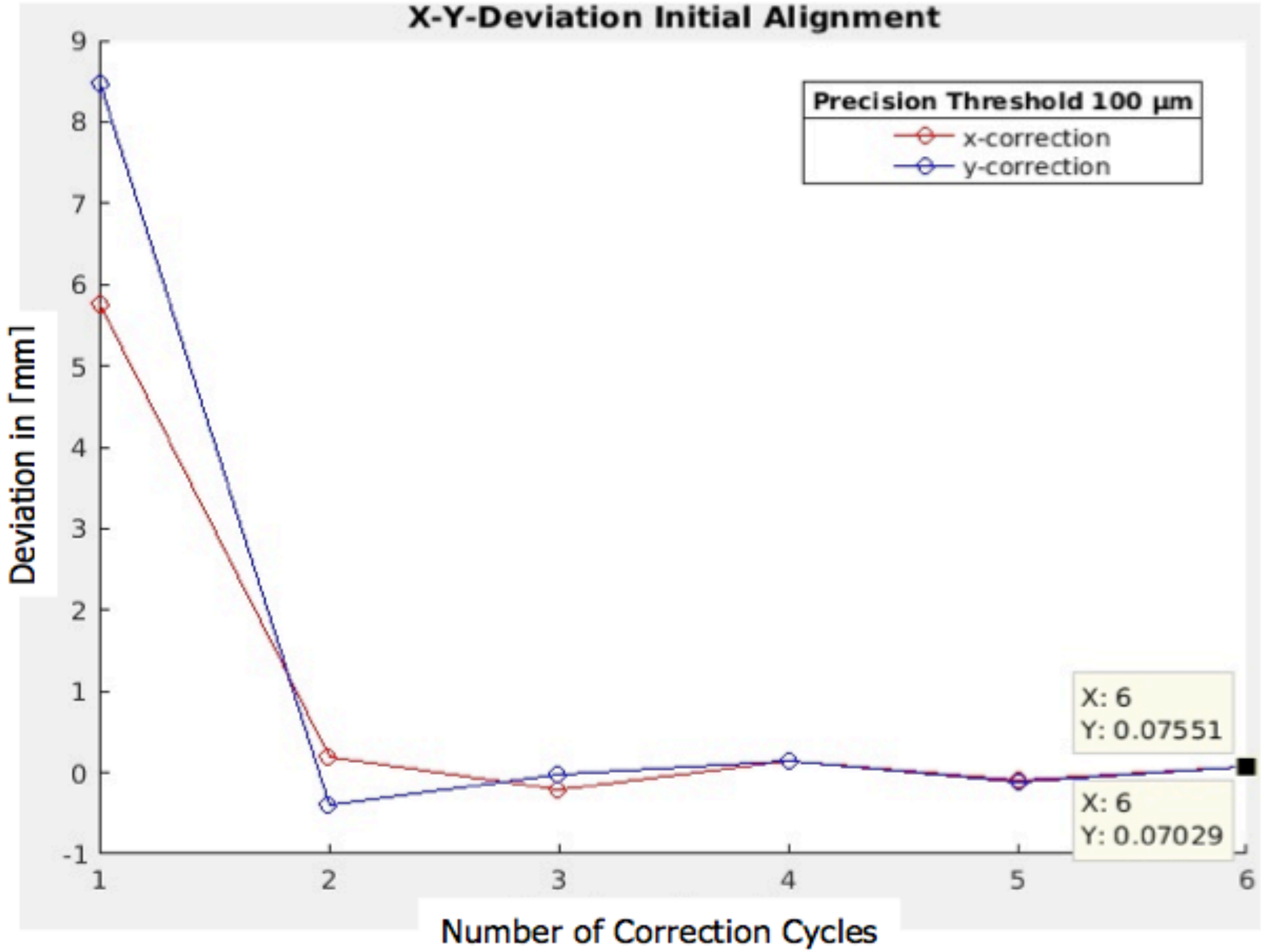
- Valid for one Direction Alignment in Task Coordinate System
- Repeat Gaussian Fit Curve Method with second Camera for other Direction Alignment in Task Coordinate System
- Apply Inverse Mapping (2D → 3D)



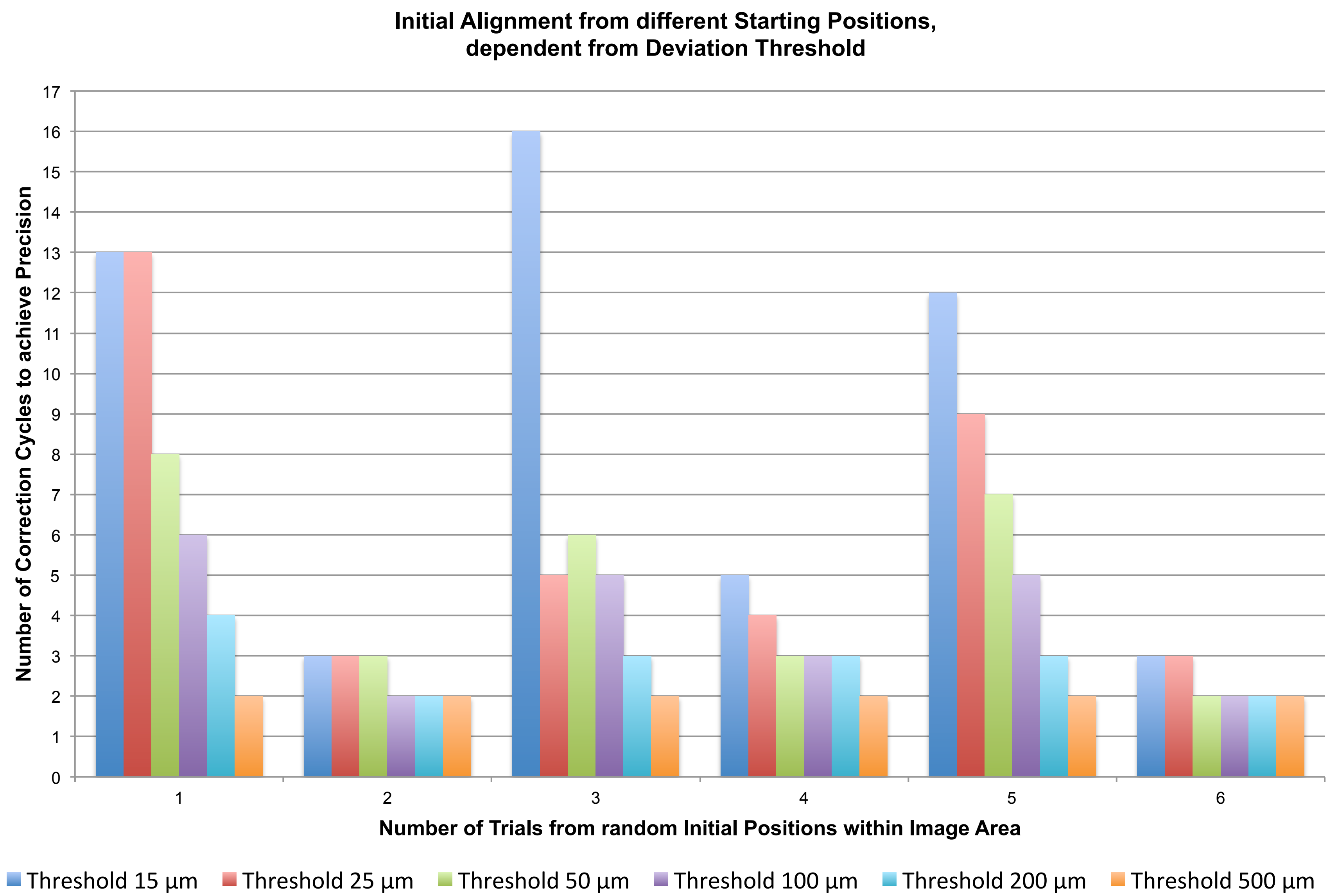
Results – Initial Alignment



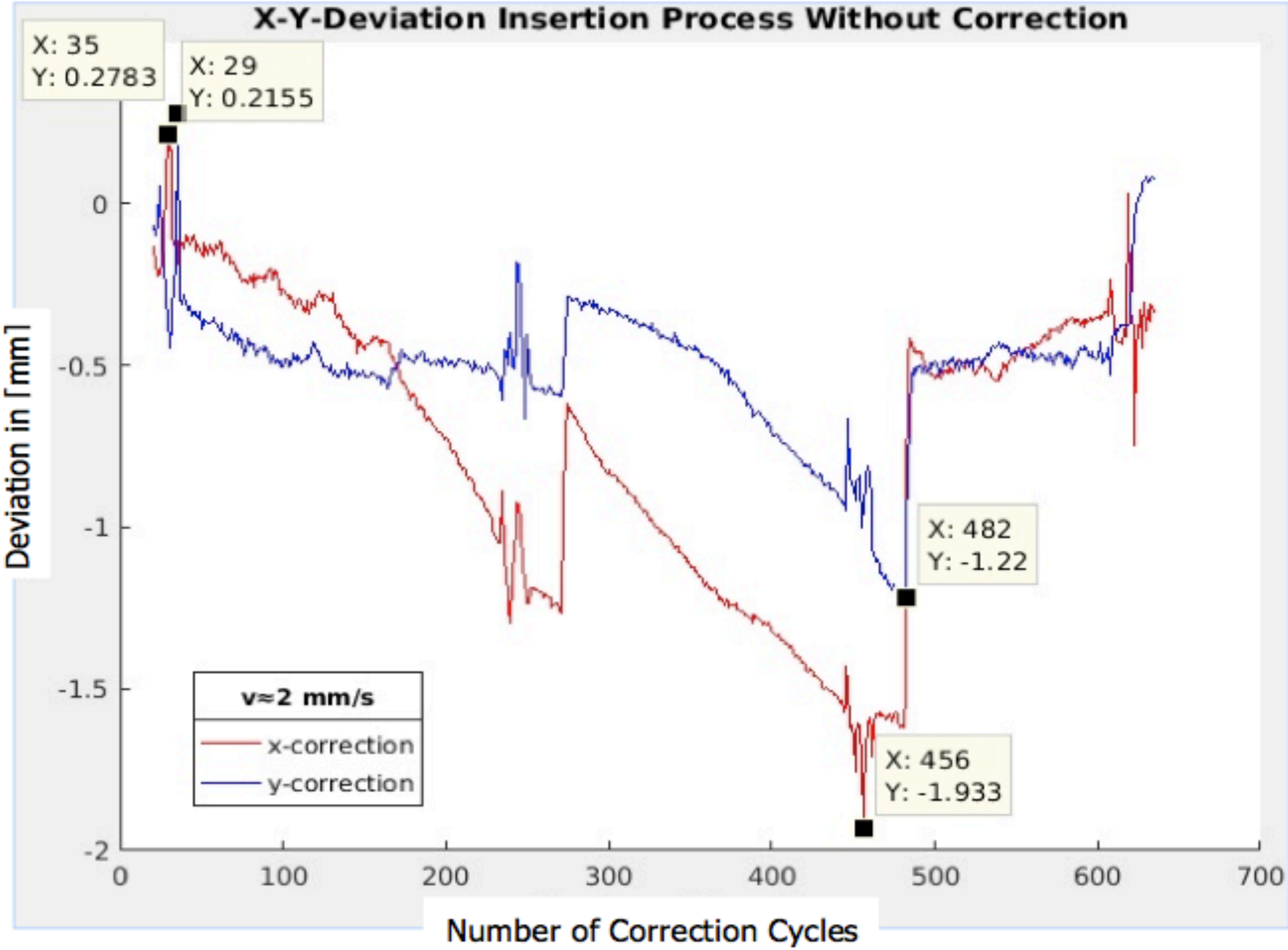
Results – Initial Alignment



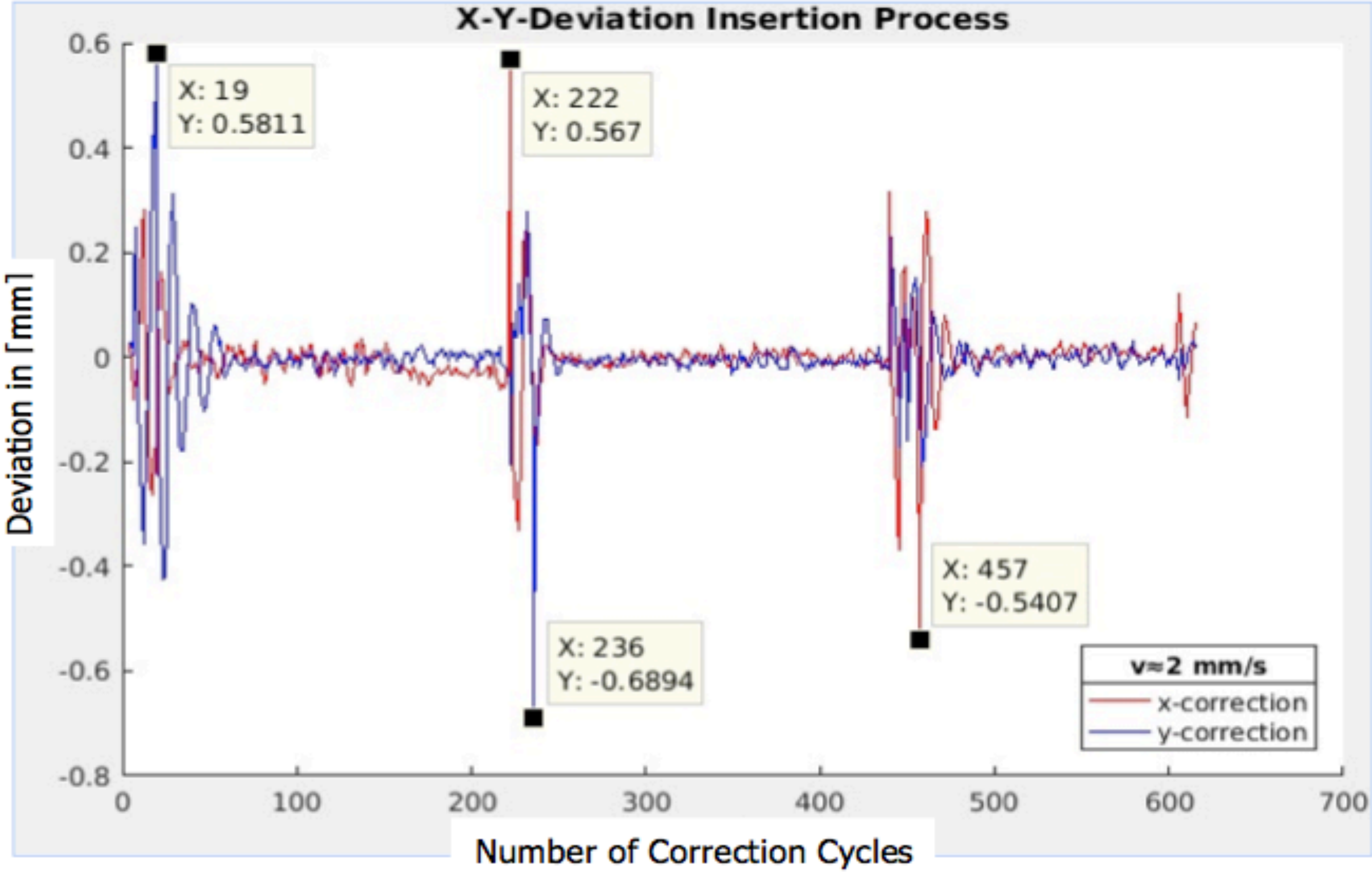
Results – Initial Alignment



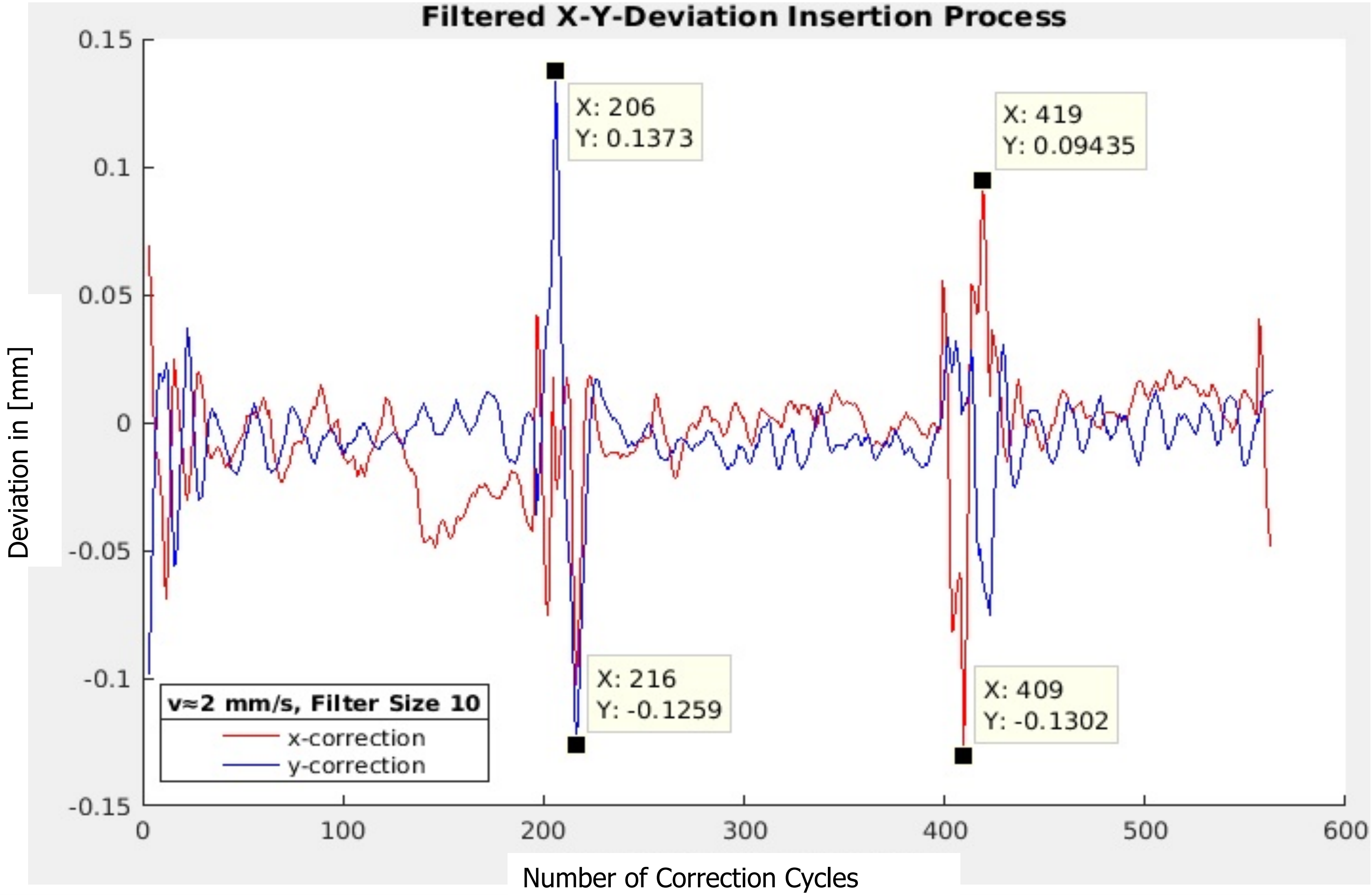
Results – Insertion Process



Results – Insertion Process

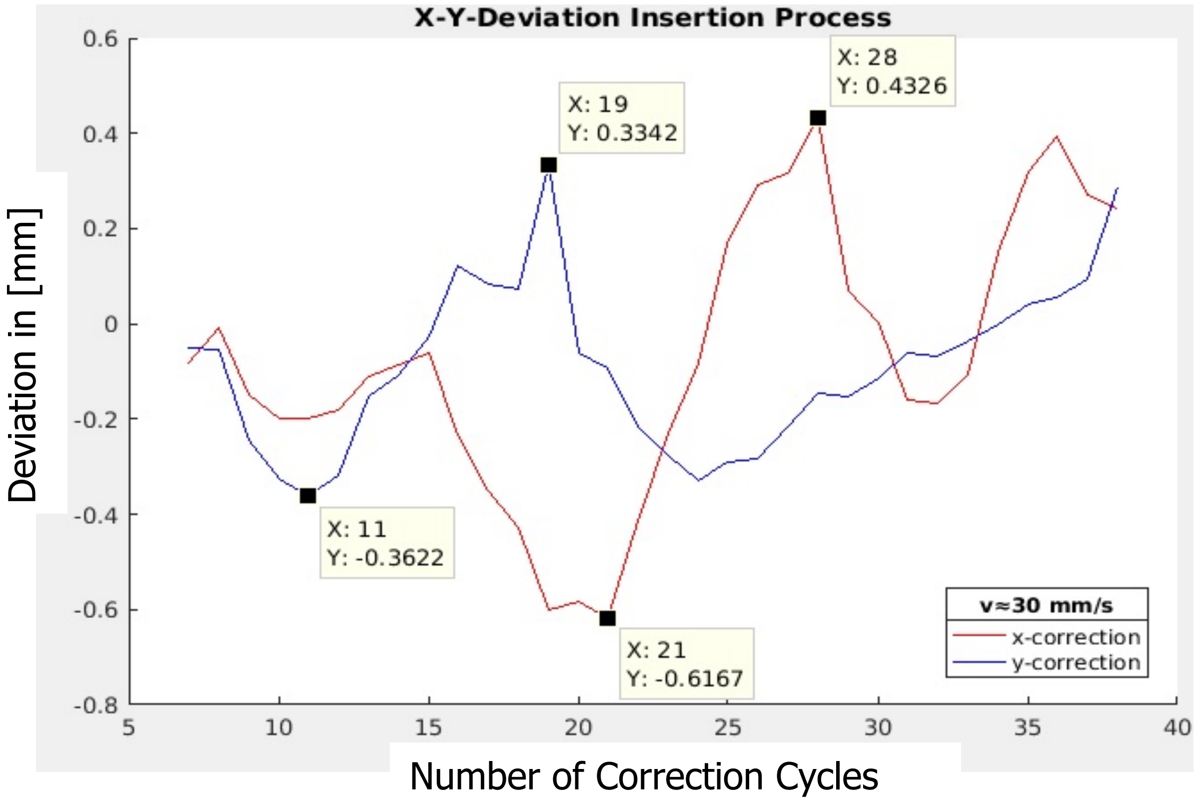


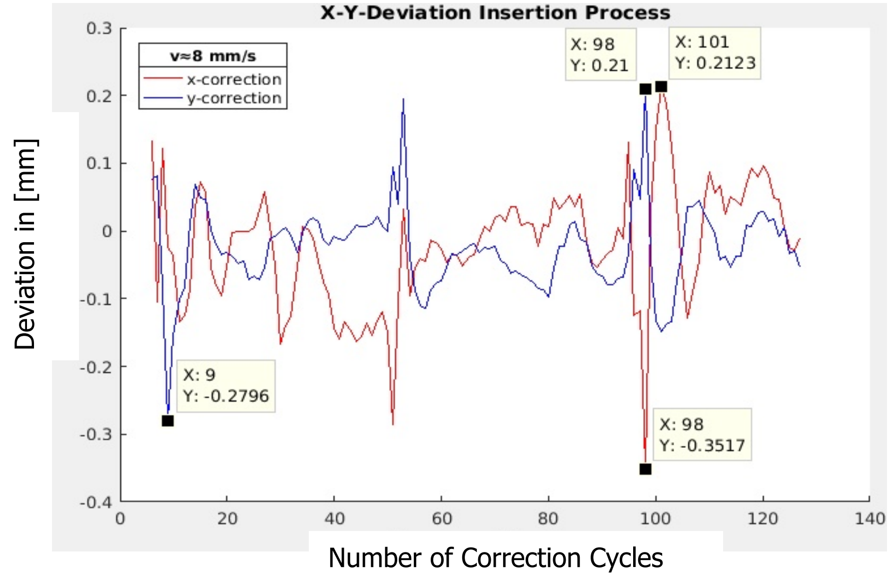
Results – Insertion Process

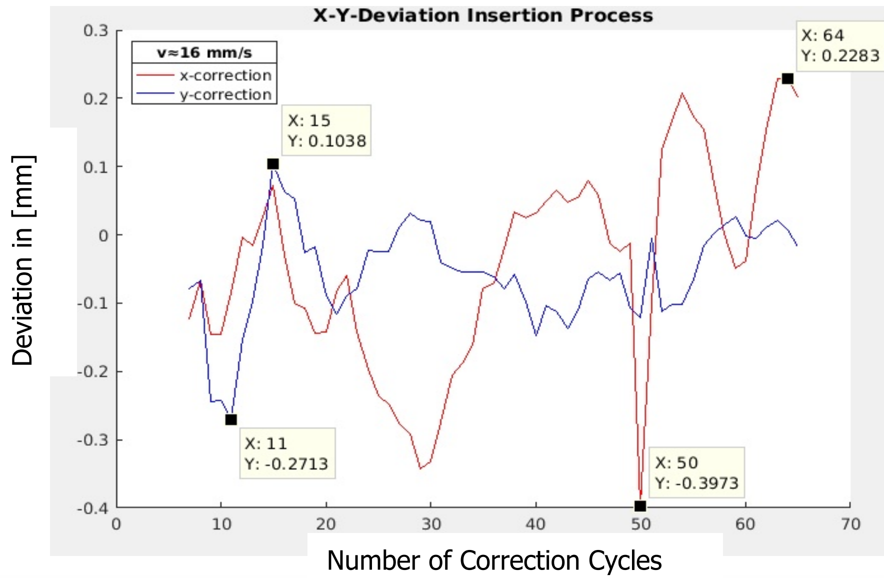


Results – Insertion Process

Insertion Process with different speeds







Summary

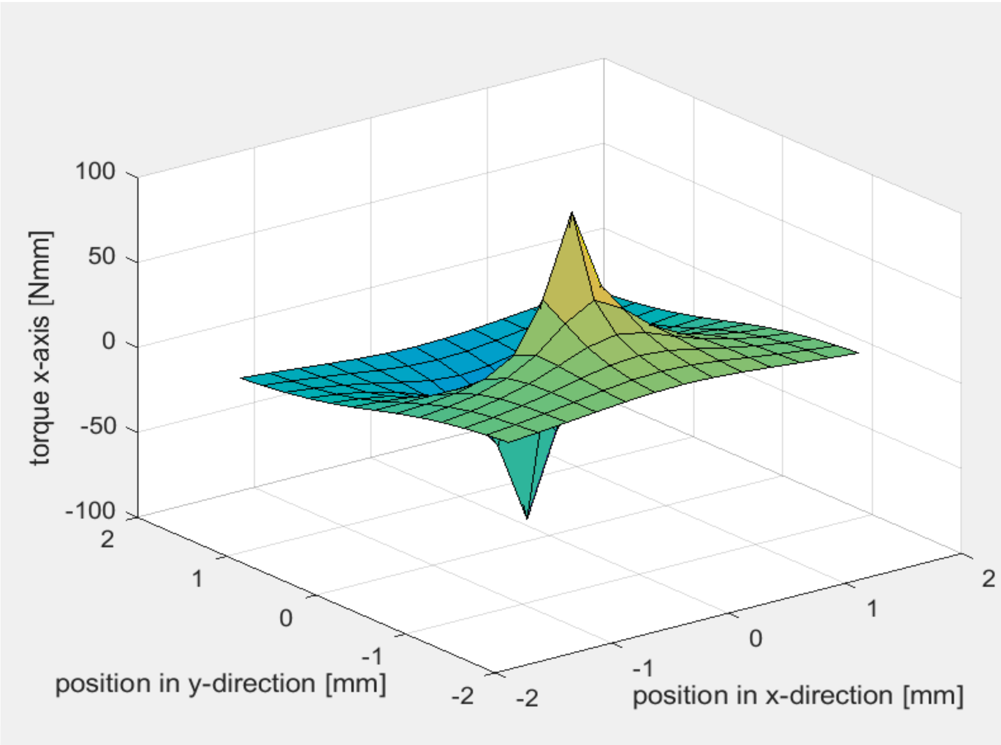
- Alignment accuracy of sample stick and sample tube of the cryostat model ✓
  - down to 15 µm depending on the number of cycle corrections
- Alignment accuracy during the insertion process on the cryostat model ✓
  - in the range of +/- 300 µm with appropriated speed of around 8 mm/s
- Speed performance during the initial alignment
  - up to maximum robot speed (consider sample stick vibrations) ✓
  - alignment in a time basically <5 s, depended on specified deviation threshold
- Speed performance during the insertion process ✓✖
  - 50 mm/s feasible, however only without position correction while inserting
  - 30 mm/s maximum speed with real time (4 ms) position correction while inserting
- High sample throughput within reasonable times ✓
  - sample change cycle <1 min
  - conditions: empty cryostat model, in initial state robot in home position
- User-selectable sequencing ✓
  - user can take a choice between available sample sticks

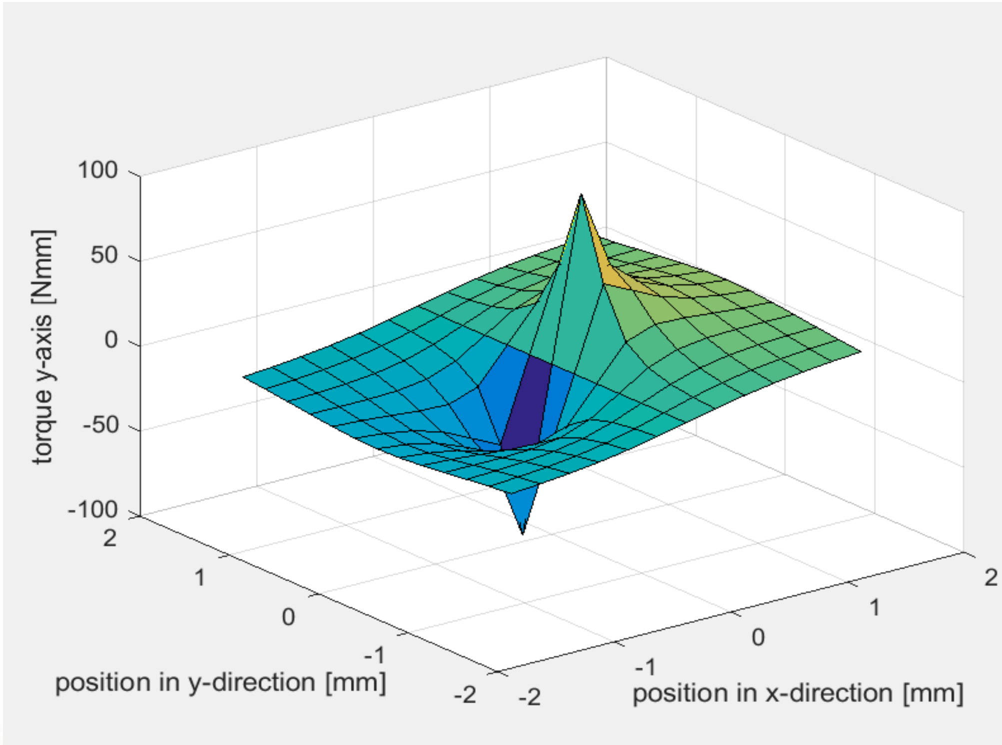
Summary

- Sample identification ✓✖
  - mechanical design and QR-code attachment established
  - improvement of identification implementation necessary
- No significant influence of the sample change procedure regarding cryostat performance ✓✖
  - sample change procedure is not influencing cryostat performance
  - influence of temperature changes not considered so far within laboratory environment
- Appropriated amount of samples ✓
  - amount of samples for test purposes sufficient enough
- Unattended operation cycle ✓
  - robot can perform complete sample change procedure in automatic mode without any interruption
- Potential of increasing the sample throughput ✓
  - Expansion and new sample magazine design feasible
  - Reduce distance between Sample Magazine and Cryostat Model to save time
- Reliability of sample change mechanics ✓
  - robot exchange after 20 000 working hours (in compliance with regular maintenance interval)

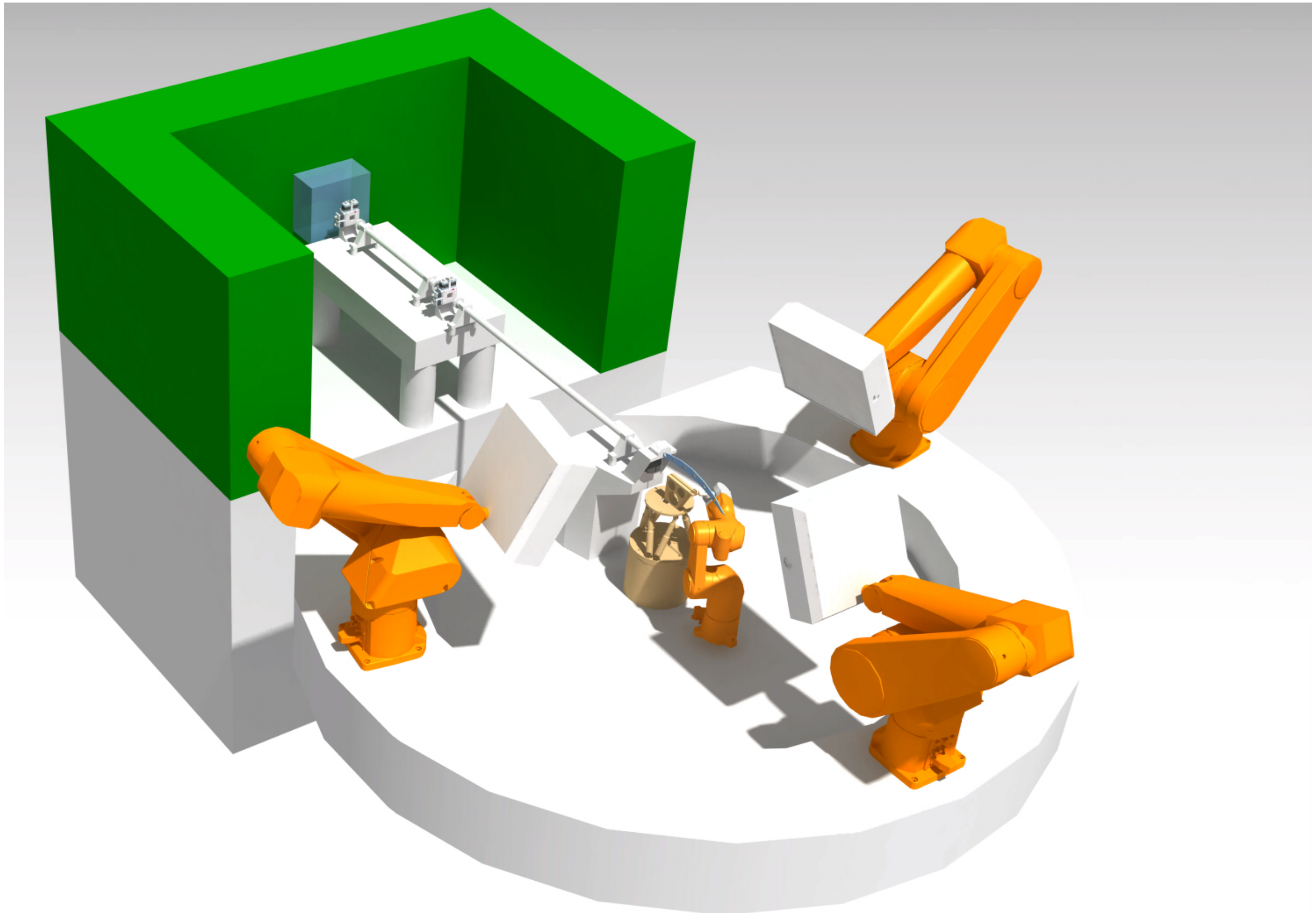
Outlook

- Illumination Performance – Reduction of Daylight Influence
- Camera Calibration – Calibration Pattern
- Software Performance – EPICS Integration
- Cryogenic Environment
- Image Evaluation – other Fit Curve Variants, Rotation Invariance
- Force-Feedback Option





Future Perspective – Application on a Neutron Instrument



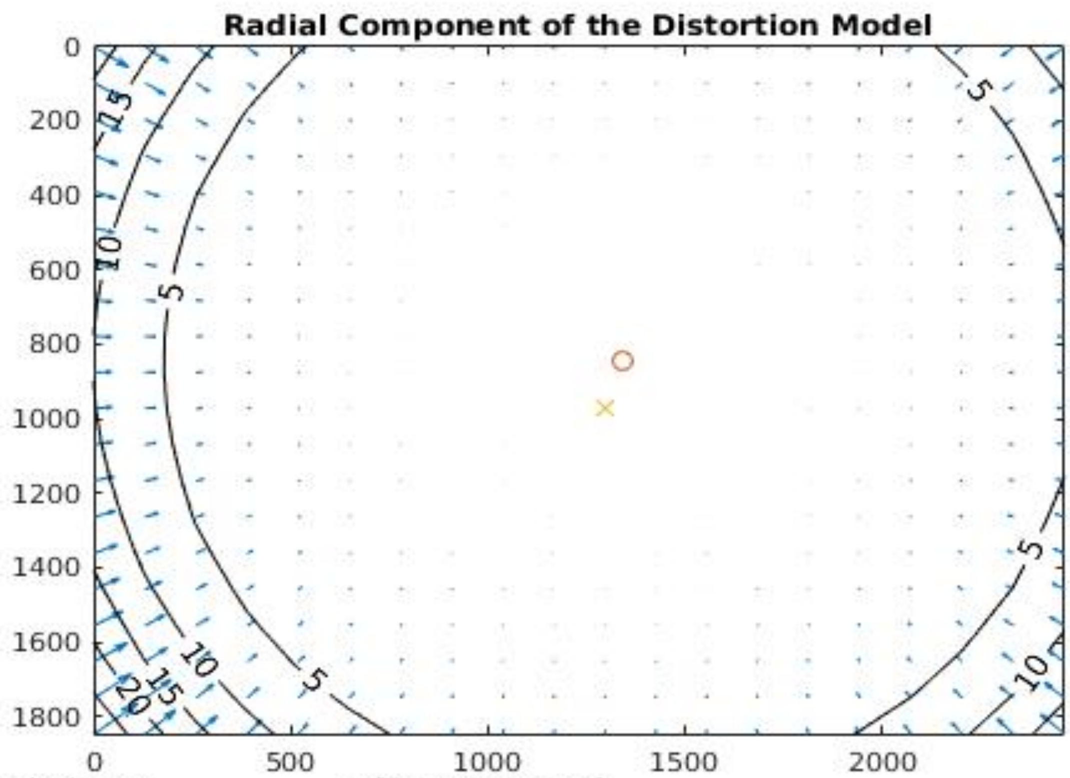
EUROPEAN SPALLATION SOURCE

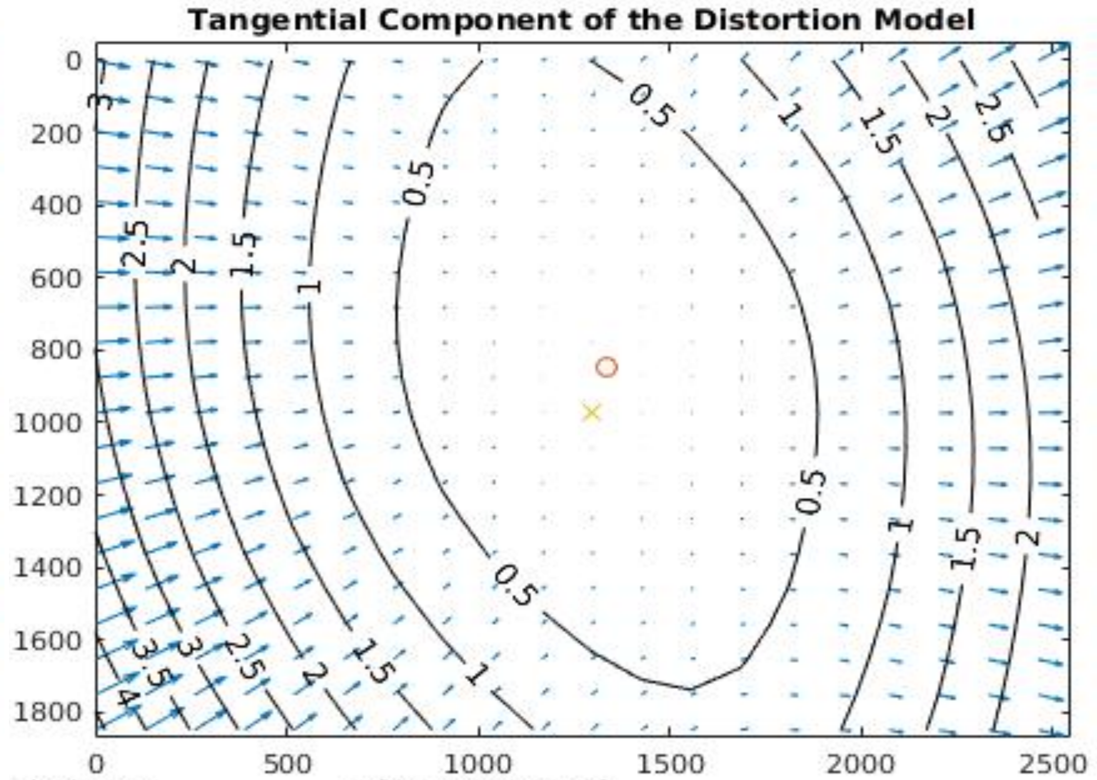
Thank you for your attention

EUROPEAN SPALLATION SOURCE

Cryostat Application Example
PSI (SINQ) Switzerland, Instrument Rita II

Distortion

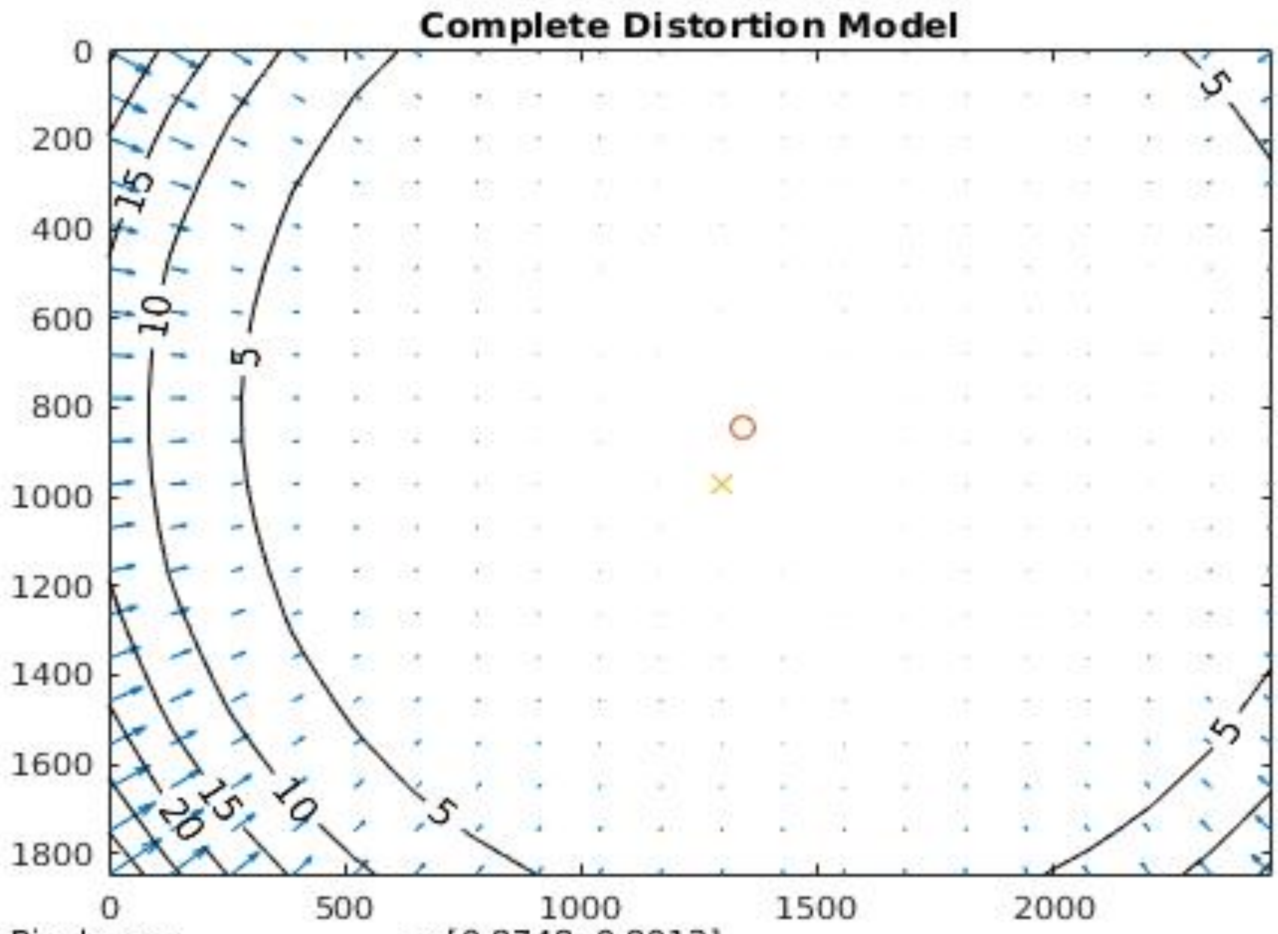




- geometric distortion due to spherical surfaces in lens system (camera optic)
- Scales the distance of a certain pixel coordinate to focus (center of distortion)
- Cue: Pincushion distortion, barrel distortion

- Due to lens decentering

Distortion



Pixel error	= [0.8748, 0.8012]	
Focal Length	= (7690.36, 7668.65)	+/- [179.3, 177]
Principal Point	= (1338.45, 844.498)	+/- [134.3, 128.1]
Skew	= 0	+/- 0
Radial coefficients	= (-0, -8.089, 0)	+/- [0, 4.176, 0]
Tangential coefficients	= (-0.001262, 0.004309)	+/- [0.004985, 0.00507]

Sources

[1] Presentation MCAG Motion Control, Thomas Gahl

[2] Usage of Sample Environment at BENSC - Technical Handbook – Hahn Meitner Institut Berlin, July 2002, Michael Meissner

[3] http://s.baslerweb.com/fp-1461728579/dist/live/1/0/7/4/a92880ae034503b4.png

[4] http://www.prophotonix.com/uploads/photos/sb-ringlight-top.jpg

[5] http://www.baslerweb.com/3/1/8/8/6/a65e78fa14af9200.jpg

[6] https://sv.wikipedia.org/wiki/Matlab#/media/File:Matlab_Logo.png

[7] https://www.robots.com/images/staubli%20studio.jpg

[8] Dissertation Konturverfolgung mit Industrierobotern, Heiko Koch, 2013