Calibrating a low-cost, 5 Axis 3D Printer

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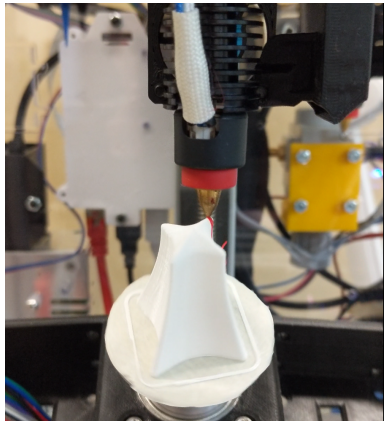
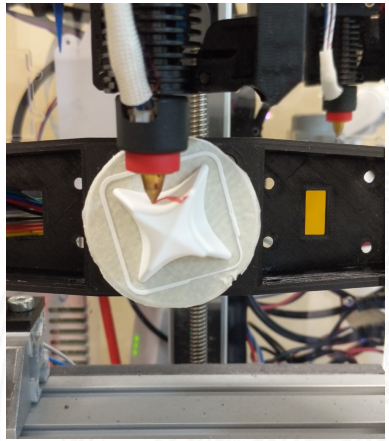
Outline

Introduction
Hardware
Calibration Journey
Demo
Slicers
Conclusion

What is 5 axis 3D printing?



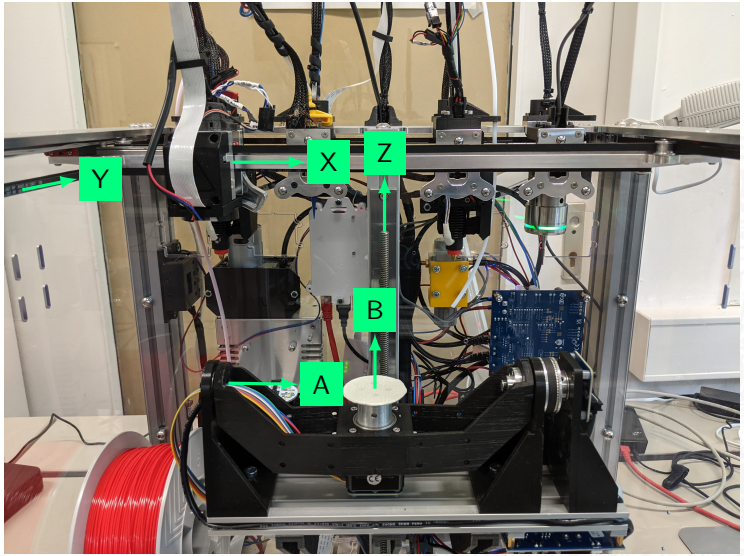


- two additional rotational axes
- using standard 3d print-head
- similar to 5 axis cnc
- two positions of same print process
- using this surfaces can be followed

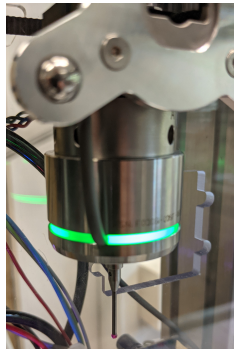
Potential of 5 axis 3D printing

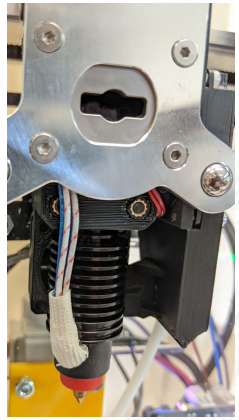
- Better surface quality [8]
- Less supports [8]
- Desirable mechanical properties [6]
- Printed electronics [1]
- Efficient multi-material printing

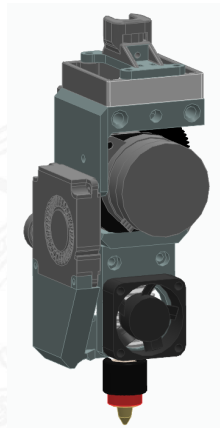
- surfaces can be printed directly, not with layer lines
- less supports as the direction of gravity can be controlled
- better strength by controlling layer direction
- printed electronics using conductive materials directly on surfaces
- multi-material with less switching



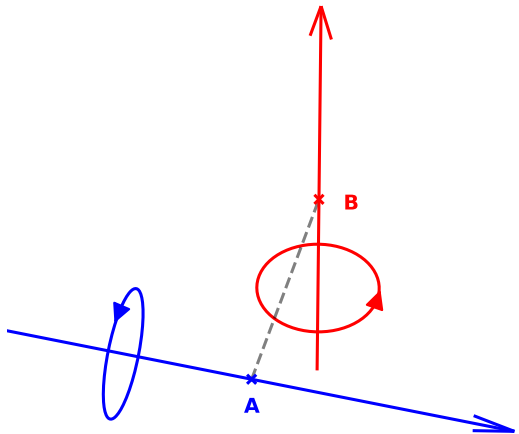
- overview, whole system based on project open5x -> E3D frame
- adapted at the 3D printing lab
- XY in top
- Z holds A and B
- B attached to A





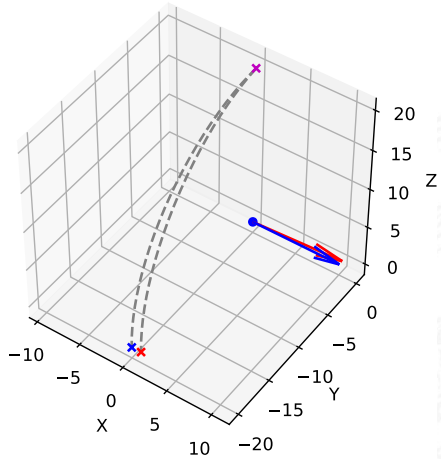


- 3D touch probe
- can measure in X and Y directions and downwards Z
- small ruby sphere diameter 2mm
- introduce the most important tool for checking
- custom long extruder
- developed by German
- high clearance allows extensive 5x use



- Two axes in space
- closest position of both
- offset between closest
- axes don't intersect
- b position is defined as 0,0,0

Why is calibration needed?



- point 2cm from rotation axis
- axis is 2° off
- 1mm error in 90° rotation

Ours
System Cost:
≈10,000€

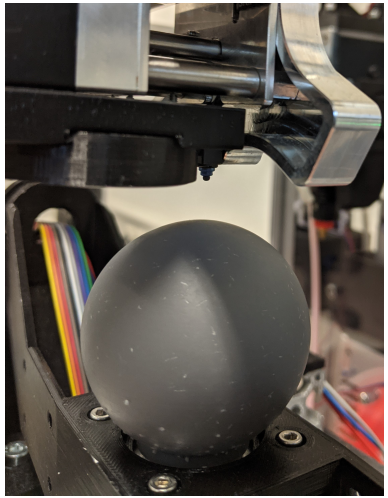
Measure Instrument:
500€

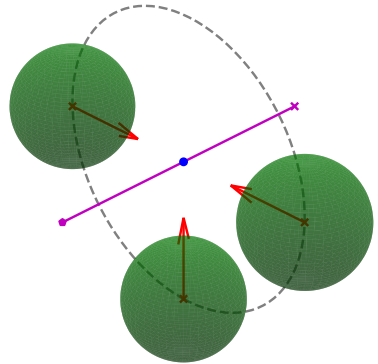
Others
System Cost:
>30,000€

Measure Instrument:
>3,500€

- other option, pay for it
- our system cost around 10k
- tool only 500 -> main part really cheap
- others usually use modified cncs (cost approximated)
- expensive laser scanners
- though more generally speaking -> one paper with a cheap printer + conductive probe -> results ok
- often either instrument or machine expensive

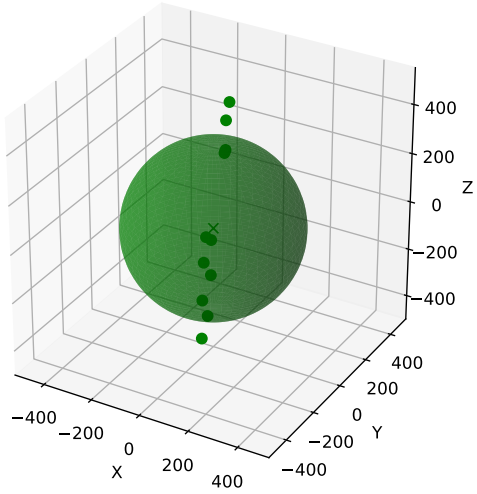
Calibration of Axes Model: Round 1





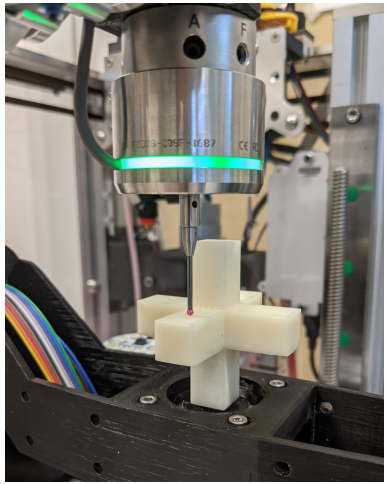
- first using a sphere → finding center point
- rotating axes and finding multiple centers
- axes are found in result structure

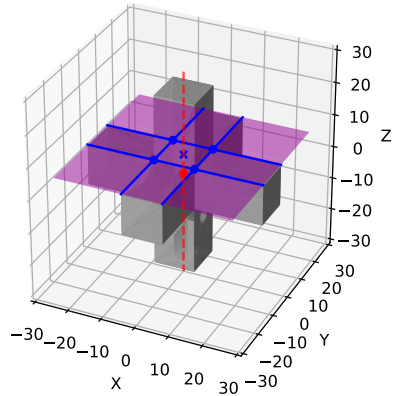
Sphere Results



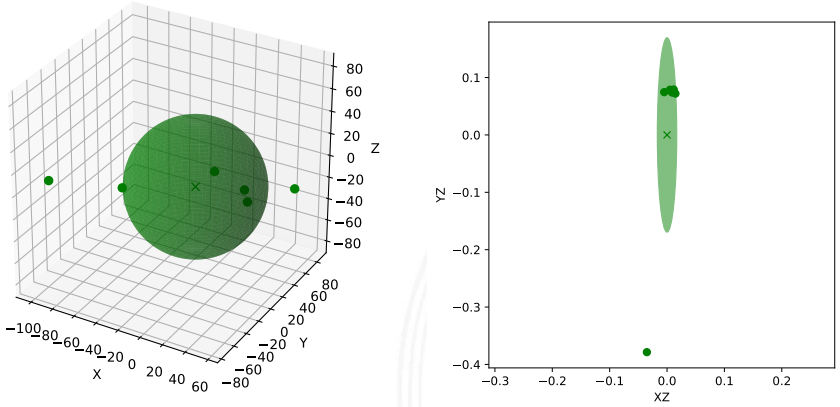
- not reliable (11 measure)
- axes are in microns
- plot shows center points and biggest standard dev as sphere
- but would only use standard Z switch

Calibration of Axes Model: Round 2



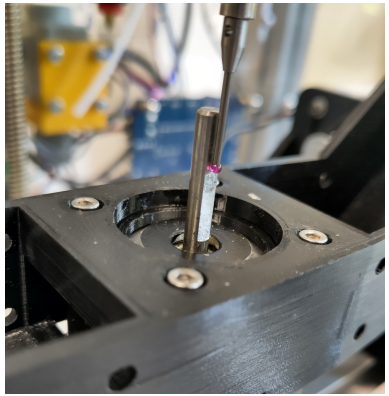


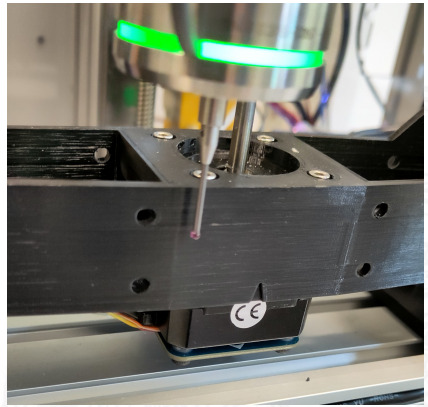
- similar for cross → center and orientation
- using a plane fitted to probed points and projecting points into it



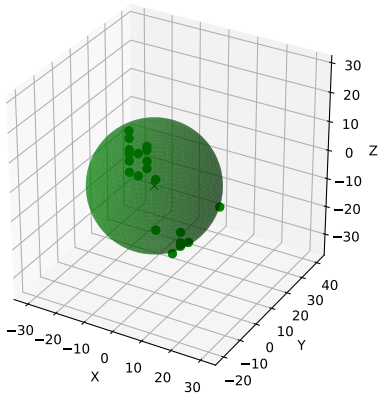
- orientation plot in degrees in plane from mean
- center and orientation ok (though >100mu) (6 measurements)
- but, only worked for B, not A -> motor loaded / wiggle
- -> problem with calibration objects not being reliable
- (able to measure more properties)

Calibration of Axes Model: Round 3

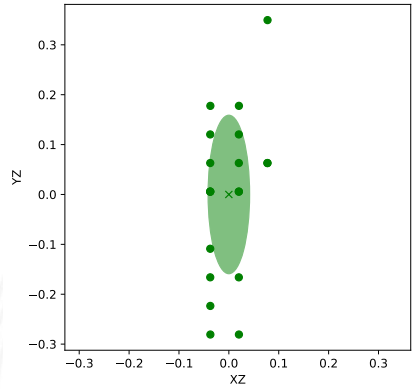




- conclusion -> use objects already on printer
- B metal axle + 3d printed structure of A axis
- split into 4 measure -> position and orientation for each



A position



B orientation

- worst components
- A position is good -> movement probably because of the probe structure holding -> Y variation
- B orientation is too varied -> good enough in practice though
- expected to be Y movement too, but no certain
- simple -> works really well

Axes Precision:
$\approx 10\mu m$

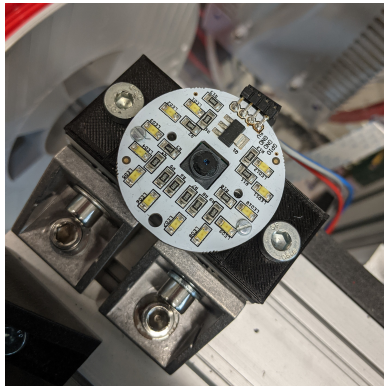
Pickup Repeatability:
$\approx 10 - 20\mu m$

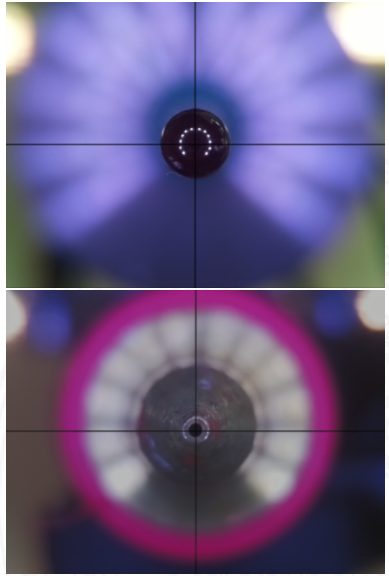
Probe Precision:
$\approx 10 - 20\mu m$

A position:
$\approx 55\mu m$

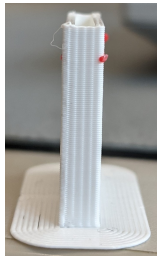
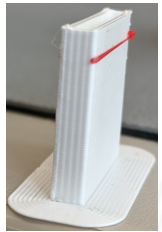
B position:
$\approx 35\mu m$

- comparing the position res to machine precision
- for pickup and probe this includes axes
- for pickup manu says 4

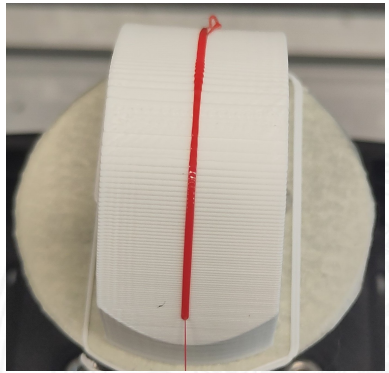




- tool have to be calibrated to each other
- camera mounted to the Z bed
- probed moved to center of camera
- position of camera saved
- extruder moved into center
- now relative to probe -> probe measures everything

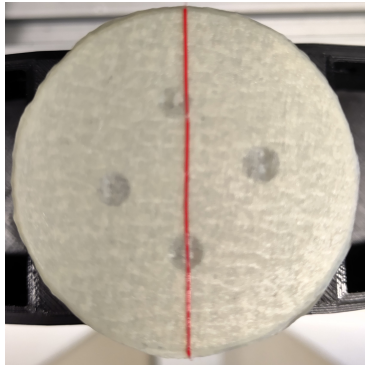




A position

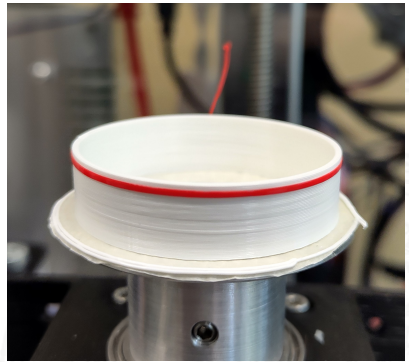


A direction

- position by drawing line on both sides of obj and comparing height only using A rotations
- direction by drawing straight line on surface

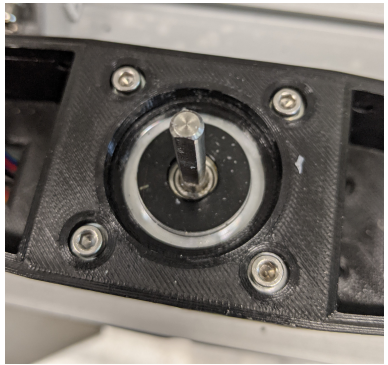


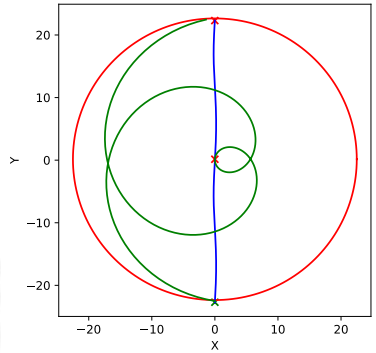
B position



B direction

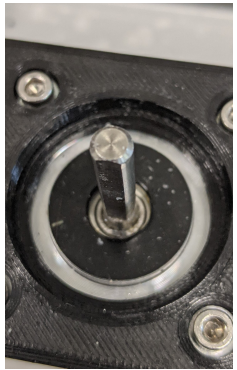
- position by trying to draw a straight line on rotating table
- orientation line on rotated surface

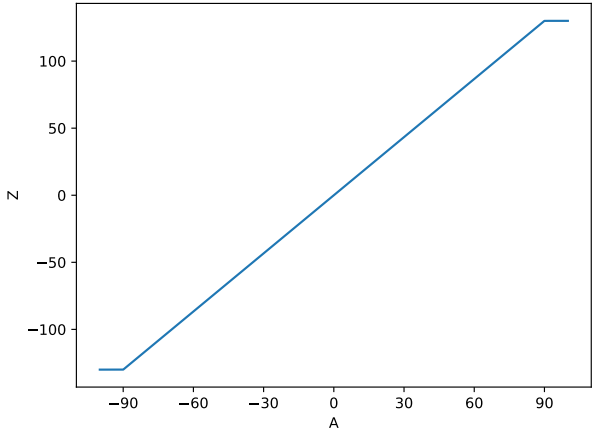




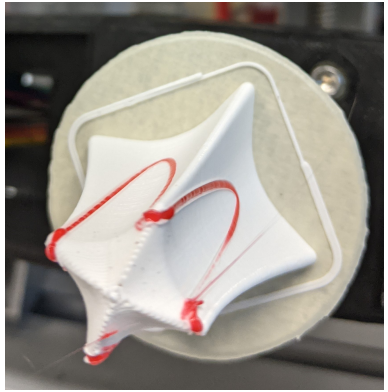
- B axle as reference object
- size is known and very accurate
- used to find dimensionality errors (squished or stretched objects) with probe
- the b position test used to find X/Y bias of probe -> characteristic wave pattern based on error
- flat side also used to find z offset (gesture)

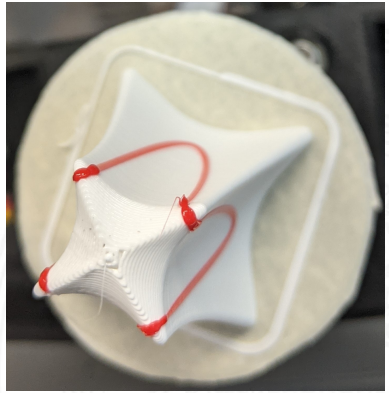
A Axis





- scaling by finding slope of flat side in $\pm 90°$
- found error of $\approx 0.6°$ -> significant effects
- thought to come from drive belt slack
- Z wobble found in test -> shift Z height of rotation axis
- beyond axes model
- linear effect worked for good results





- first with 0 pos calibrated, but nothing else
- second full calibrated
- first embedded plastic into object
- second actually printed on top
- rotation error in top lines

Printed Results

- first with 0 pos calibrated, but nothing else
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- second actually printed on top
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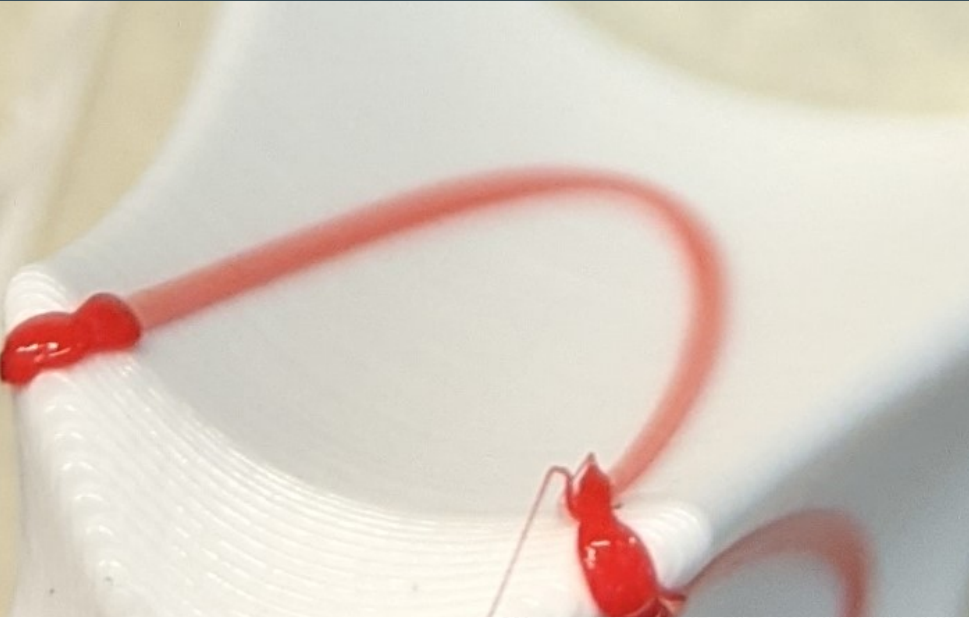
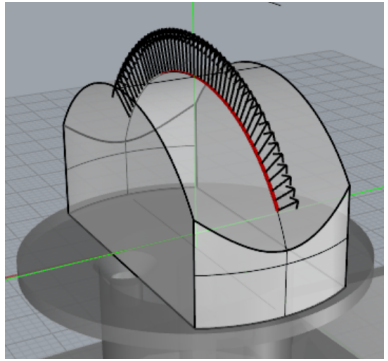
Printed Results

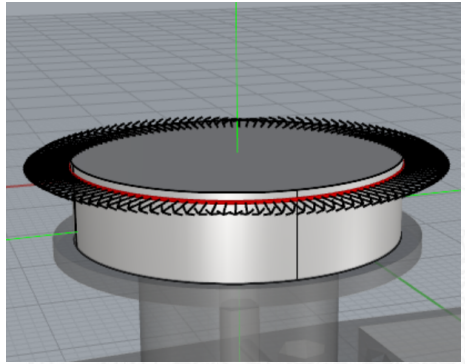


- first with 0 pos calibrated, but nothing else
- second full calibrated
- first embedded plastic into object
- second actually printed on top
- rotation error in top lines

Demo

- real world demo
- or backup video





- 5 axis slicer is needed
- development by Florens and Daniel
- red line is the line to print
- arrows are the normals of the lines
- but open source not really present

- Development of open 5 axis slicers
- Using 5 axes to print electronics
- Error model based approach
- Adaptation for current printers
- Test analysis automation through image processing

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Contributions & Outlook

- Procedure for Calibration
- Tests for calibration components
- Showing extensions beyond line model needed
- Proving feasibility of low-cost 5 axis

- Procedure for calibration for our printer or similar
- Tests for Calibration Components
- Showing extensions beyond line model needed
- Proving feasibility of low-cost 5 axis
- -> probably will see the technology more soon + more research

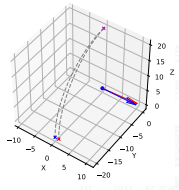
Potential of 5 axis 3D printing

- Better surface quality [8]
- Less supports [8]
- Desirable mechanical properties [6]
- Printed electronics [1]
- Efficient multi-material printing

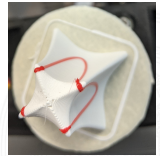
Cost Comparison

Ours	**Others**
System Cost: ≈10,000€	System Cost: >30,000€
Measure Instrument: 500€	Measure Instrument: >3,500€

Why is calibration needed?



Printed Results



Demo Links

Printing:
`https://youtu.be/QCpKqnp3P4I`

Calibration:
`https://youtu.be/AuEFCgAx3H4`

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[1] Freddie Hong et al. "5-axis multi-material 3D printing of curved electrical traces". In: *Additive Manufacturing* 70 (2023), p. 103546.

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[3] WT Lei and YY Hsu. "Accuracy enhancement of five-axis CNC machines through real-time error compensation". In: *International journal of machine tools and manufacture* 43.9 (2003), pp. 871–877.

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[6] Ren C Luo et al. "3D digital manufacturing via synchronous 5-Axes printing for strengthening printing parts". In: *IEEE Access* 8 (2020), pp. 126083–126091.

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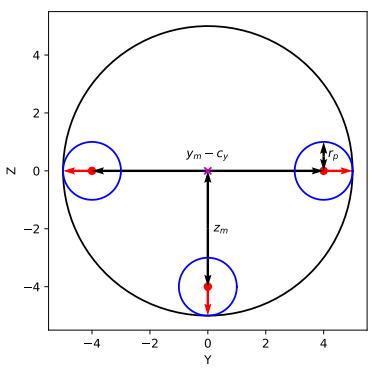
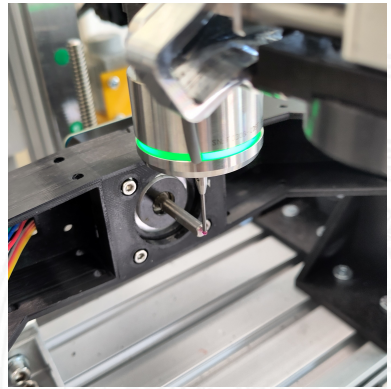
[9] Yujie Shan et al. "Additive manufacturing of non-planar layers using isothermal surface slicing". In: *Journal of Manufacturing Processes* 86 (2023), pp. 326–335.

Goal

- Good quality prints
- $< 100\mu m$ position error
- $< 0.2°$ orientation error

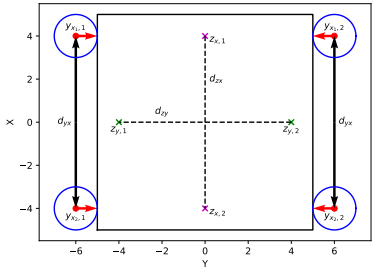
- Good quality prints
- $< 100\mu m$ position error
- $< 0.2°$ orientation error

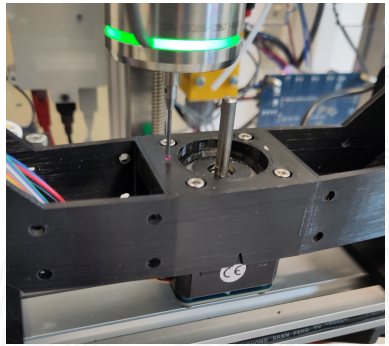




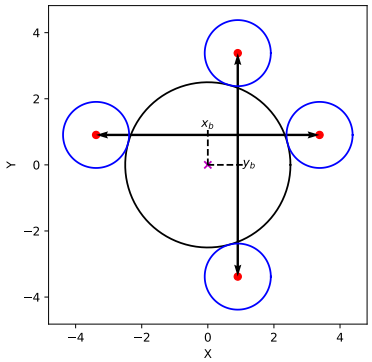
- internal circle by rotating axis
- 3 rotations
- approximation, but low expected error (single digit μm)

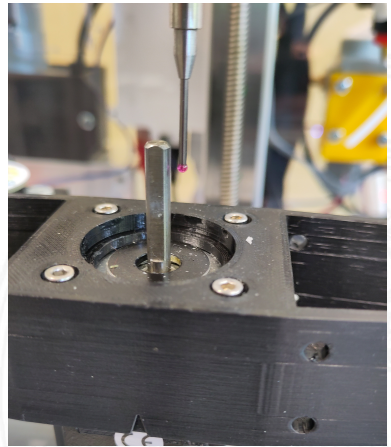
Measurements: A Direction





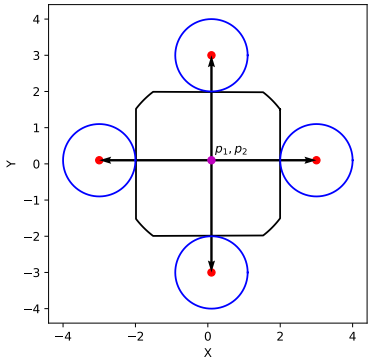
- measuring 3D printed structure
- first from top to get slope in X and Y
- the sides to get rotation in Z

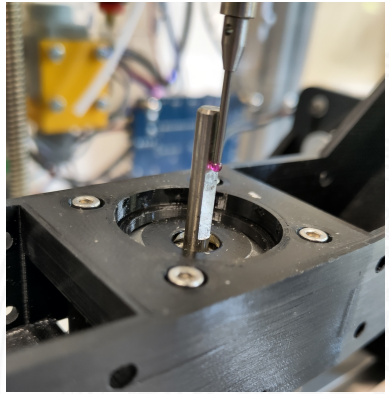




- using the b motor axle
- rotating it to create cylinder shape (has flat side)
- finding center

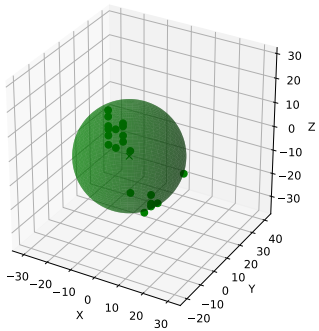
Measurements: B Direction

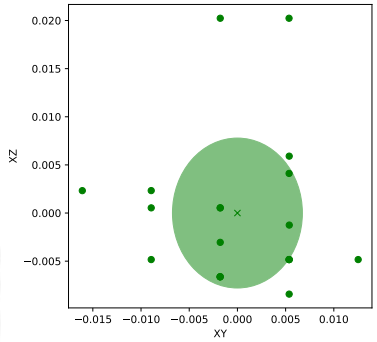




- Using the flat side to find two points at diff heights
- find vector between in orientation

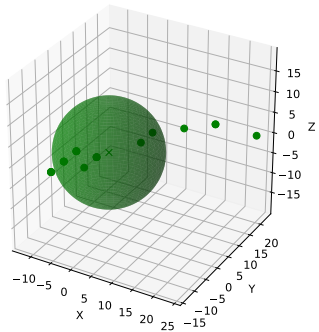
Evaluation: A Axis

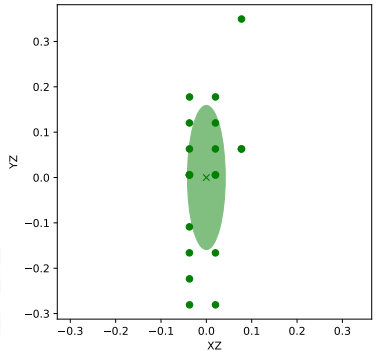




- 20 measurements
- first positional error in μm
- second angle error in projected plane from mean
- position to less than $30\mu m$
- orientation very stable

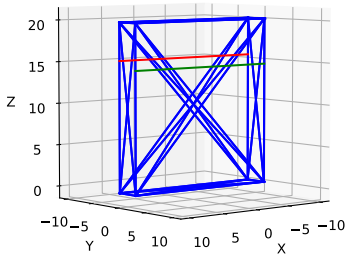
Evaluation: B Axis

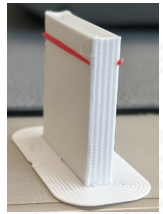


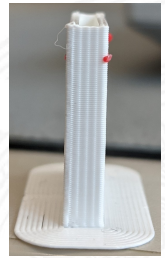


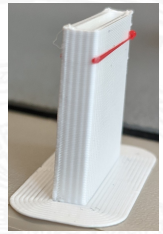
- for b axis
- position really good
- orientation less stable $> 0.2°$

A Position Test



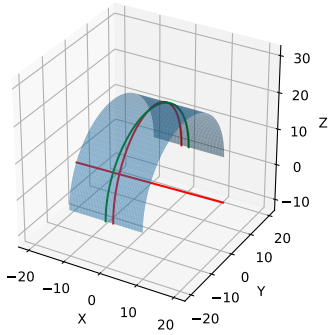


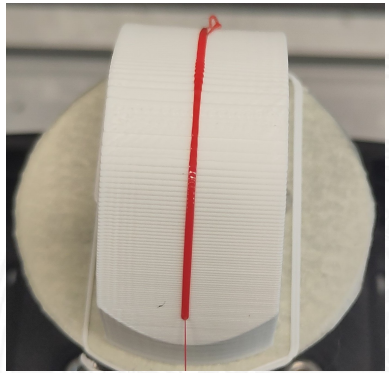




- line heights
- equal extrusion
- good result (extrusion needed a bit to stabilize)

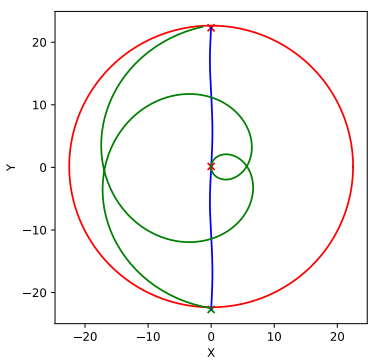
A Direction Test

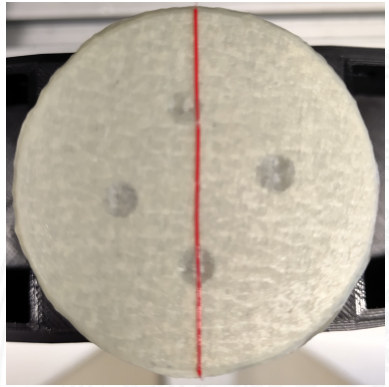




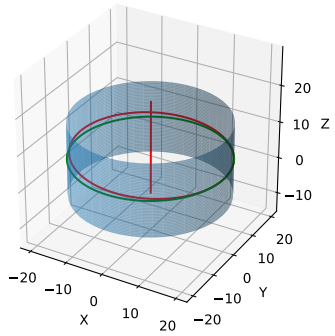
- a direction by drawing in rotation
- green is good $\rightarrow$ red example error
- result with excellent line (checked with caliper)

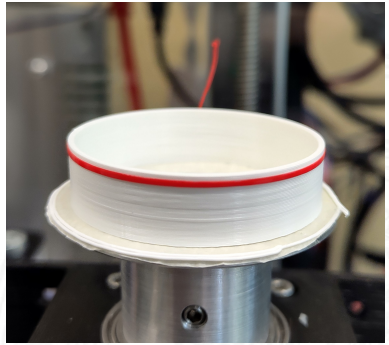
B Position Test



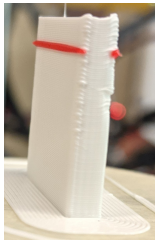
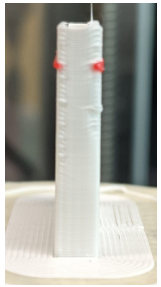
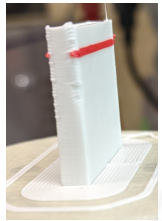
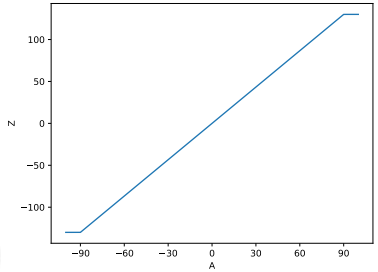


- trying to draw line while rotating print-bed
- if position is off, line waves
- blue is simulated result, green is 3D space movement of nozzle
- actual result shows almost straight line with error less 100mu
- very important test, as it allows conclusion about offset
- $\rightarrow$ used to find error in the measurement probe





- drawing line on rotating cylinder
- orientation is wrong, distance from top will change
- did not observe such error

- A Axis Rotation axis wobble
- Beyond the line model
- linear z height correction
- theory for problem is not really round axis