

10th
UCAAT

**User Conference on
Advanced Automated Testing**

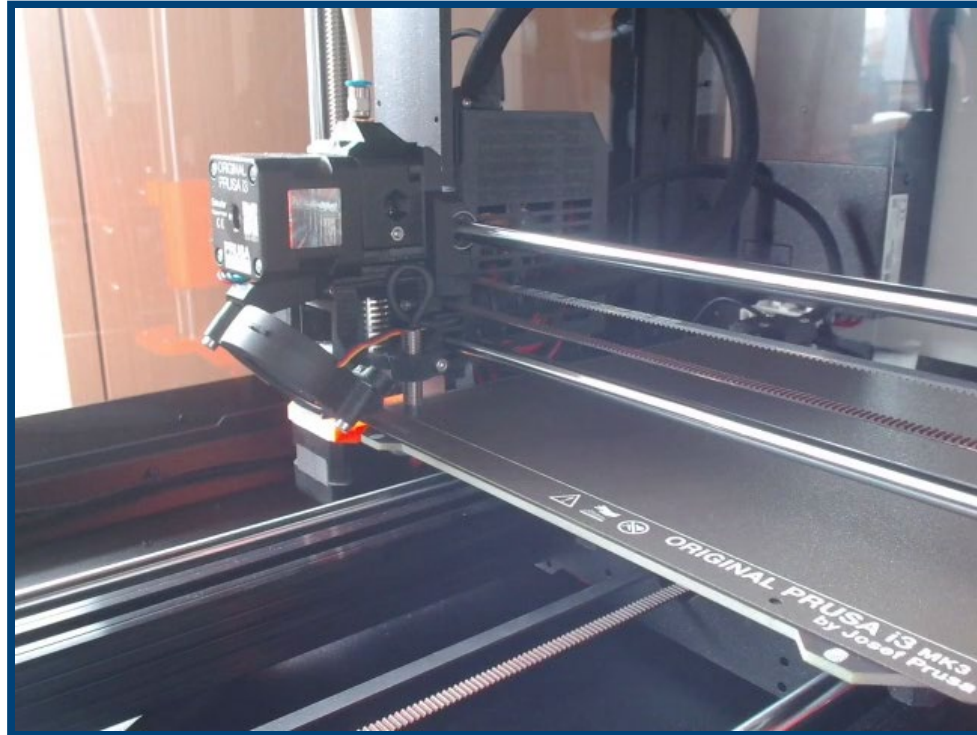
Test Oracle Generation for Audio Cues in Additive Manufacturing

Johannes Erbel, Kolja Thormann, Alexander Trautsch

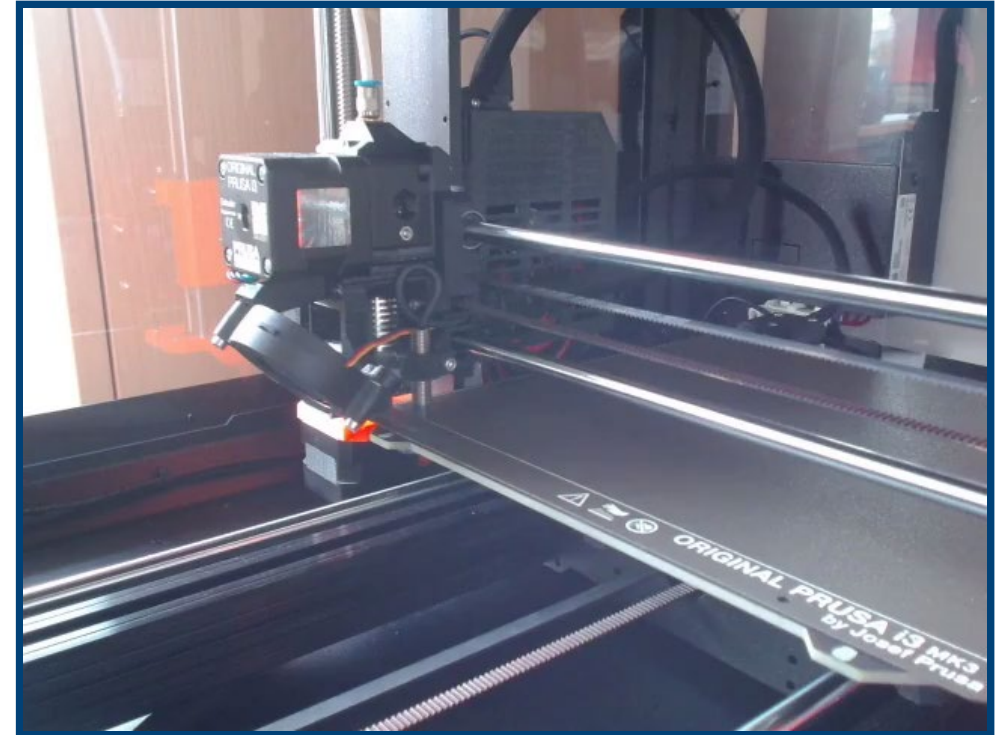


Can you detect the difference?

Visual information is not sufficient!



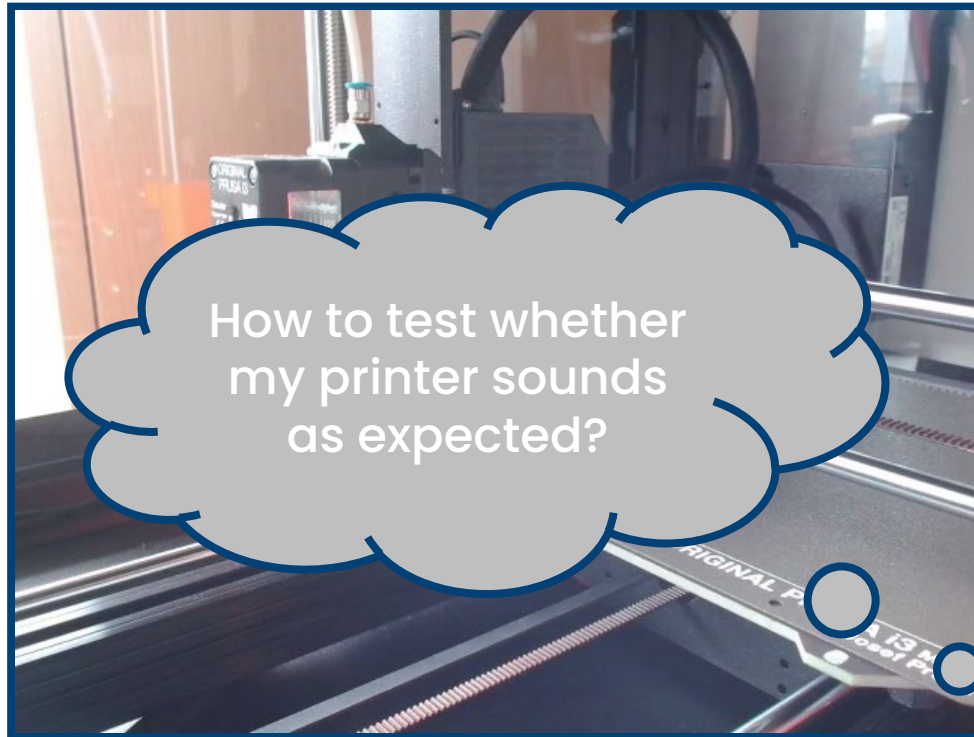
Recording 1



Recording 2

Can you detect the difference?

Visual information is not sufficient!



Recording 1



Recording 2



- Additive Manufacturing
- Audio Cue Test Oracle
- Early Results
- Conclusion

Motivation

Challenges of AM in different contexts



Individual



Single Machine



Milenium Falcon (Star Wars)



Industry



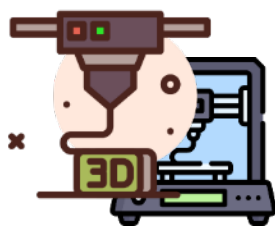
Homogenous



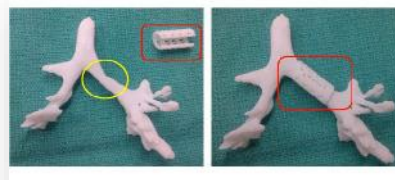
Shoe cleats (NIKE)



Research



Heterogenous

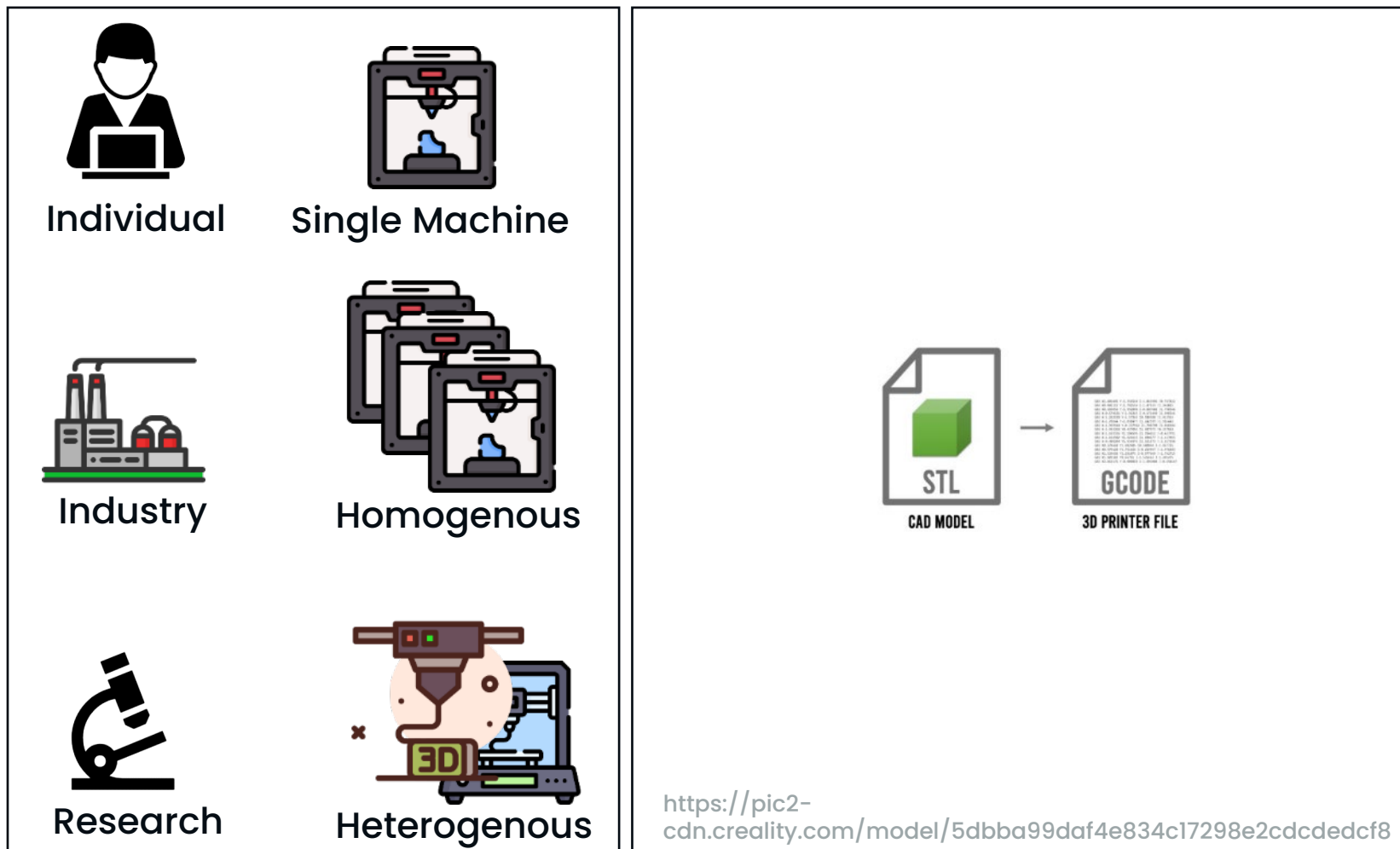


Custom airway stent (U. Michigan)

3D printer images from: www.freepik.com

Motivation

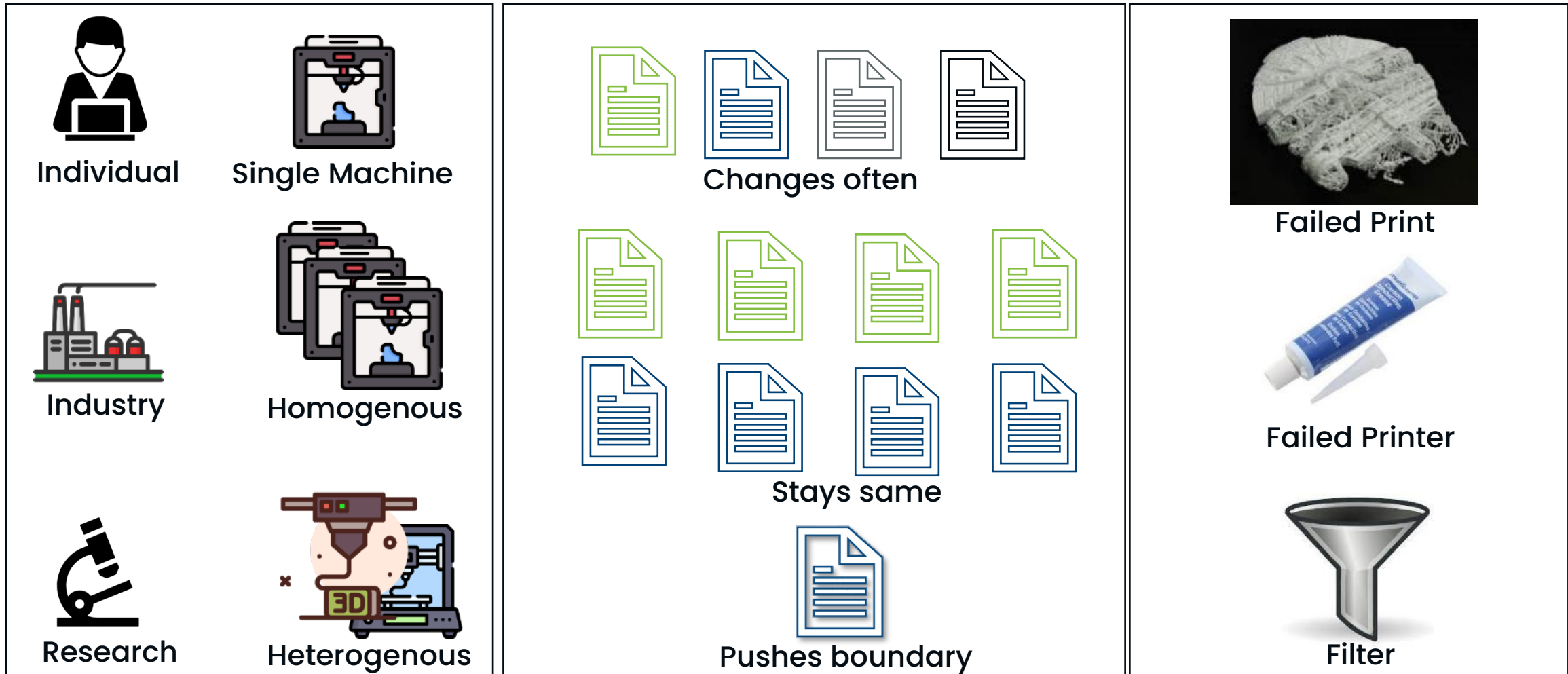
Challenges of AM in different contexts



3D printer images from: www.freepik.com

Motivation

Challenges of AM in different contexts



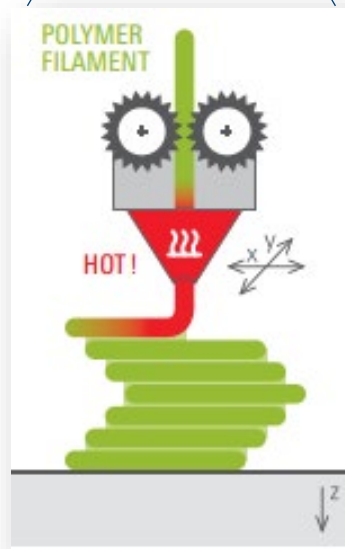
3D printer images from: www.freepik.com

Fused Deposition Modeling

How do printer instructions look like?



FDM



Gcode

```

;TYPE:External perimeter
G1 F1200
G1 X81.41 Y81.41 E.53867
G1 X98.59 Y81.41 E.53867
G1 X98.59 Y98.59 E.53867
G1 X81.47 Y98.59 E.53678
M204 P1000
G1 X81.514 Y98.204 F9000
G1 E-2.24 F2700
;WIPE_START
G1 F7200
G1 X81.461 Y96.03 E-.912
;WIPE_END
G1 E-.048 F2700
G1 Z.4 F720
    
```



Each line instructs the printer's motors

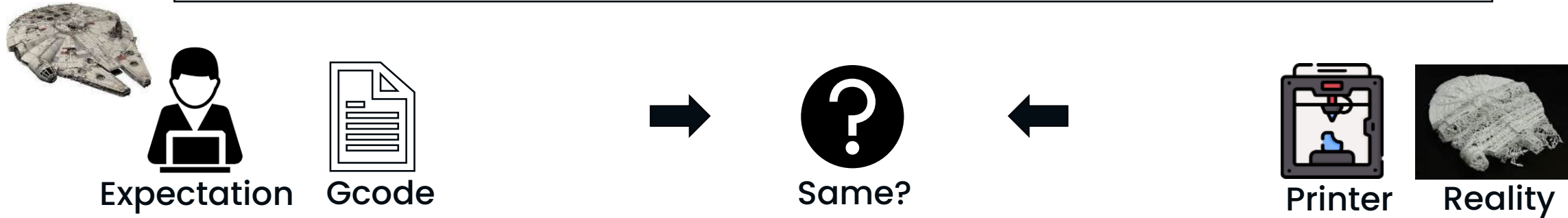
Formnext, AM Field Guide, Messe Frankfurt, 2021

Related Work

What does exist?



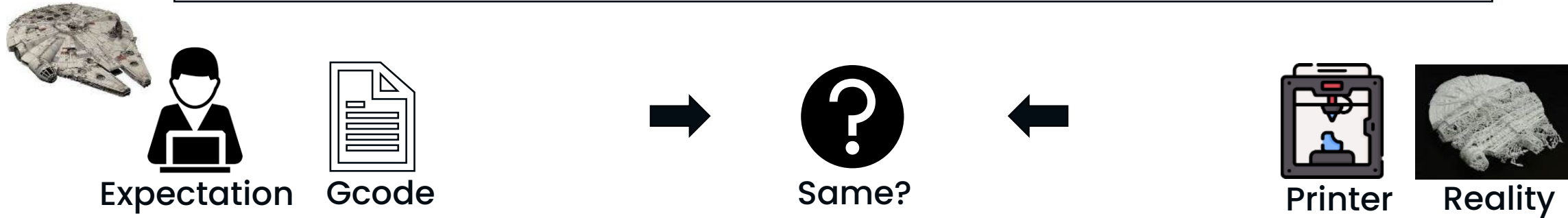
Belikovetsky et al.,
Digital Audio Signature
for 3D Printing Integrity,
IEEE Transactions on
information forensics
and security 2019



Qin et al., Research and
application of machine
learning for additive
manufacturing, Additive
Manufacturing 2022

Related Work

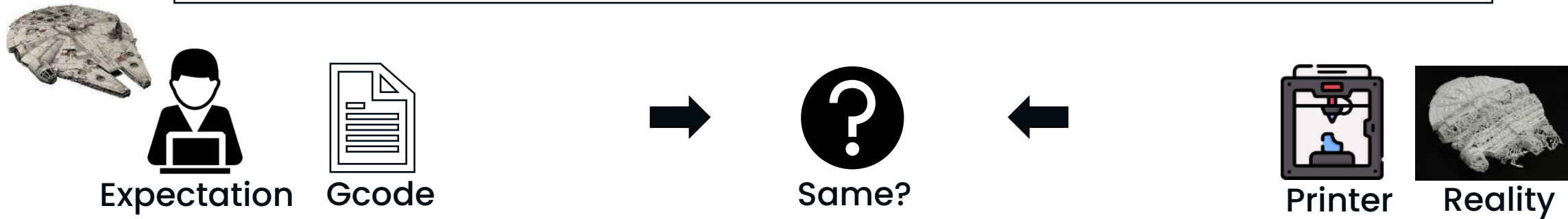
What does exist?



- File specific
- No match to instructions
- Not applied for predictive maintenance

Research Gap

Where is the gap?

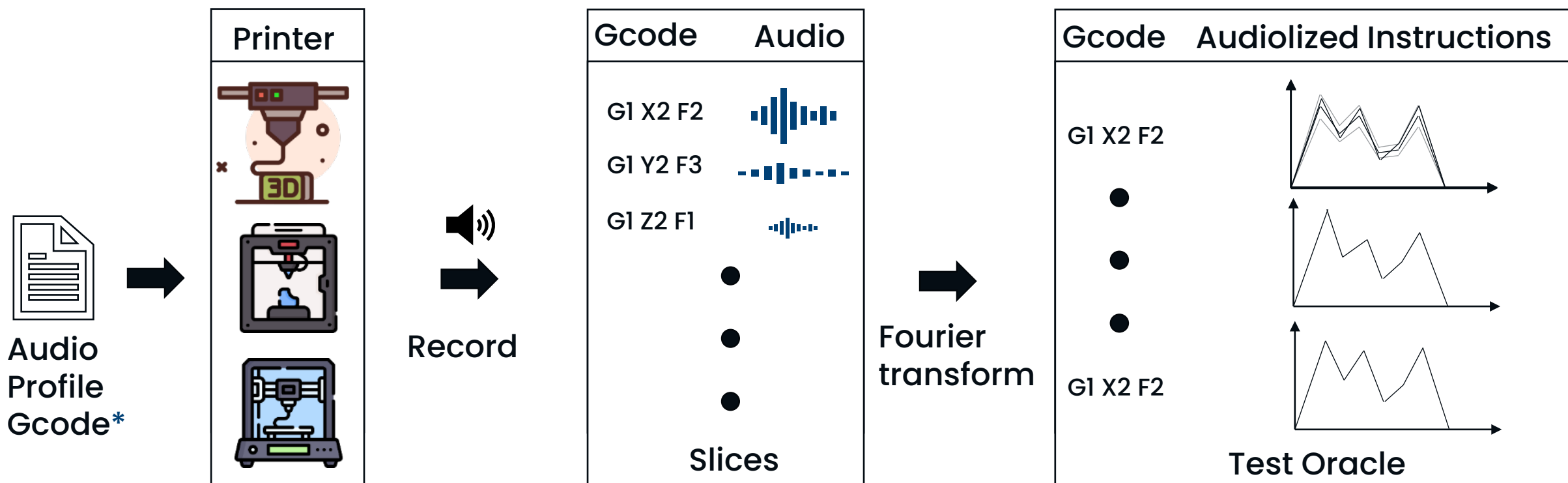


- File agnostic
- Mapping: Instructions <-> Sound
- Applied for predictive maintenance

- Additive Manufacturing
- **Audio Cue Test Oracle**
- Early Results
- Conclusion

Audio Cue Test Oracle

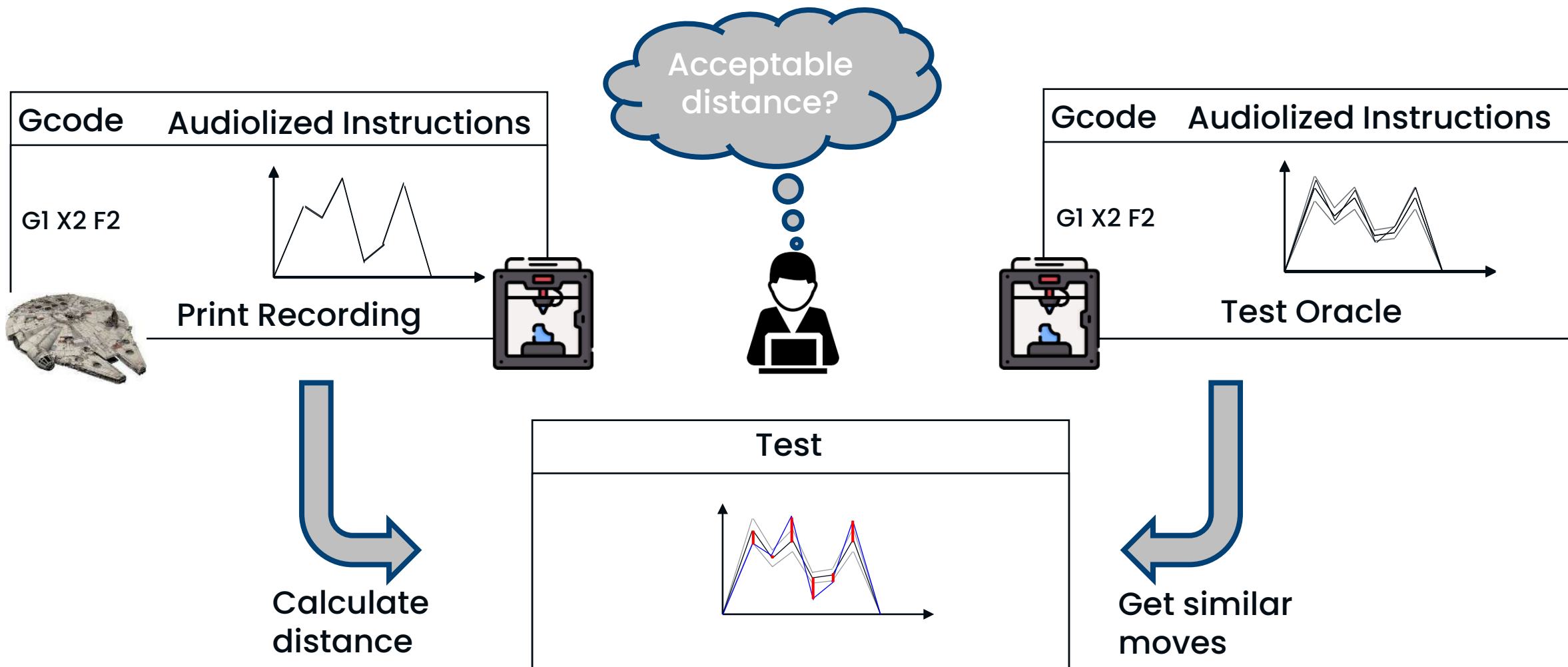
Generation



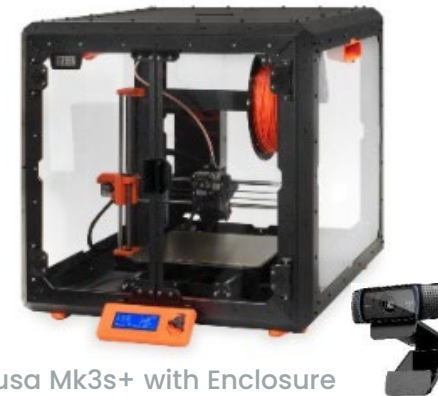
*Requires instrumented segmentation

Audio Cue Test Oracle

Assertion



- Additive Manufacturing
- Audio Cue Test Oracle
- **Early Results**
- Conclusion

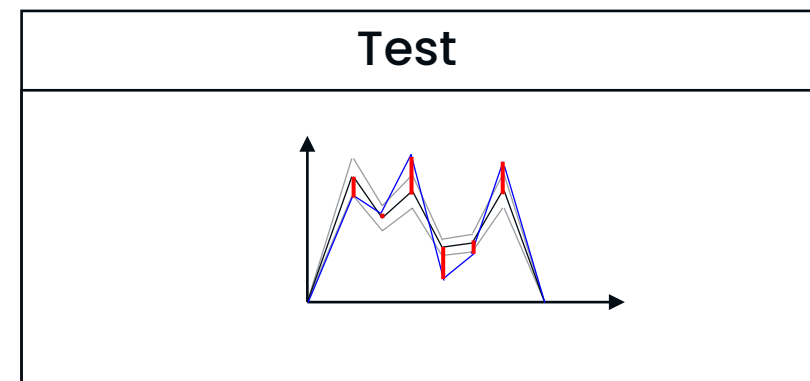
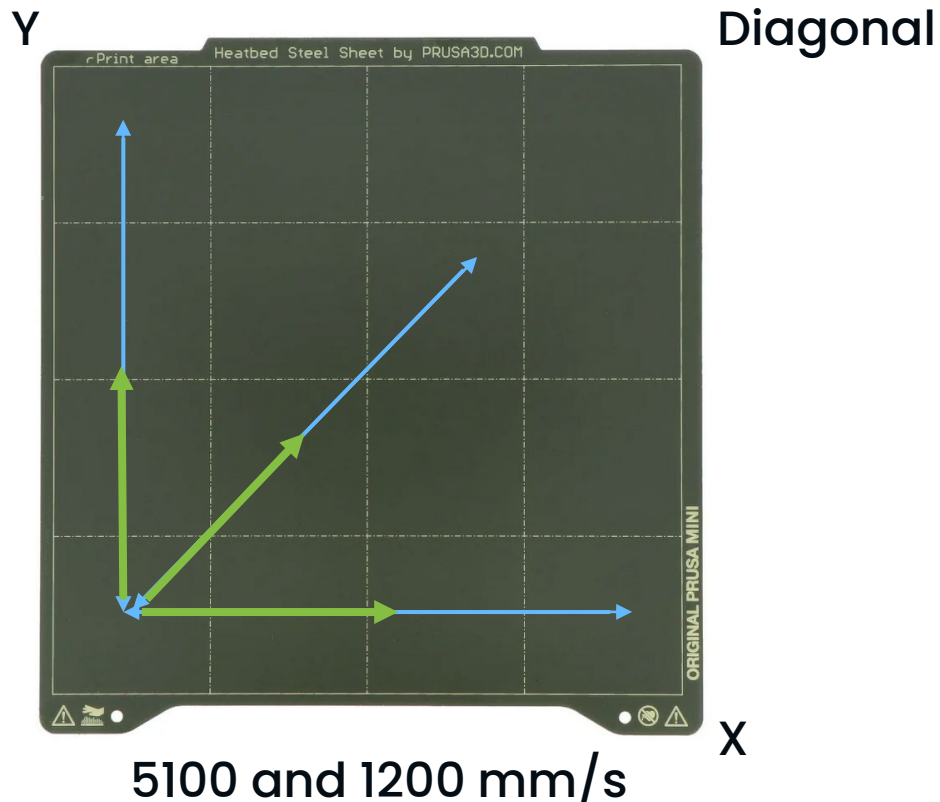


Prusa Mk3s+ with Enclosure

Logitech Webcam

Basic movements

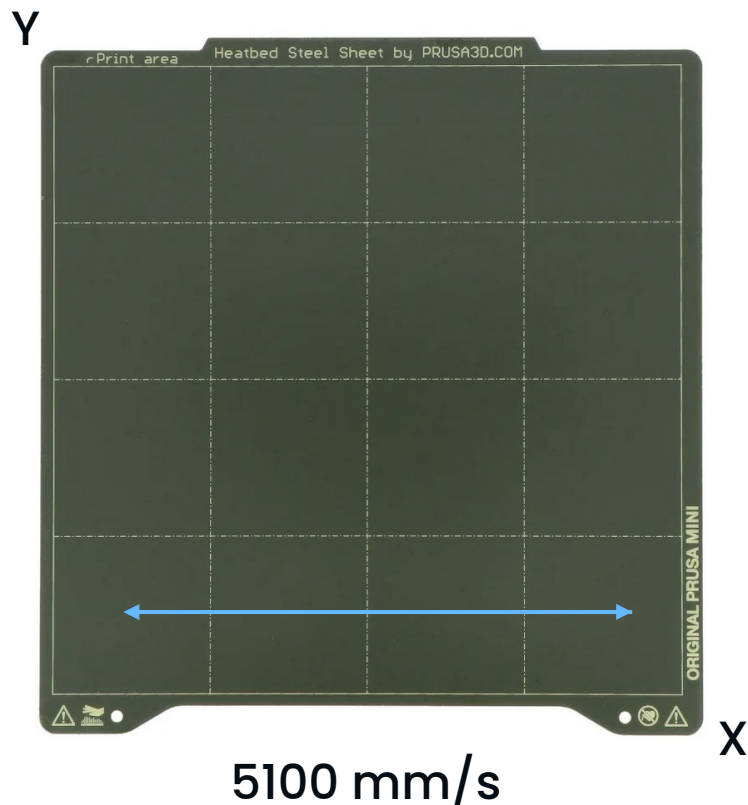
What are distinguished features?



- Distance for basic movements?
 - Inverse directions
 - Different lengths
 - Different feedrate

Basic movements

What are distinguished features?

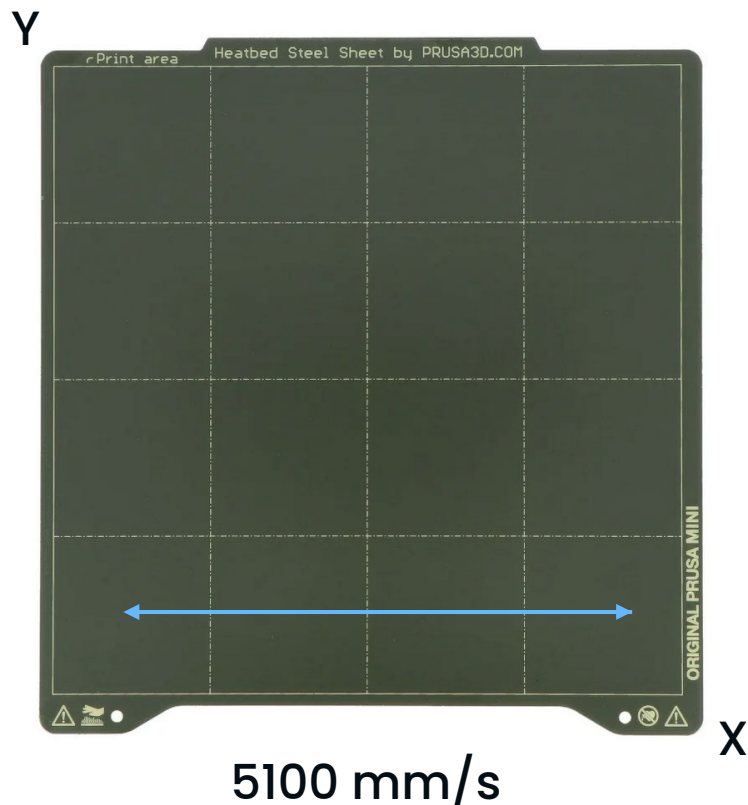


Gcode Instructions
(Recording)

```
(150.00, 0.00, 0.00)_5100  
(-150.00, 0.00, 0.00)_5100
```

Basic movements

What are distinguished features?



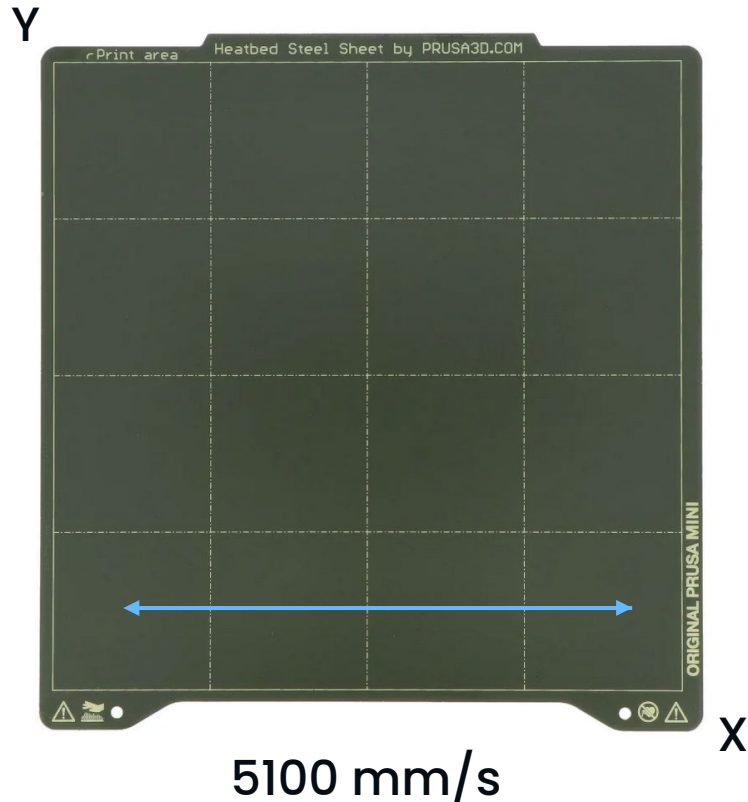
(150.00, 0.00, 0.00)_5100
(-150.00, 0.00, 0.00)_5100

```
(0.00, 0.00, 5.00)_0
(150.00, 0.00, 0.00)_5100
(-150.00, 0.00, 0.00)_5100
(0.00, 150.00, 0.00)_5100
(0.00, -150.00, 0.00)_5100
(150.00, 150.00, 0.00)_5100
(-150.00, -150.00, 0.00)_5100
```

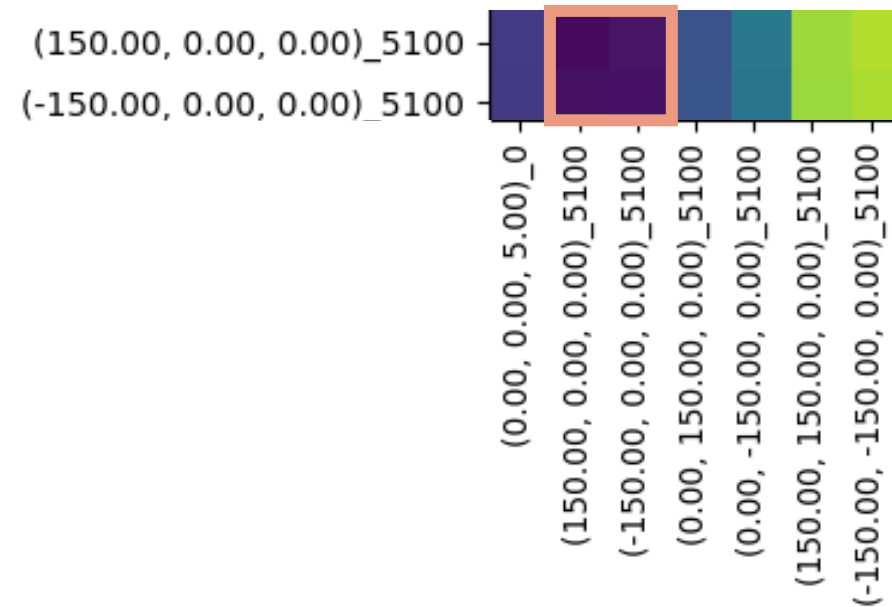
Gcode Instructions
(Profile)

Basic movements

What are distinguished features?

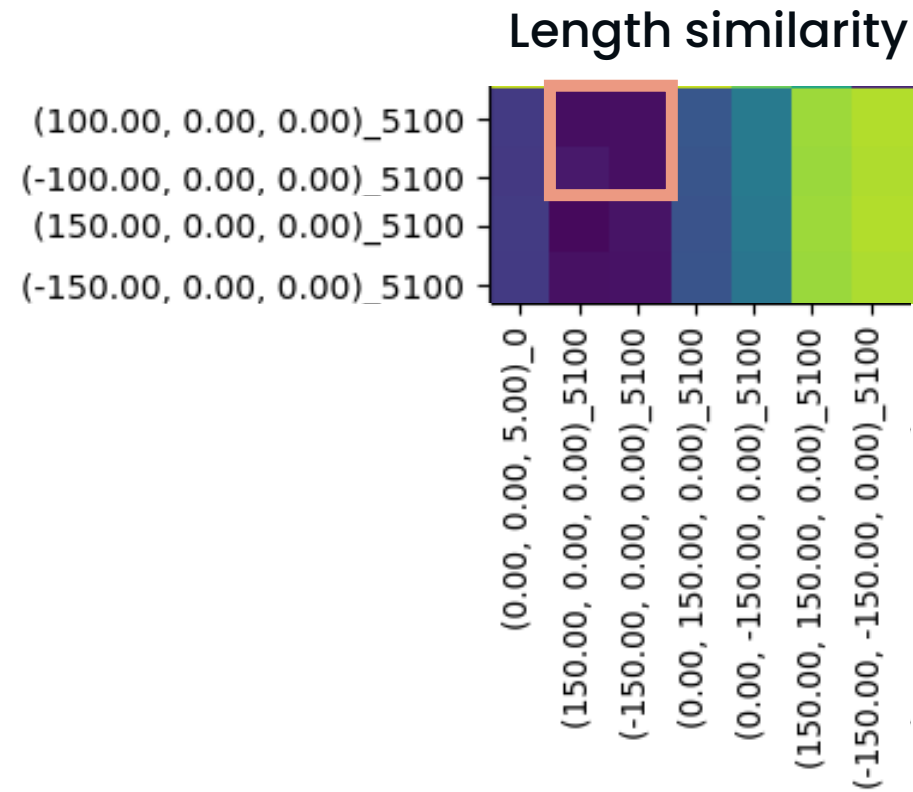
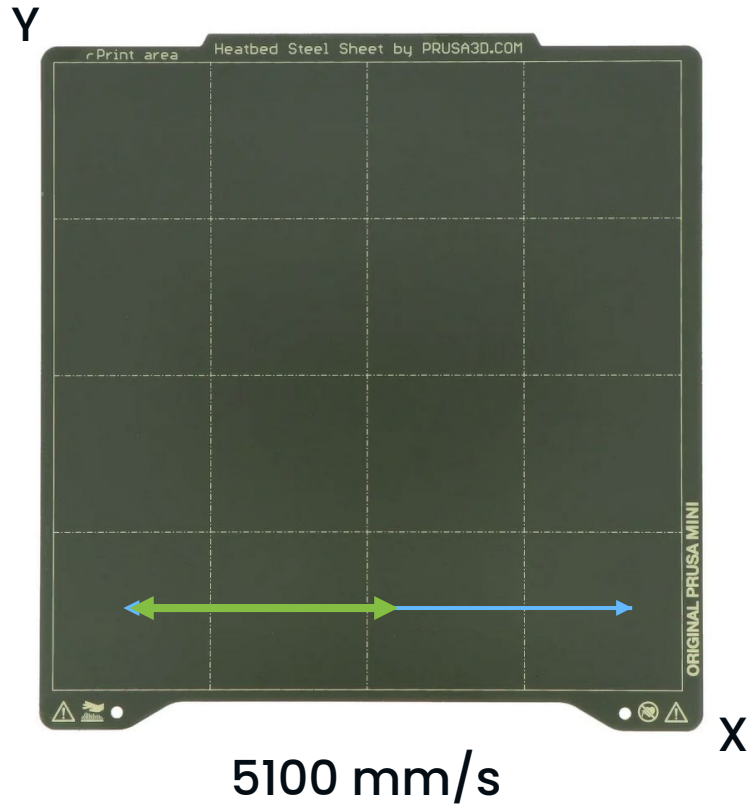


Inverse direction similarity



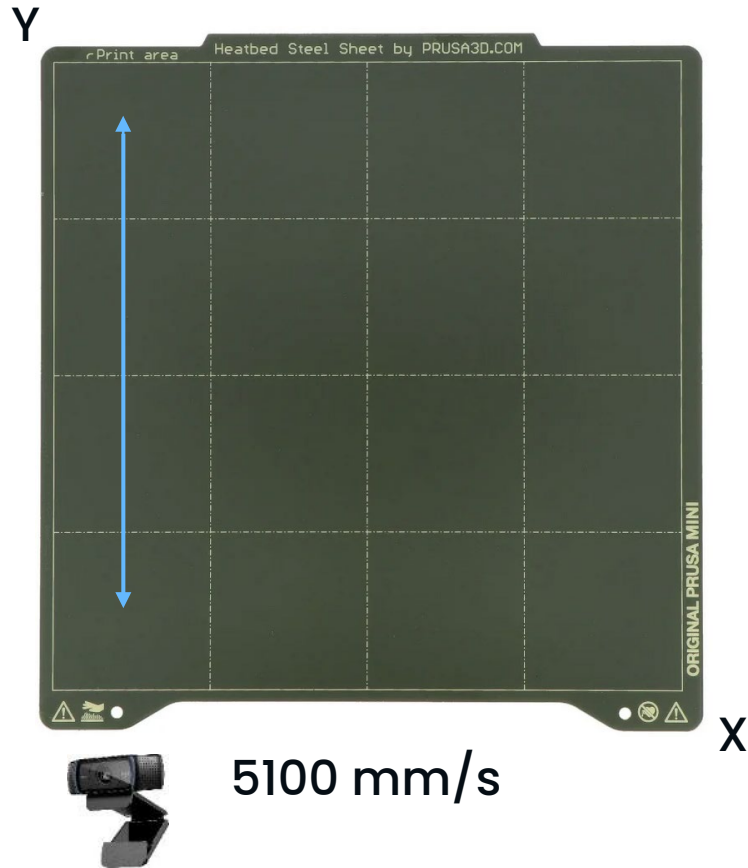
Basic movements

What are distinguished features?

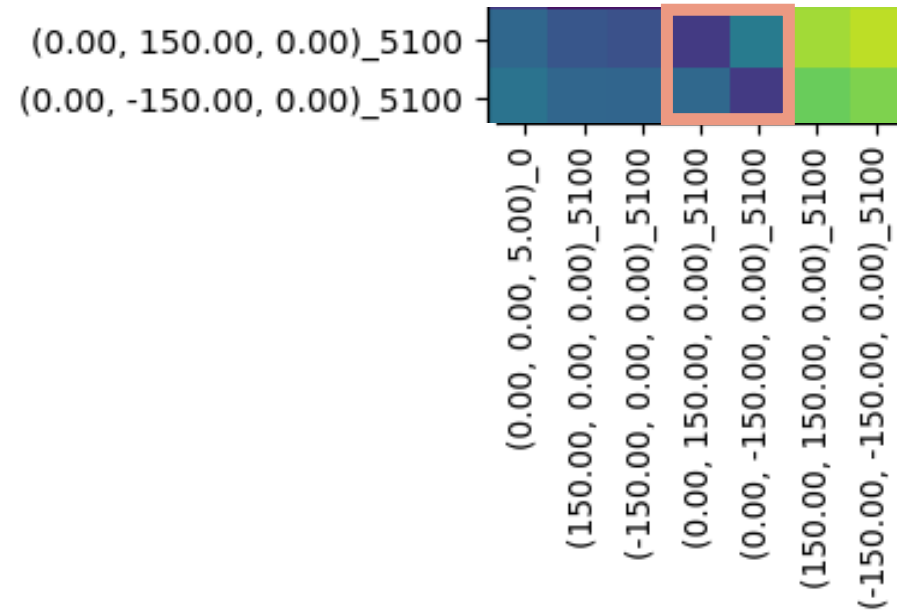


Basic movements

What are distinguished features?

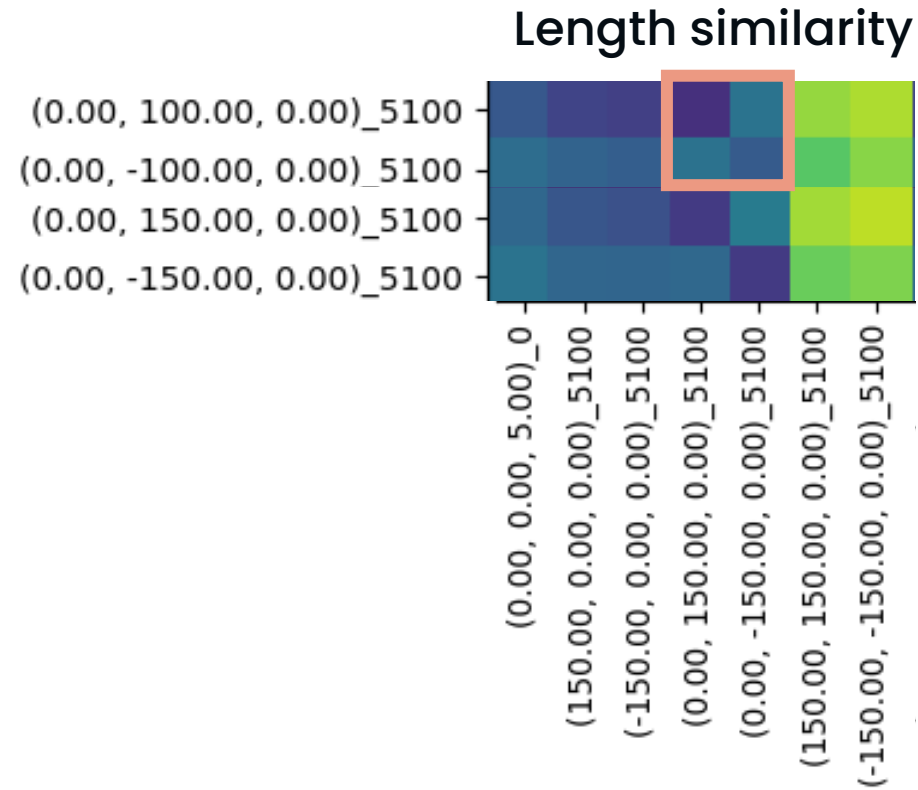
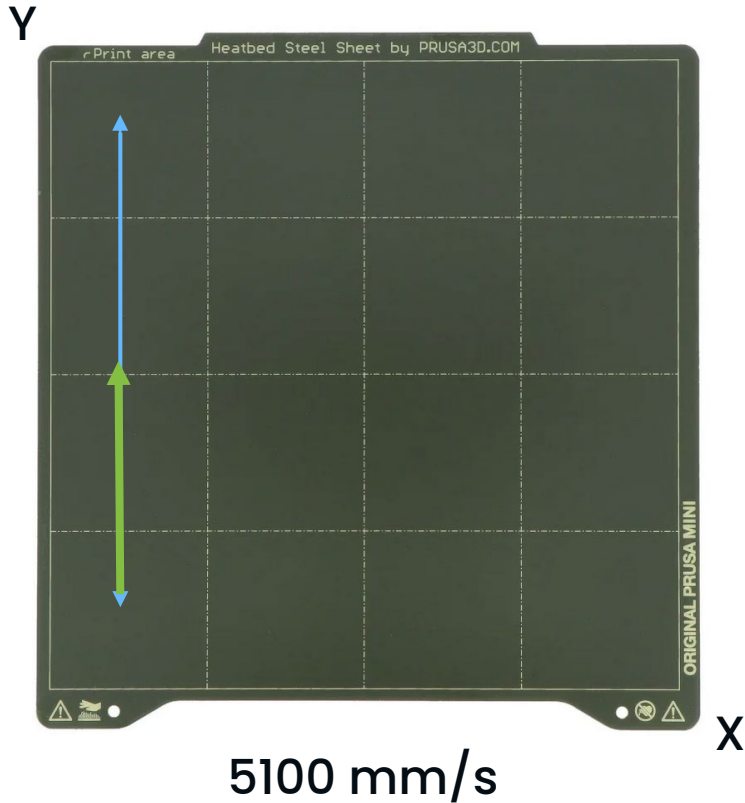


Direction difference



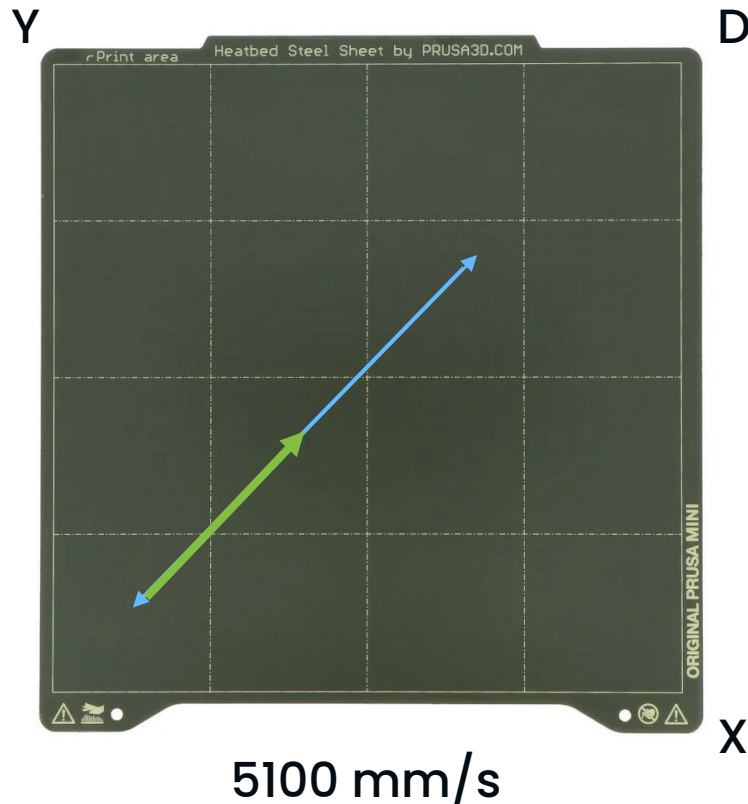
Basic movements

What are distinguished features?



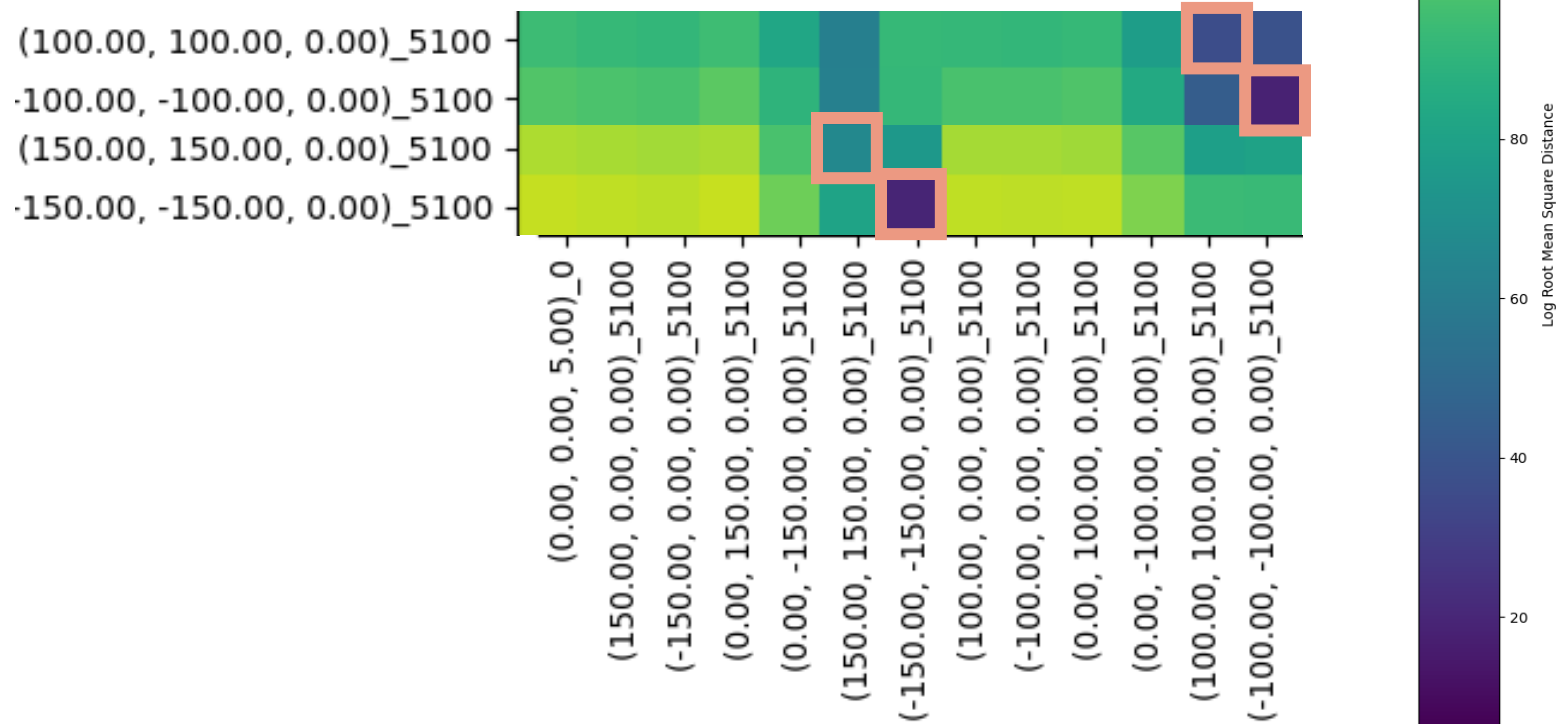
Basic movements

What are distinguished features?



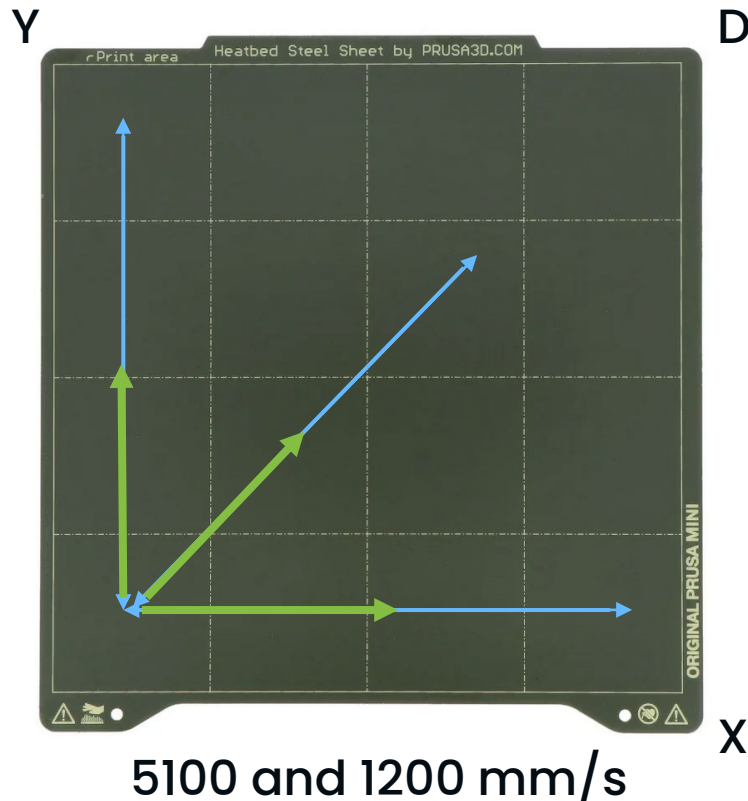
Diagonal

Differs to individual axes

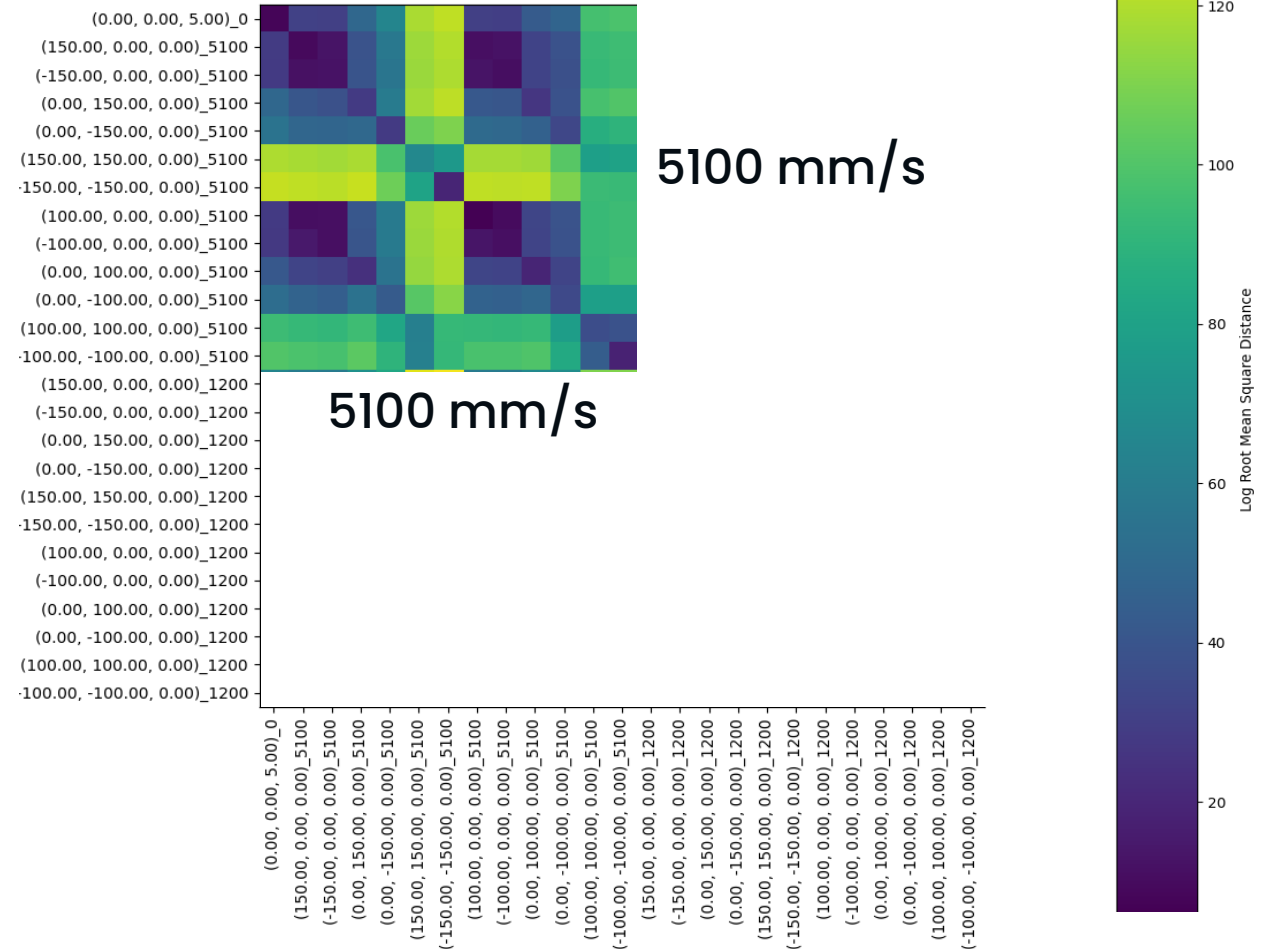


Basic movements

What are distinguished features?

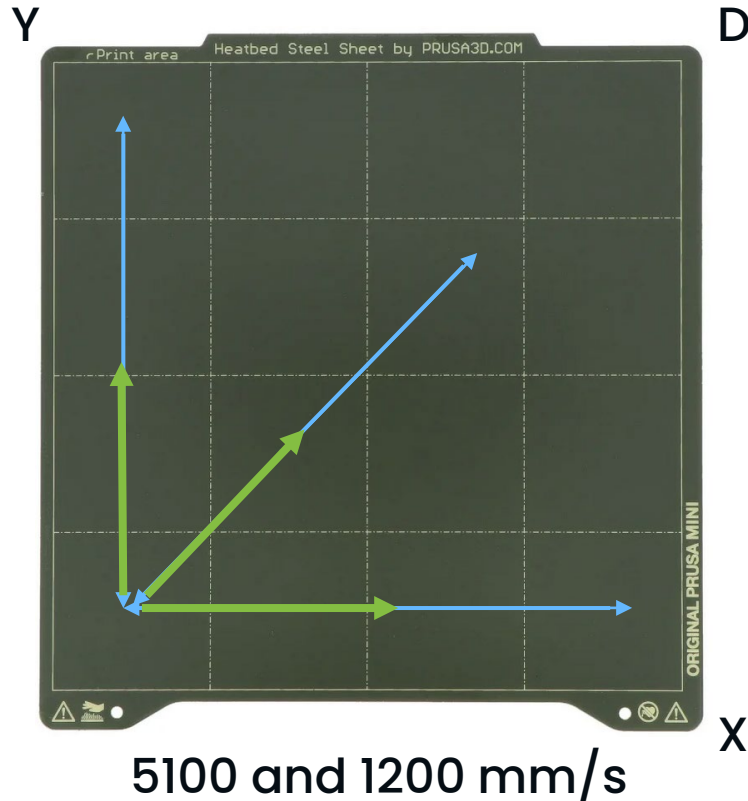


Diagonal

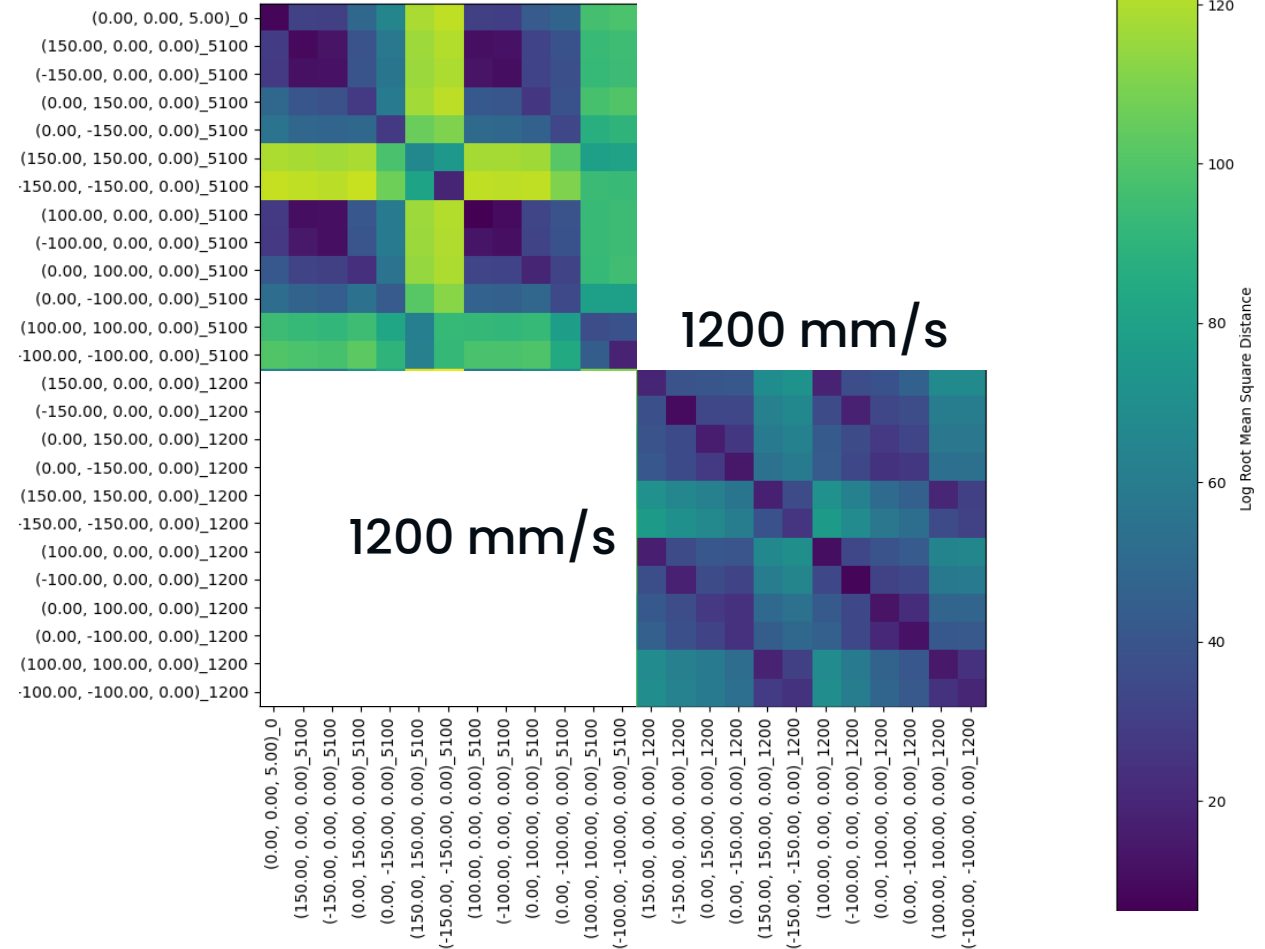


Basic movements

What are distinguished features?

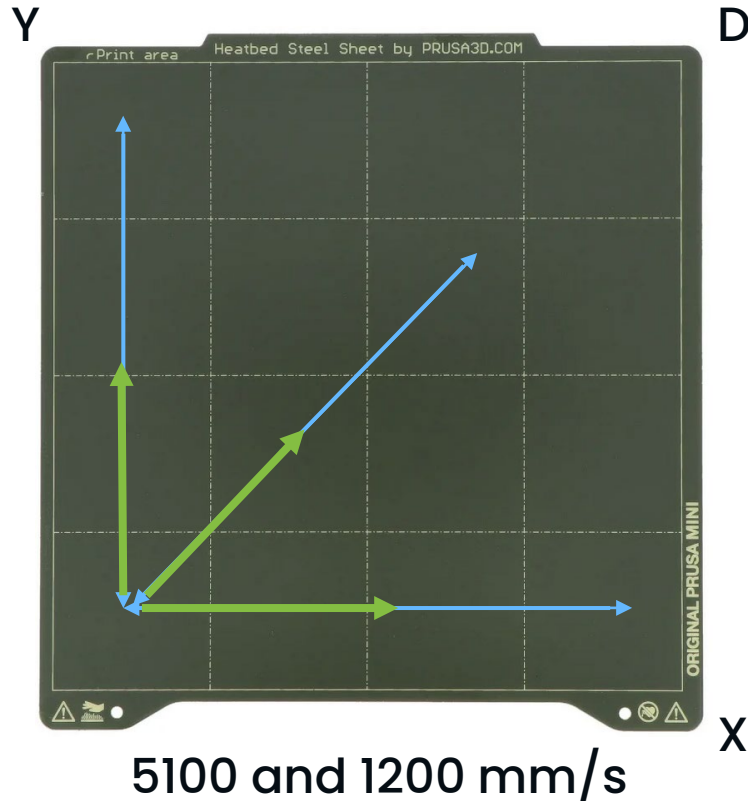


Diagonal

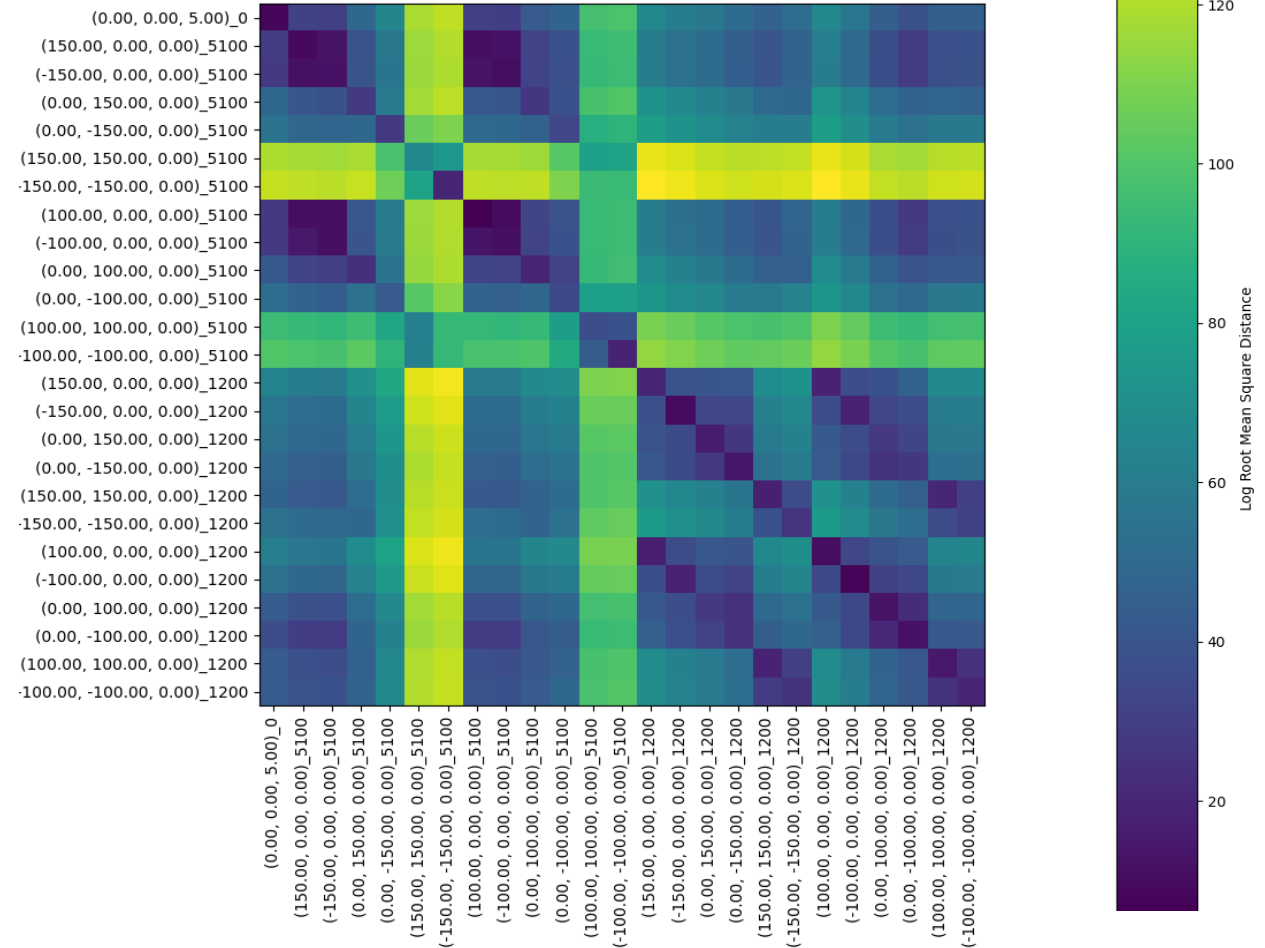


Basic movements

What are distinguished features?



Diagonal



Early Results: Basic movements

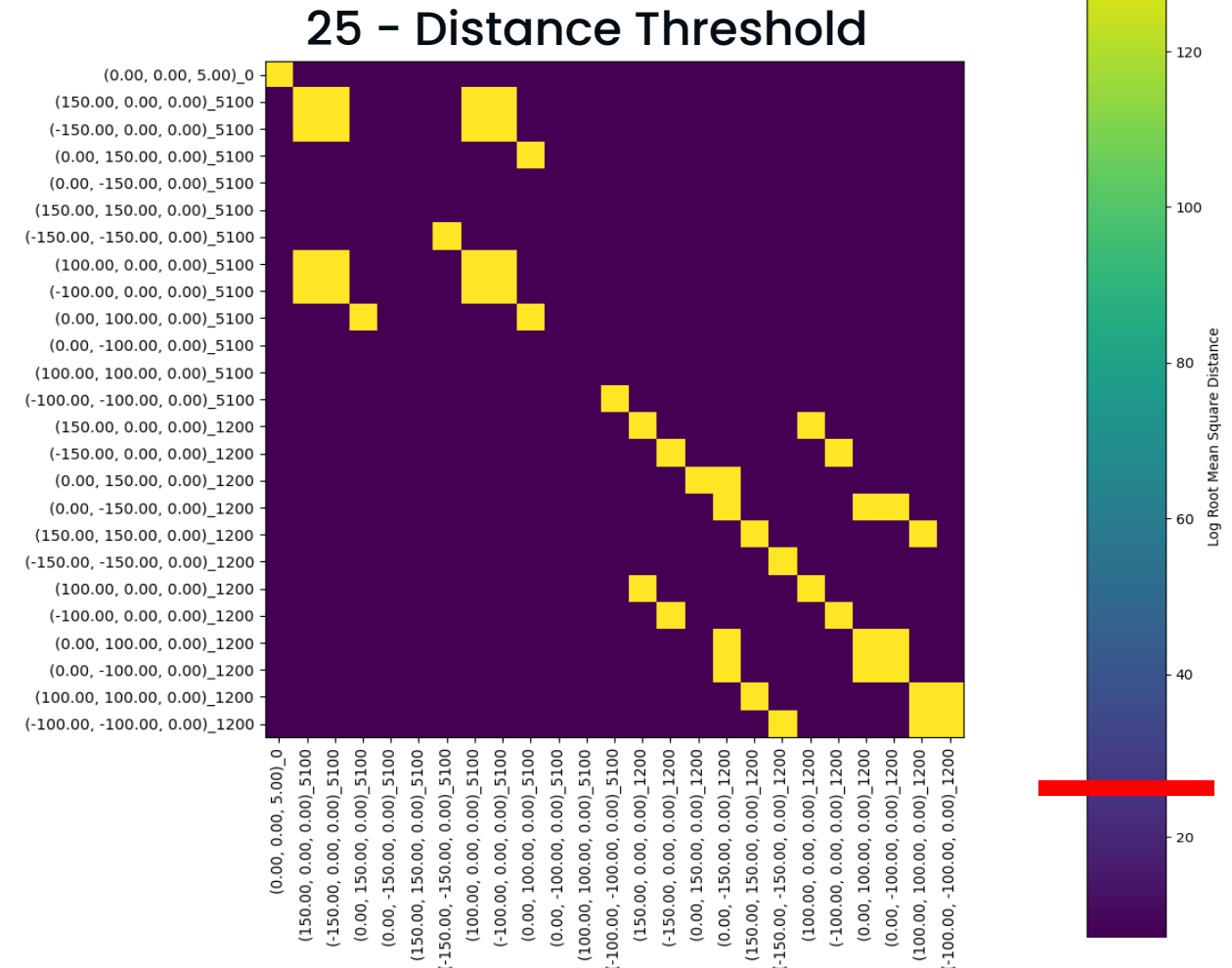
What are distinguished features?

- X-Axes:
 - Direction similarity
 - Length similarity

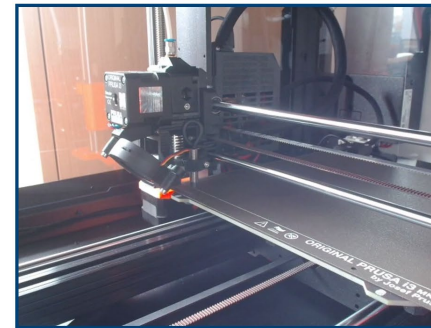
- Y-Axes:
 - Direction difference
 - Moved toward sensor
 - Length similarity

- Diagonal:
 - Differs to individual axes

- Feedrates sound different

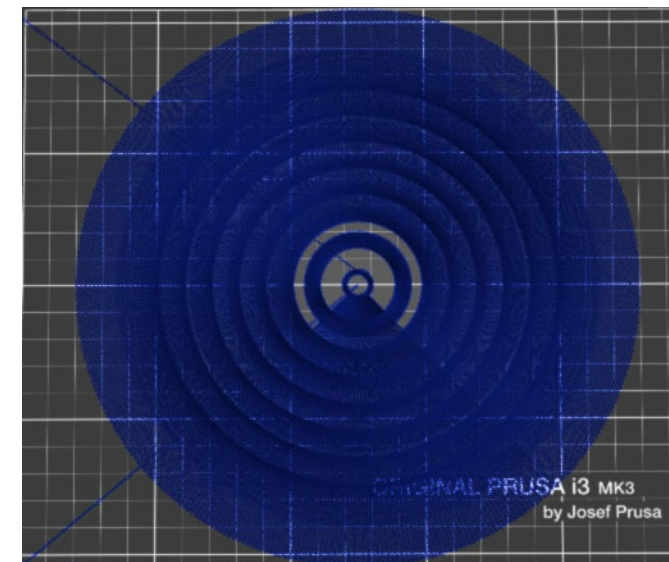
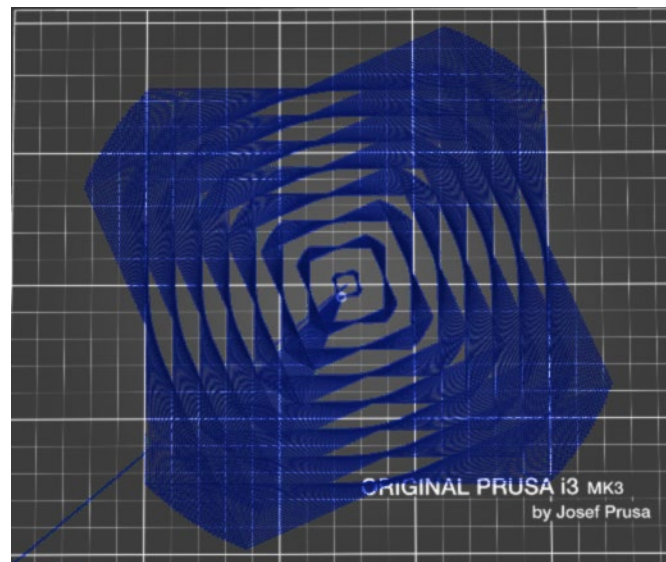
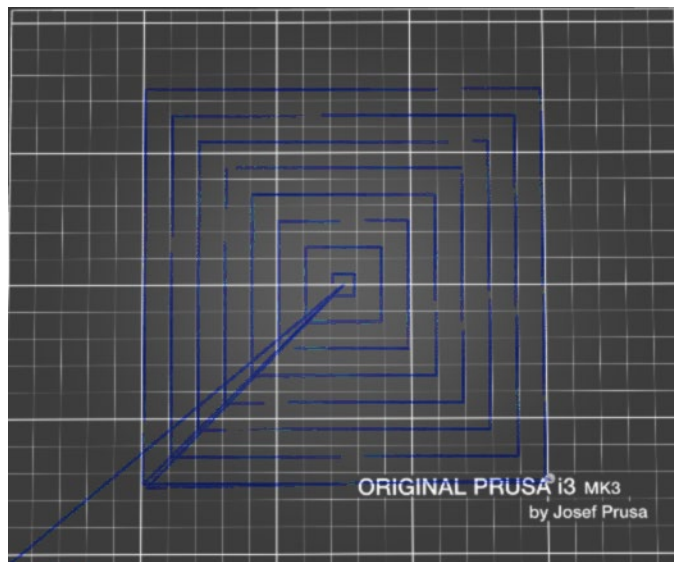


- Additive Manufacturing
- Audio Cue Test Oracle
- **Early Results**
- Conclusion



Issue detection

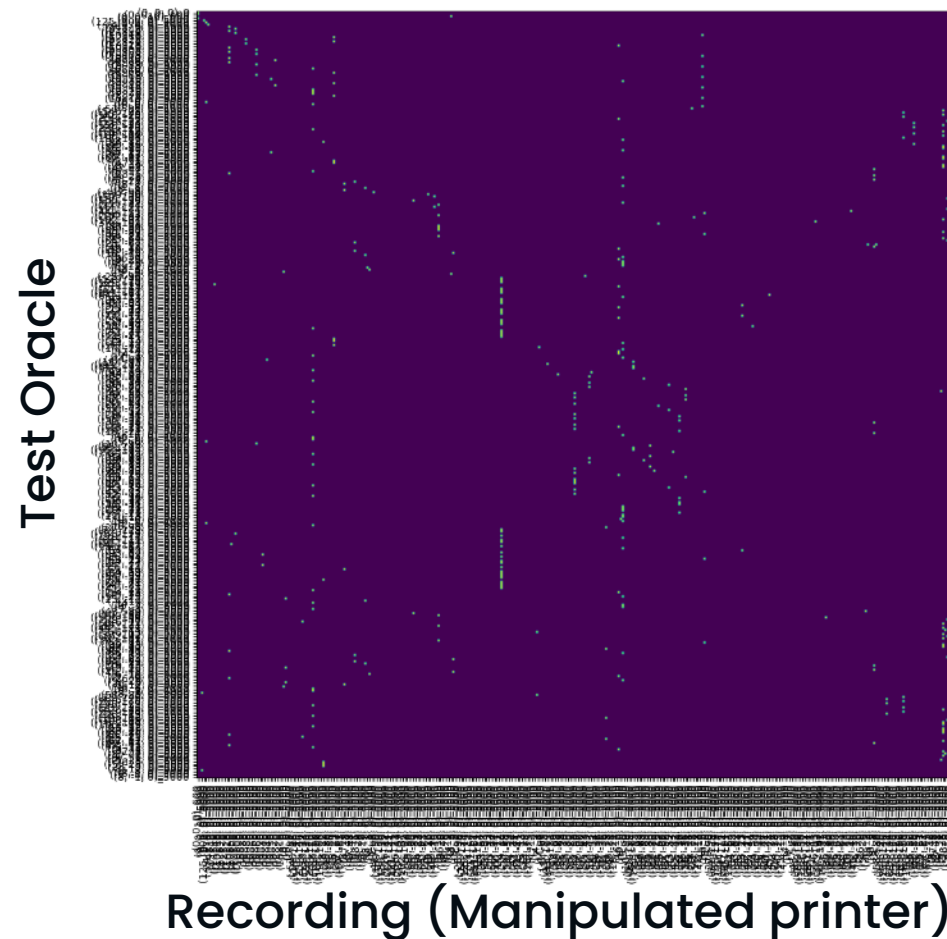
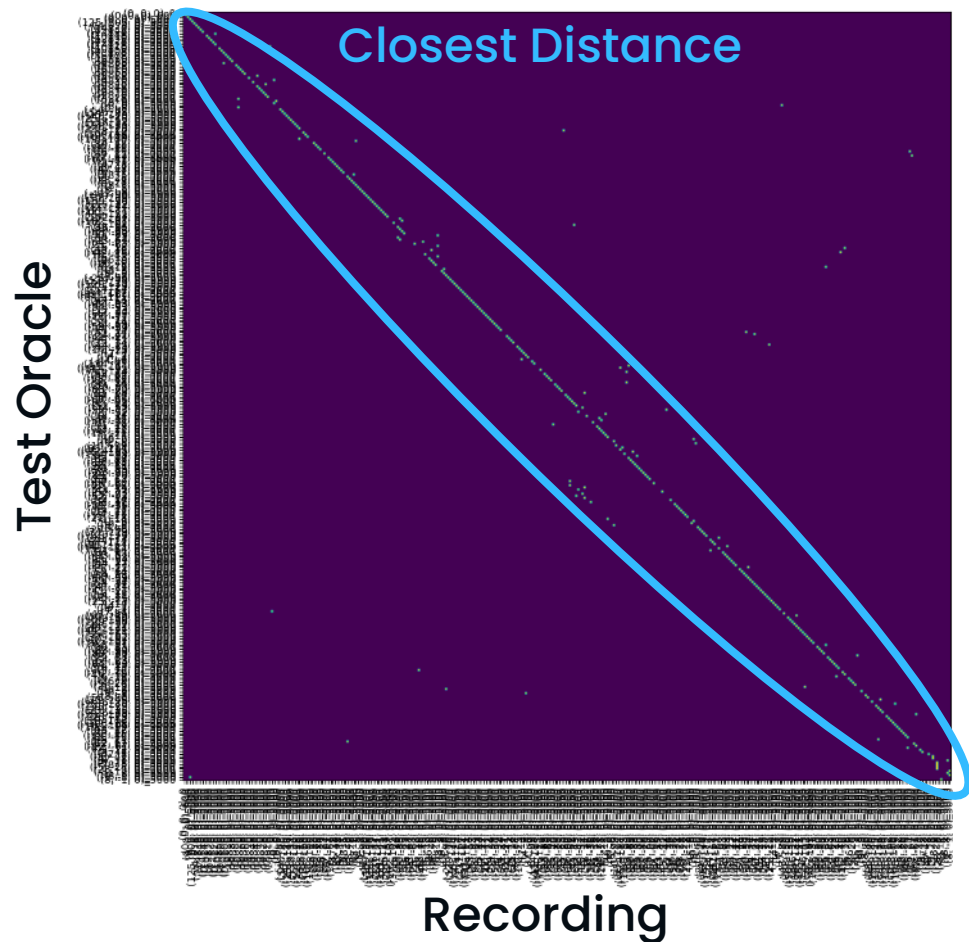
Can audiolized instructions detect printer deviations?



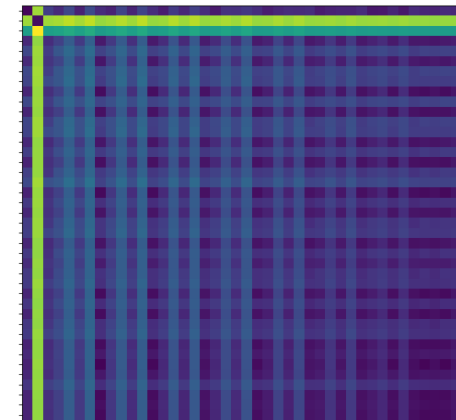
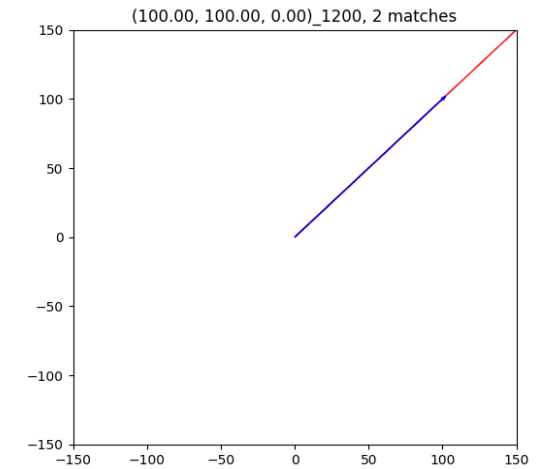
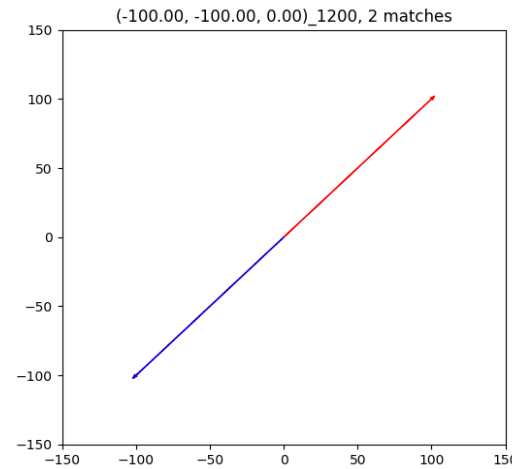
Profile: Square rotated, shrunk with different feedrates

Early Results: Issue detection

Can movements be mapped in general?



- Audio similarities in:
 - Distance
 - Same Direction
 - Inverse direction
- Variance weight improves association
 - Threshold scaled for each movement
- Limitations:
 - Small movements sound similar
 - Requires instrumentation
 - 1:1 classification not possible



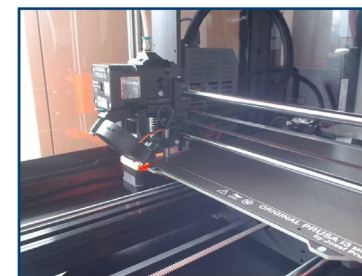
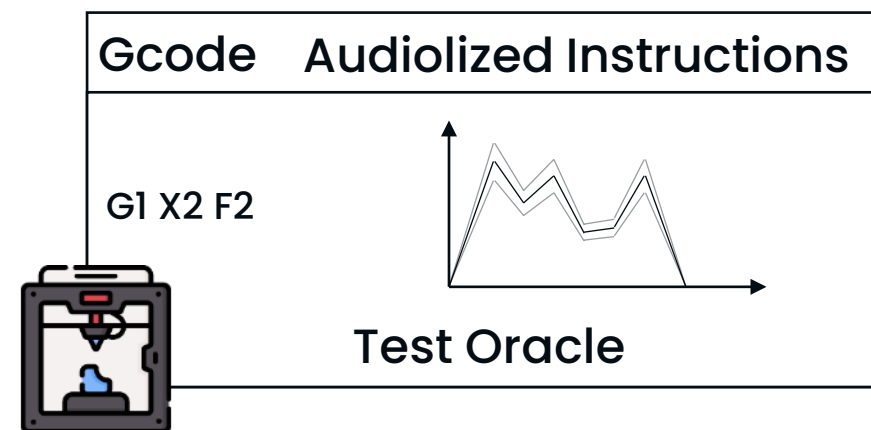
Conclusion

Summary

- Audio cue test oracle for individual gcode
- Potential for predictive maintenance

Future Work

- Different environments
- Different prints
- Different printers



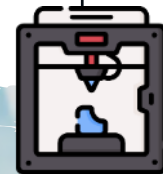
Thank you for your attention!

Contact me:
johannes.erbel@cs.uni-goettingen.de

Gcode	Audiolized Instructions
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G1 X2 F2	
----------	---

Test Oracle

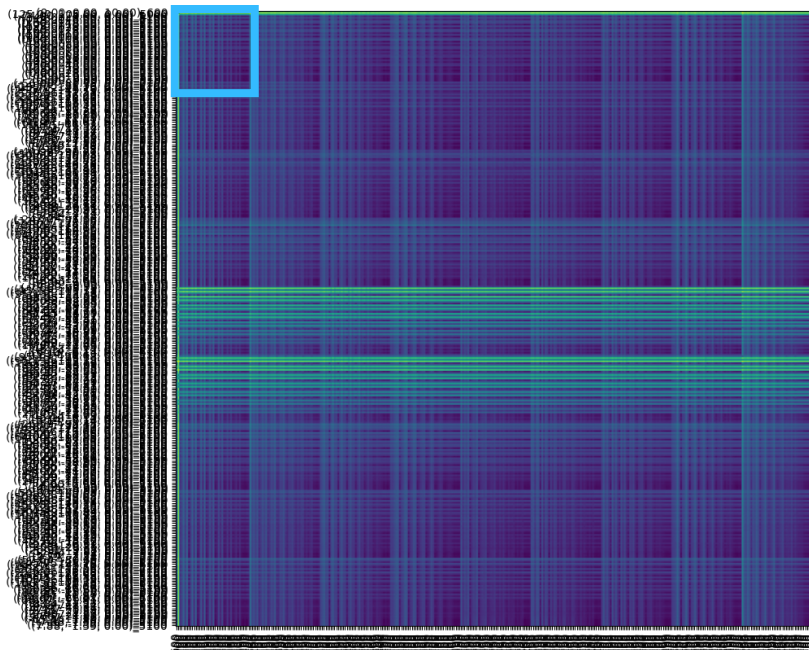


Backup



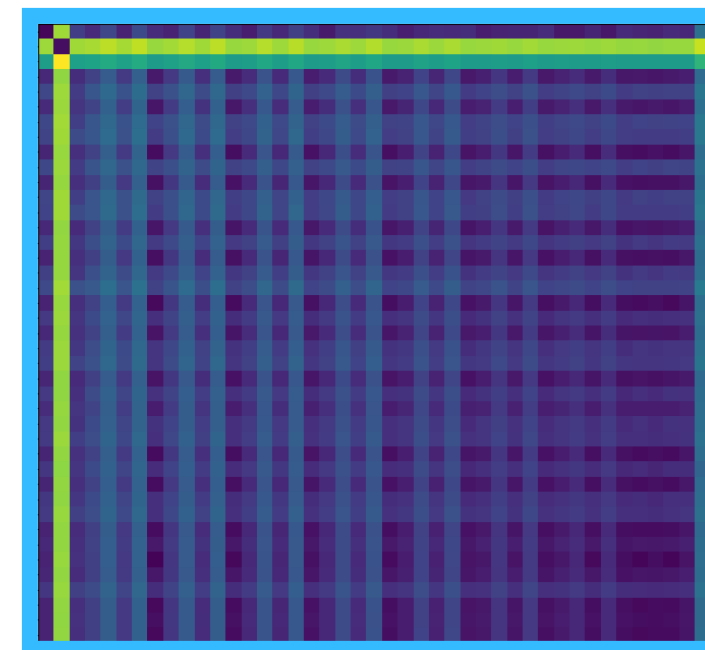
Issue detection

Can audiolized instructions detect printer deviations?



Two functional recordings

Small Movements have small distance to each other!



Close-up

Formulas

Audio slice

$$g(t) = \sum_{i=1}^N \delta(t - t_i) a_i, N \text{ discrete intensities } a_i \text{ at equidistant time points } t_i$$

Fourier transform

$$G(f) = \int_{-\infty}^{\infty} g(t) e^{-i2\pi ft} dt$$

Audiolized instruction

$$G(f) = \sum_{i=1}^N \delta(f - f_i) A_i, N \text{ discrete intensities } A_i \text{ at equidistant frequency bins } f_i$$

Mean variance

$$\hat{A}_i = \frac{1}{M} \sum_{j=1}^M A_i^{(j)}, \sigma_i^2 = \frac{1}{M-1} \sum_{j=1}^M (A_i^{(j)} - \hat{A}_i)^2$$

Profile

$$G(f) = \sum_{i=1}^N \delta(f - f_i) \hat{A}_i \text{ as well as a } N \text{ variances } \sigma_i^2$$

Difference to profile

$$d = \sqrt{\frac{1}{N} \sum_{i=1}^N \frac{(\hat{A}_i - \tilde{A}_i)^2}{\sigma_i^2}} \text{ distance for audio with audiolized instruction intensities } \tilde{A}_i$$