Research Progress

18. July 2025

윤 주 환

1. Review of the BPRM Device

- Perspective transformation
- Absolute coordinate space

2. Device Checkup

- Grid point scanning
- Motor repeatability
- Actuator linearity

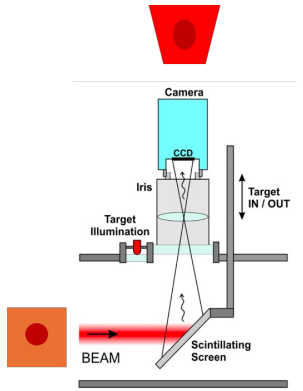
3. Beam Profile Calibration

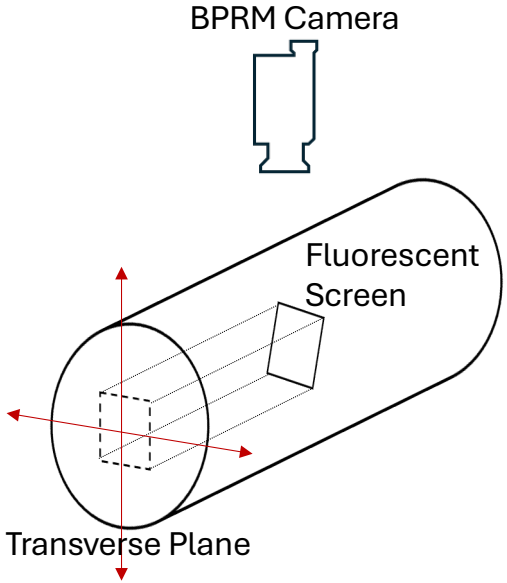
- Coordinate mapping (Spline)
- Test with laser beam profile

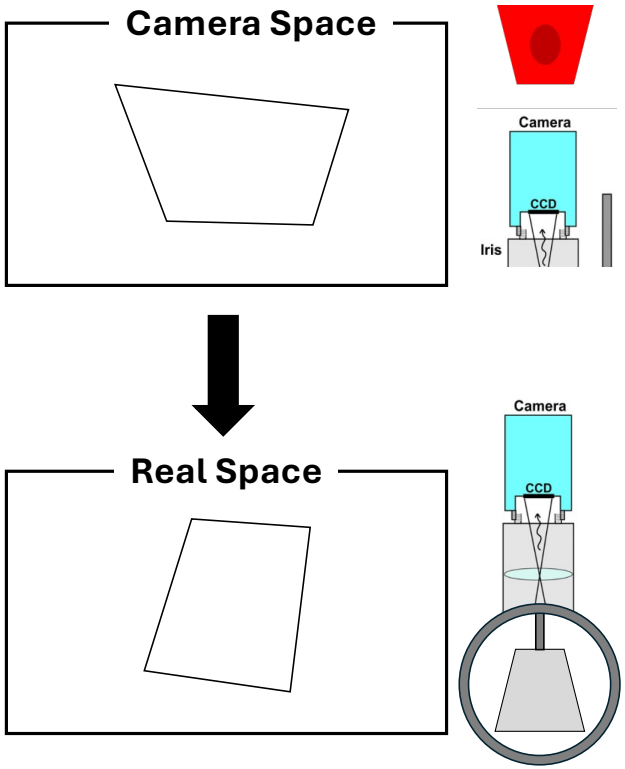
4. Result Analysis Method

- 1D profile fitting
- Comparison of original & measured

Brief Concept of the BPRM Device







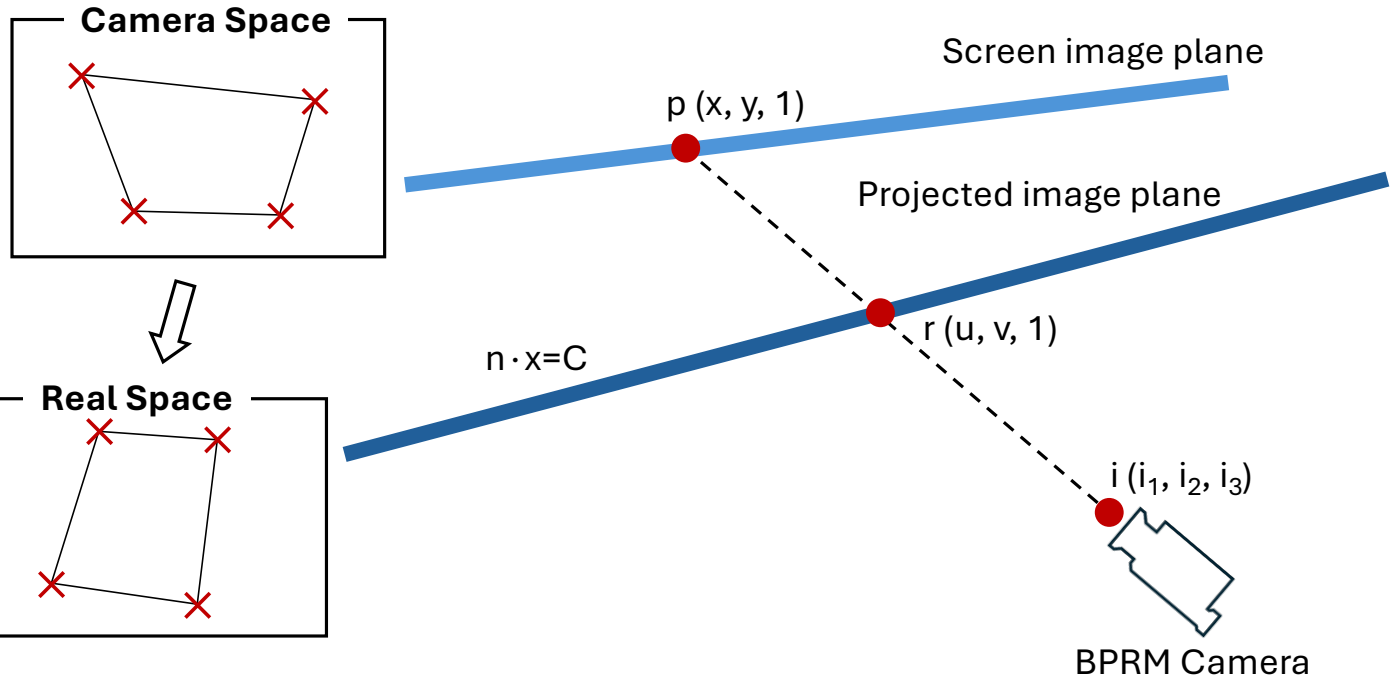
Motivation
- Obtain the transverse image to verify the original bema profile
- Need this coordinate space

Trouble
- Difference between the screen image and the transverse beam image
- Assembly torelance that precludes the measurement

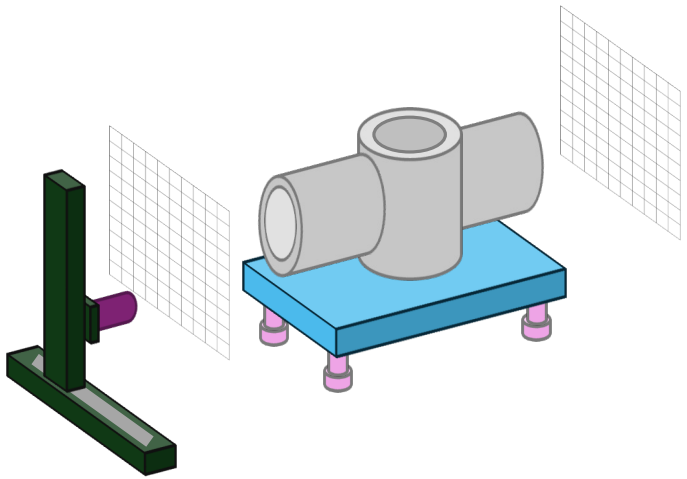
Solution
- Remap the projected beam image
- Quantify the error and calibrate the original coordinates

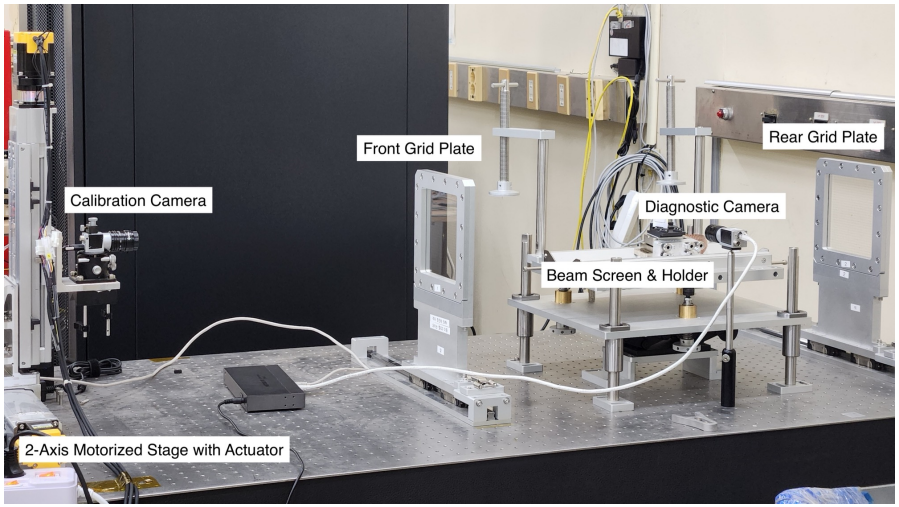
Perspective Transformation

- $(u, v) = \left(\frac{ax+by+c}{gx+hy+j}, \frac{dx+ey+f}{gx+hy+j}\right)$
- $w\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & 1 \end{bmatrix}\begin{bmatrix} x \\ y \\ 1 \end{bmatrix}$
- $\begin{cases} (x_i,\ y_i) \\ (u_i,\ v_i) \end{cases},\ i = 0, 1, 2, 3$

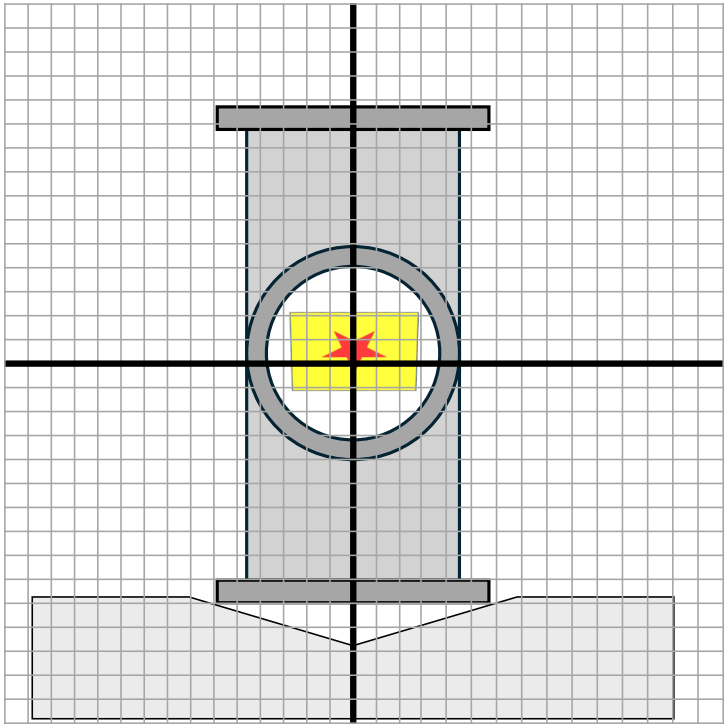


Overview of the BPRM Device





Absolute Coordinate Space



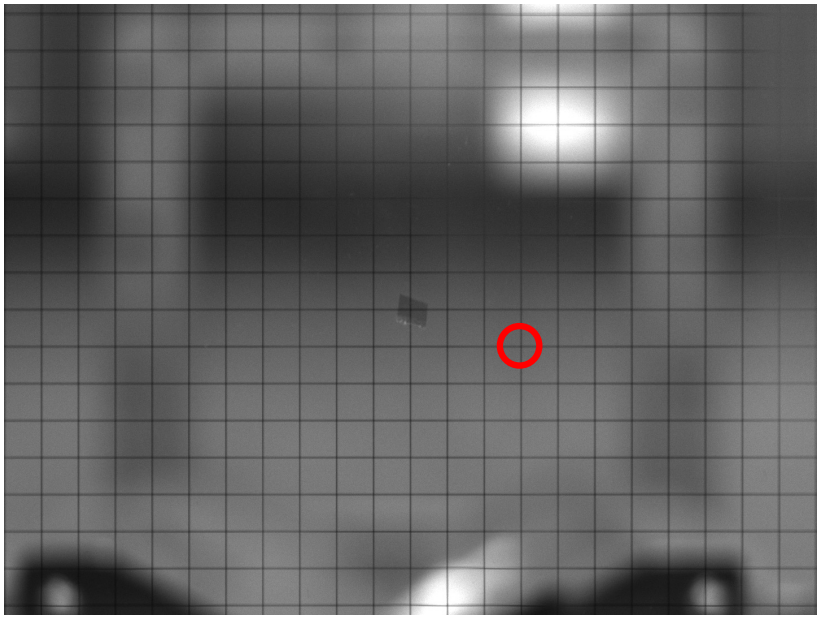
2D Transverse image plane

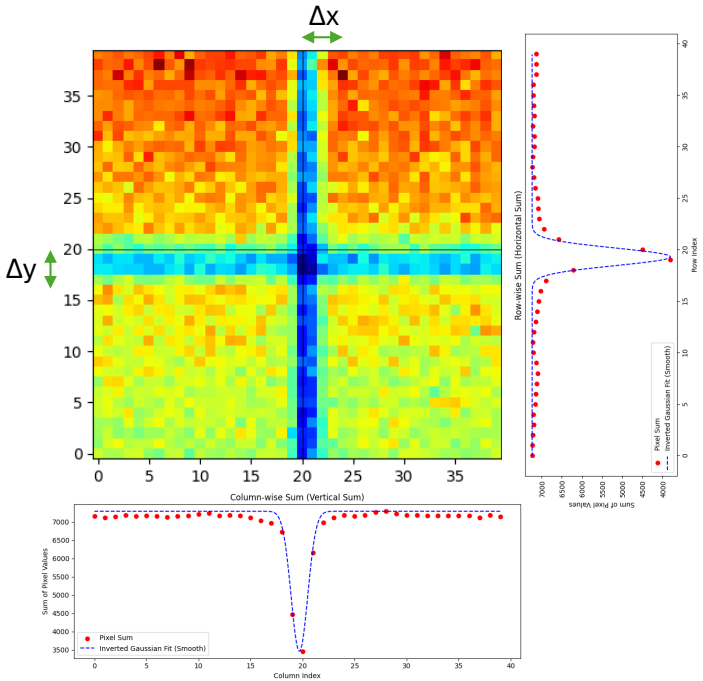
- Define the plane where the beam profile is projected.
- Four coordinates are measured to obtain the transformation matrix.
- Origin (zero-point) is needed to measure the coordinate position.

Grid plate as a reference

- Glass grid plates are aligned parallel to the BPRM chamber flange.
- Camera position is measured by a grid, and grids are removed in the experiment.

Grid Point Scanning



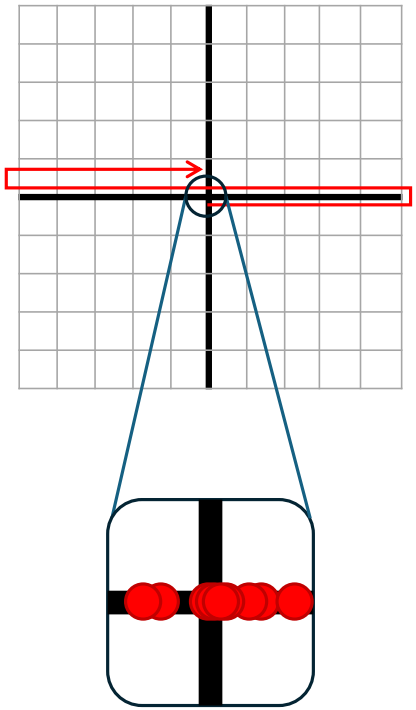


Gaussian Fitting

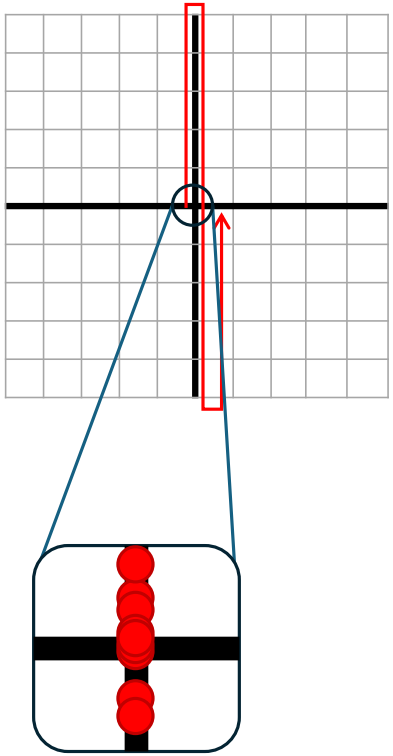
Grid point, the darkest pixel's position is acquired by the Gaussian distribution of the horizontal and vertical pixels sum of the image

Motor Repeatability

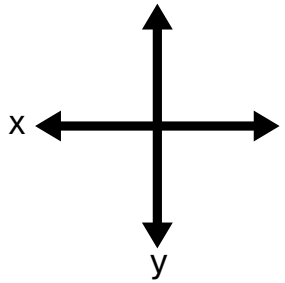
Horizontal Axis



Vertical Axis



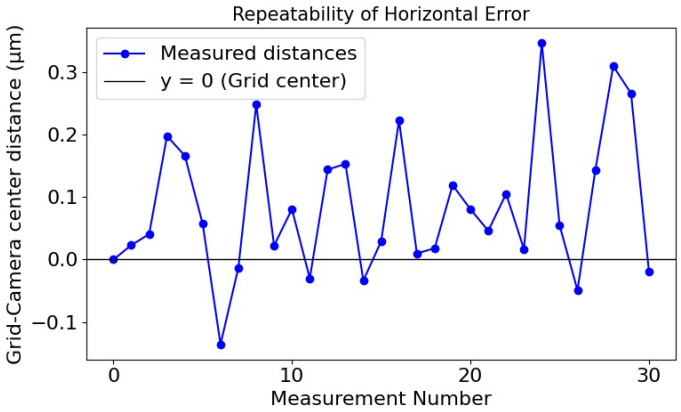
x 30 for each axis



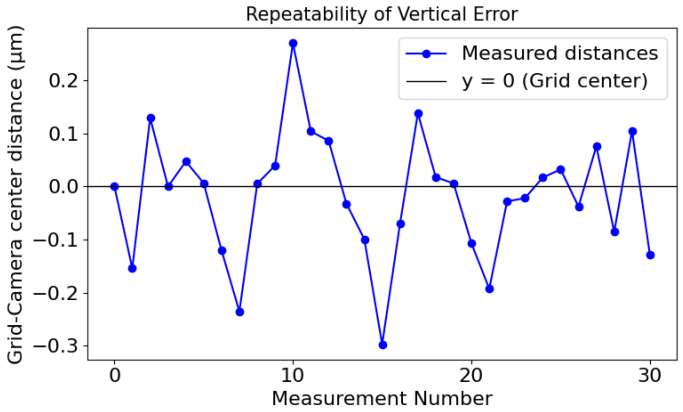
Motor spec
Resolution: 10000 ppr
Actuator screw lead: 10 mm
⇒ Move the camera 1 mm per pulse

Measurement of the repeatability
- Motor speed: 20000 pps
- Return to origin after moving to both ends of 70 mm
- $\Delta d = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}$ at origin for 30 times
- Evaluate the error via Root Mean Square

Motor Repeatability



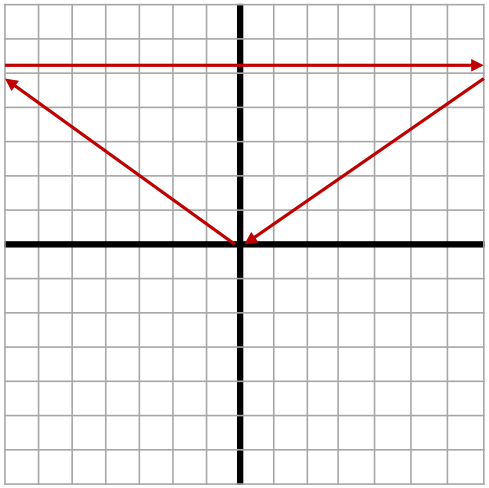
RMSE of horizontal axis motor: 0.1398 µm

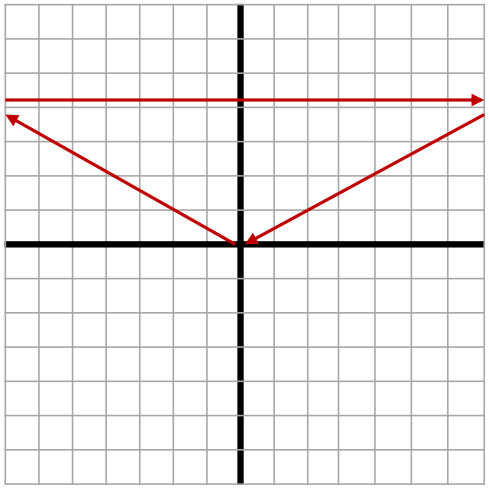


RMSE of vertical axis motor: 0.1167 µm

$$E_{repeatability} = \sqrt{E_h^2 + E_v^2} = 0.1821\ \mu m$$

Actuator Linearity Against the Grid





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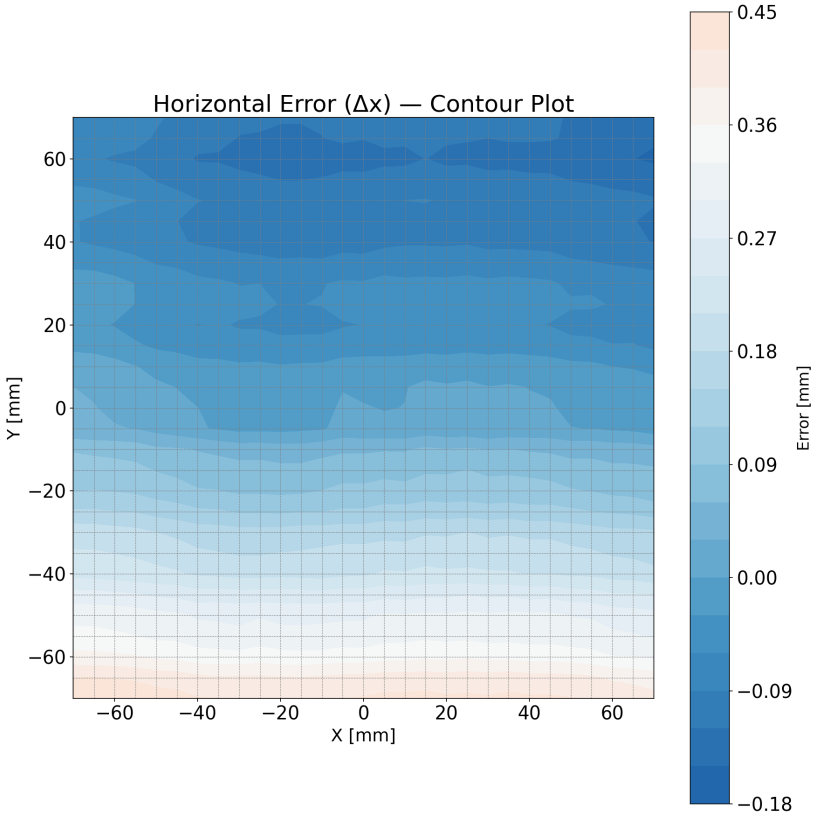
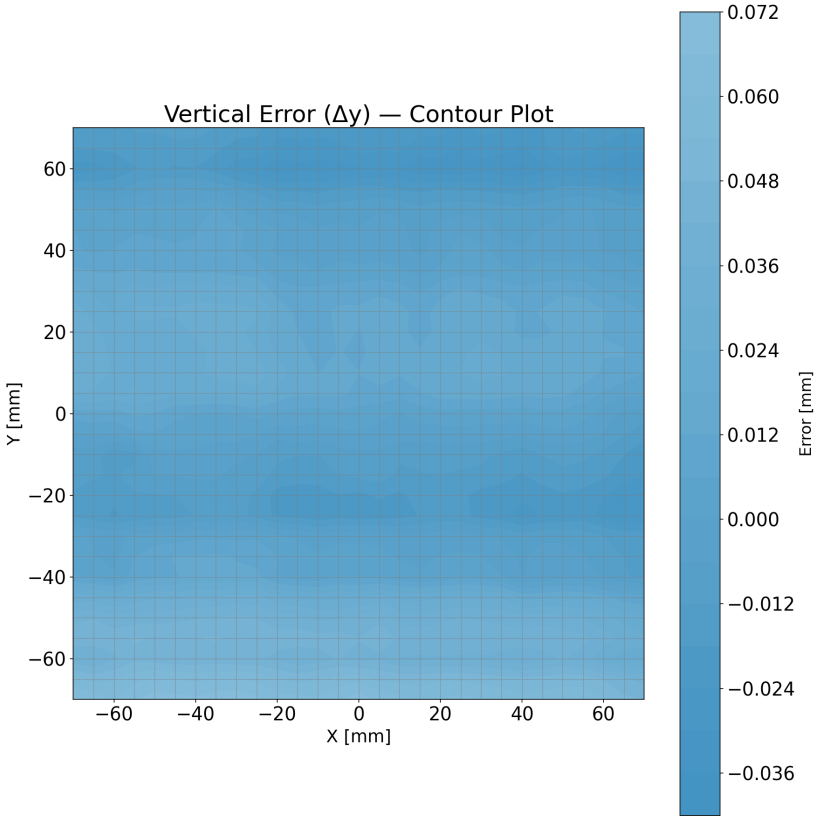
Does the camera module move in a straight line along the grid lines?

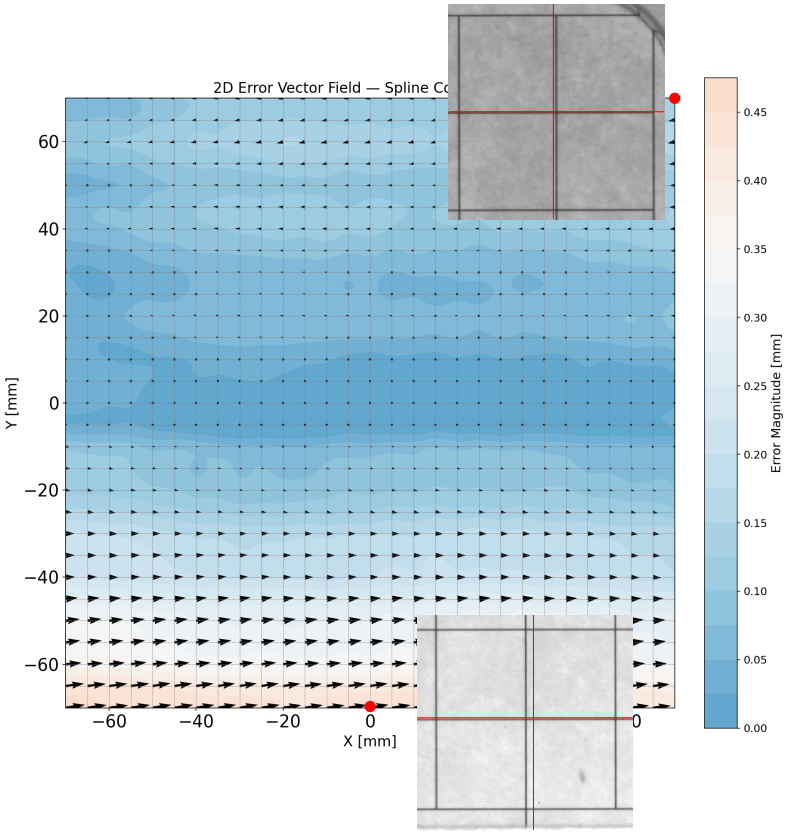
- Two-axis motor is moved and image center-grid point distance is measured.
- Each grid line is recorded separately due to the motor's repeatability problem.
- Horizontal and vertical errors on the origin are measured each time and applied as an offset.

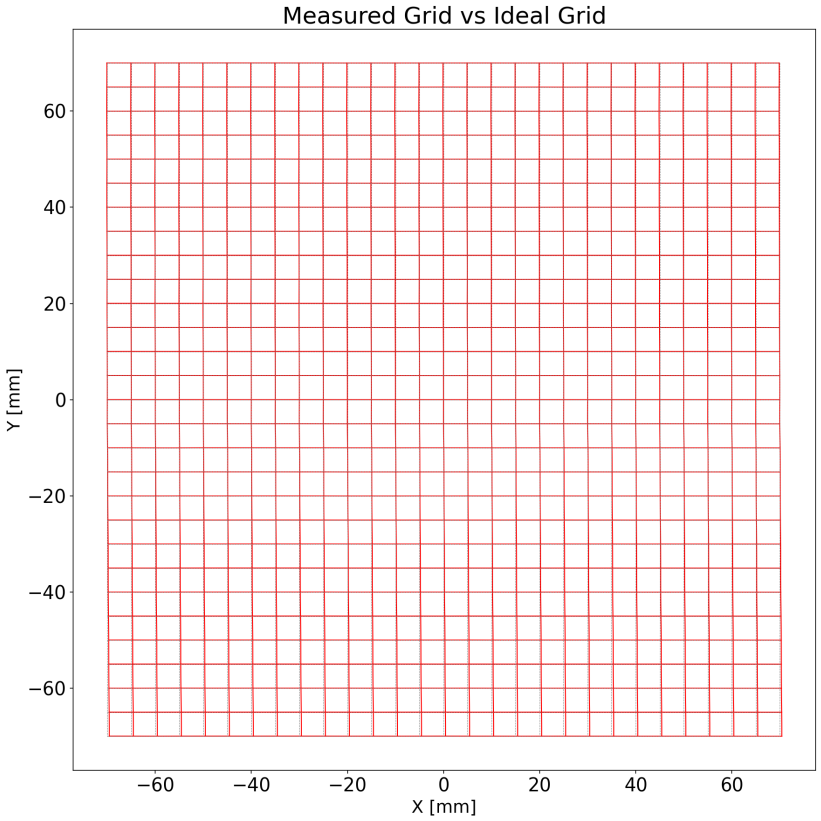
Actuator Linearity Against the Grid



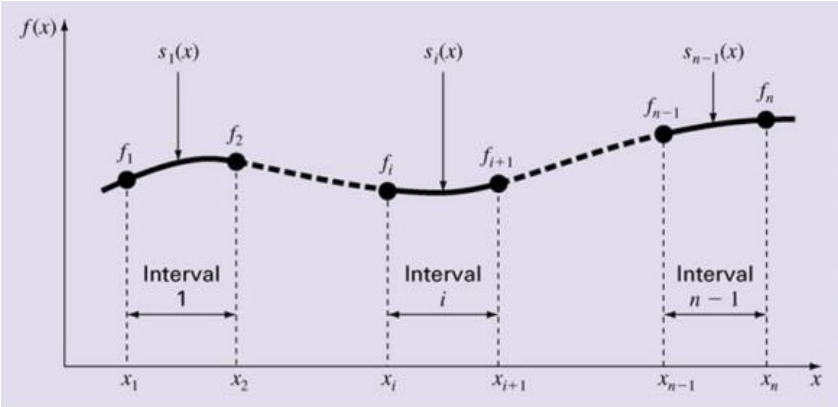


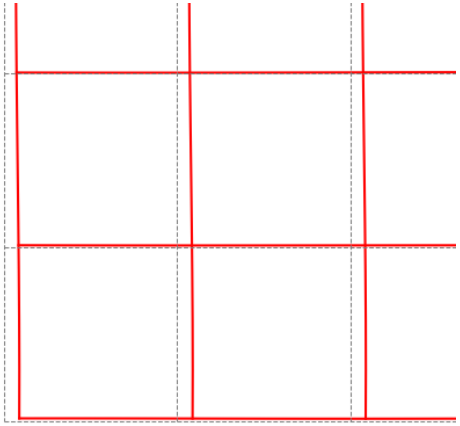
Actuator Linearity Against the Grid





Coordinate Mapping





Spline interpolation

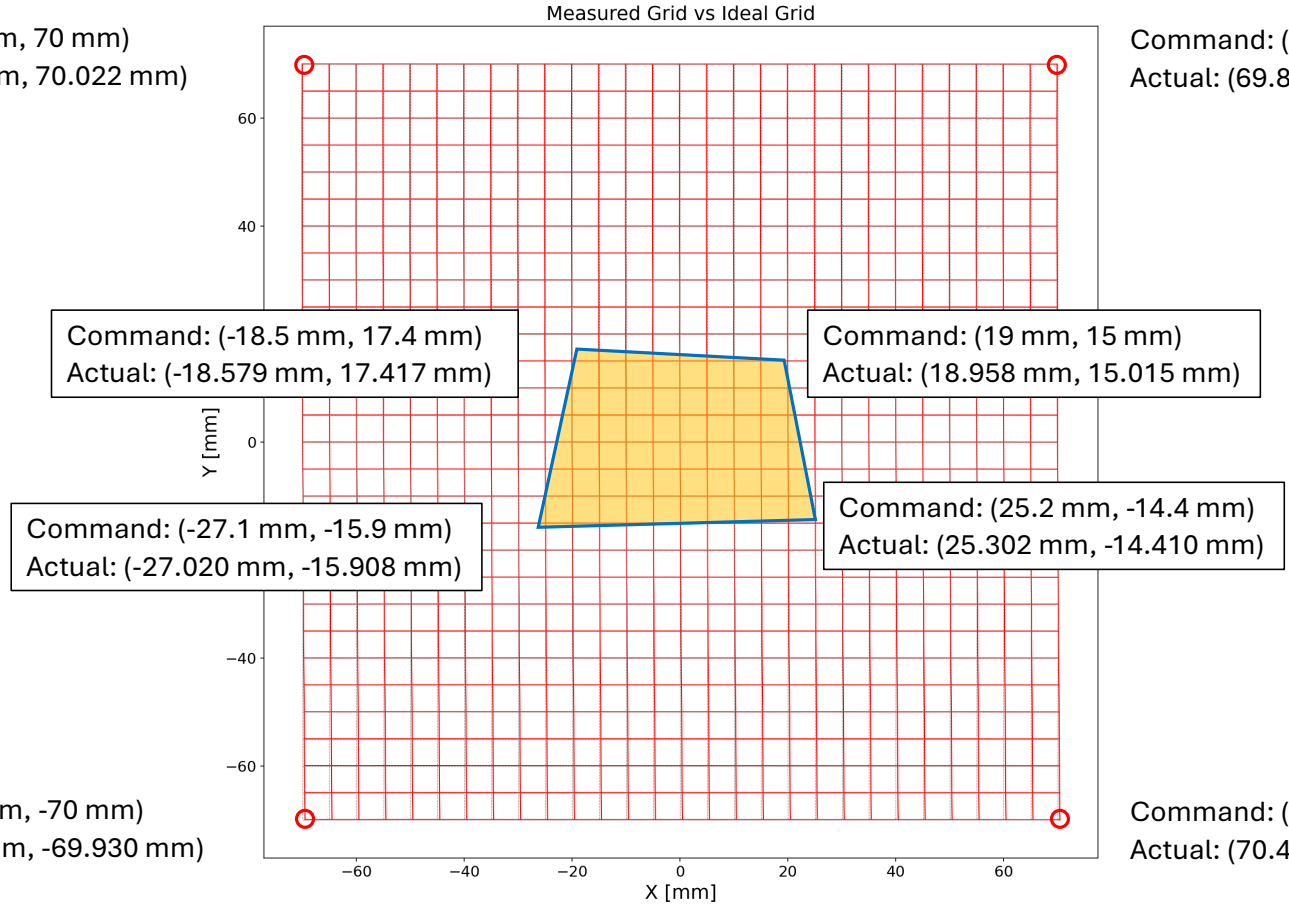
- Connecting the nonlinear data smoothly into a single curve.
- The entire data interval can be divided into piecewise functions while boundaries are continuous.

2D spline

- The deviation of the motor movement path from the ideal grid line, Δx and Δy, is interpolated.
- By applying it to the horizontal and vertical grid line, Δx and Δy can be estimated for any point within the grid.

Command: (-70 mm, 70 mm)
Actual: (-70.072 mm, 70.022 mm)

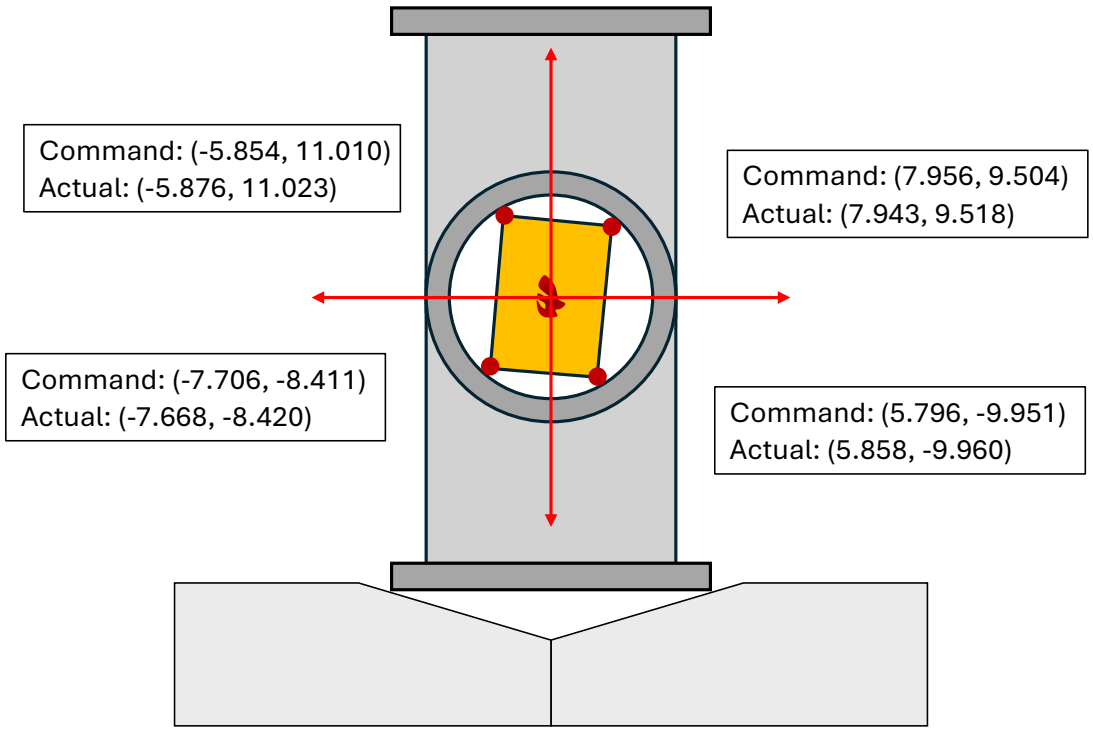
Command: (70 mm, 70 mm)
Actual: (69.889 mm, 69.992 mm)



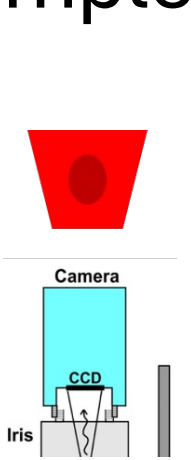
Command: (-70 mm, -70 mm)
Actual: (-69.535 mm, -69.930 mm)

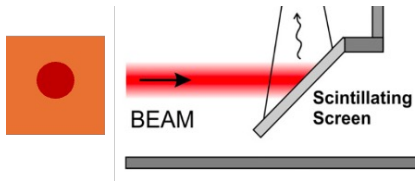
Command: (70 mm, -70 mm)
Actual: (70.426 mm, -69.959 mm)

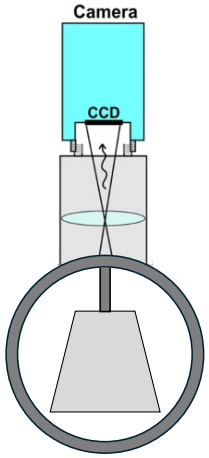
Sample Beam Profile

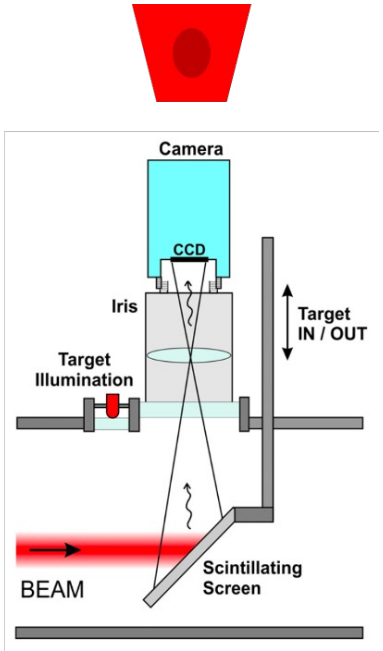


Sample Beam Profile









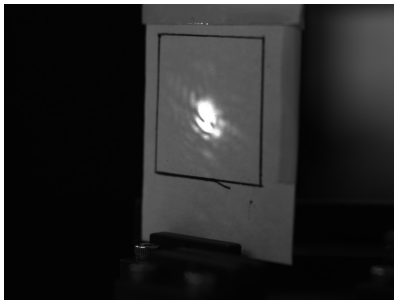
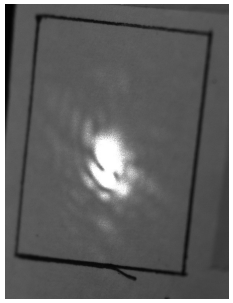


Image from BPRM camera

Perspective Transformation



2D transformed image

Comparison

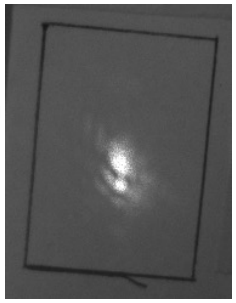
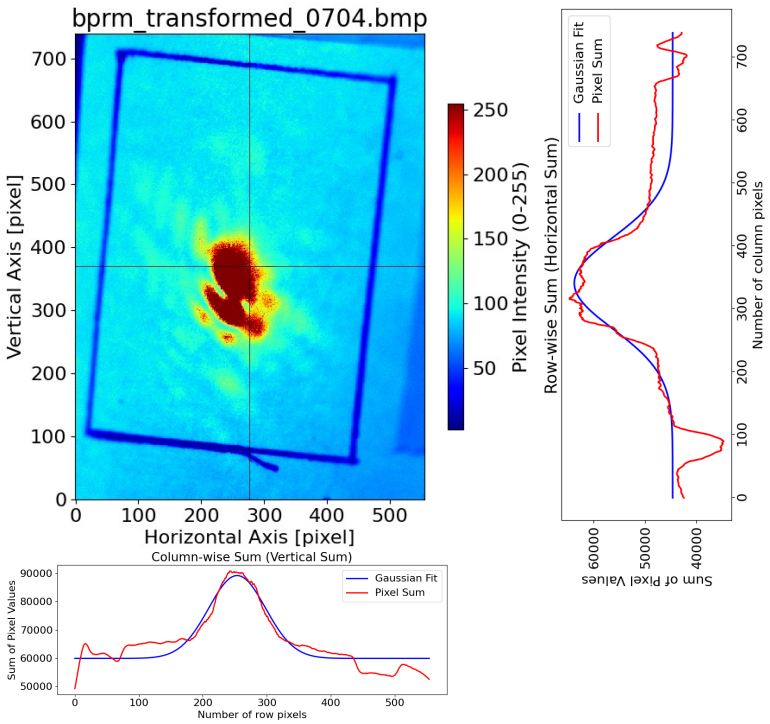
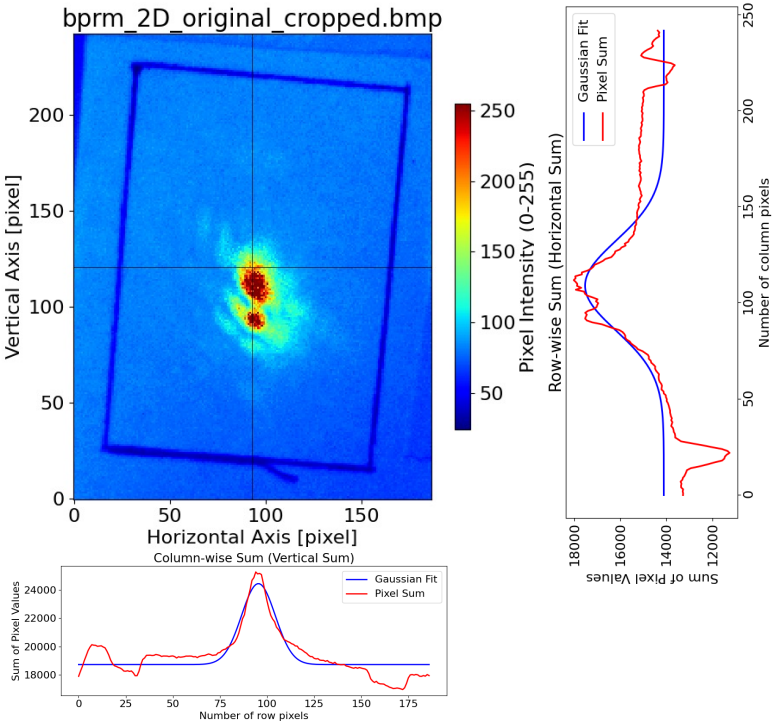


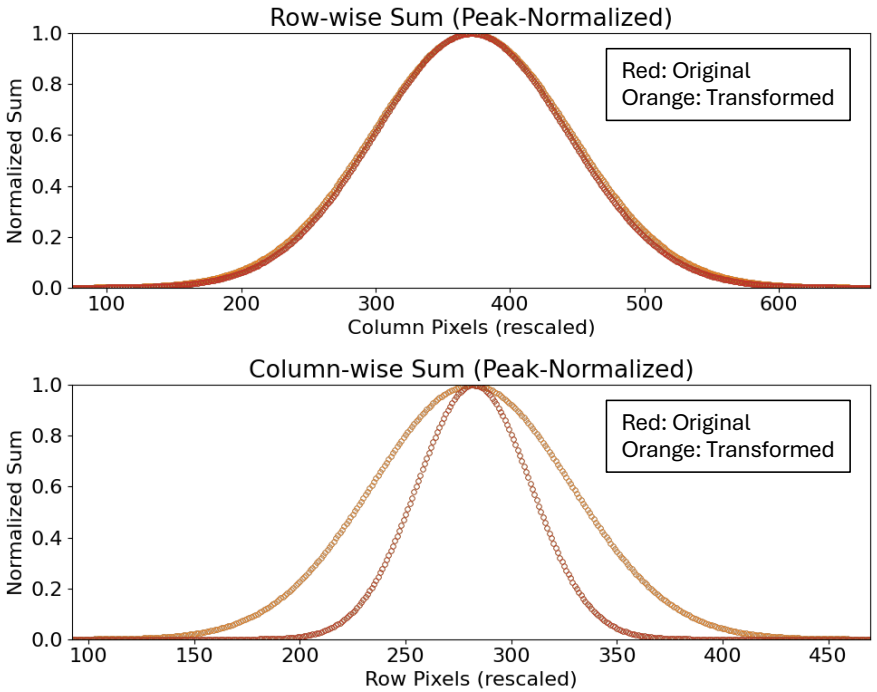
Image on the cross-section

1D Pixel Sum Fitting





Method of Processing the Fitting Data



Normalization
- Unify the maximum value into same one
- x range is also adjusted accordingly

Horizontal shift
- Equalize the mean of the Gaussian distribution
- Can identify the beam distribution error

Range fixing
- Remove the range of the extremely low value
- ±4σ from the mean value

Summary & Future Plan

2D Transverse Space Calibration and Mapping

- To check the screen image projected into the beam cross-section
- Defining an absolute coordinate plane to indicate the position of the screen
- Analyzing position error through grid point-image center distance
- Calculating the exact coordinates of an arbitrary point through a 2D spline
- Rearranging the image taken by the BPRM camera into a 2D beam image

THANK YOU