

Can a Robot Color Inside the Lines? Continuous Toolpath Planning and Geometric Validation for CMT-WAAM

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Introduction

What is CMT-WAAM?

• Wire Arc Additive Manufacturing uses robotic welding to build metal through line-by-line deposition.

Why is coloring inside the lines difficult?

- WAAM is not like large-scale plastic 3D-printing, as the processes are fundamentally different (Figure 1). Each deposited bead is molten metal, so heat, overlaps, and corners can drastically alter the final geometry.¹
- Different toolpaths can lead to better deposition quality.²

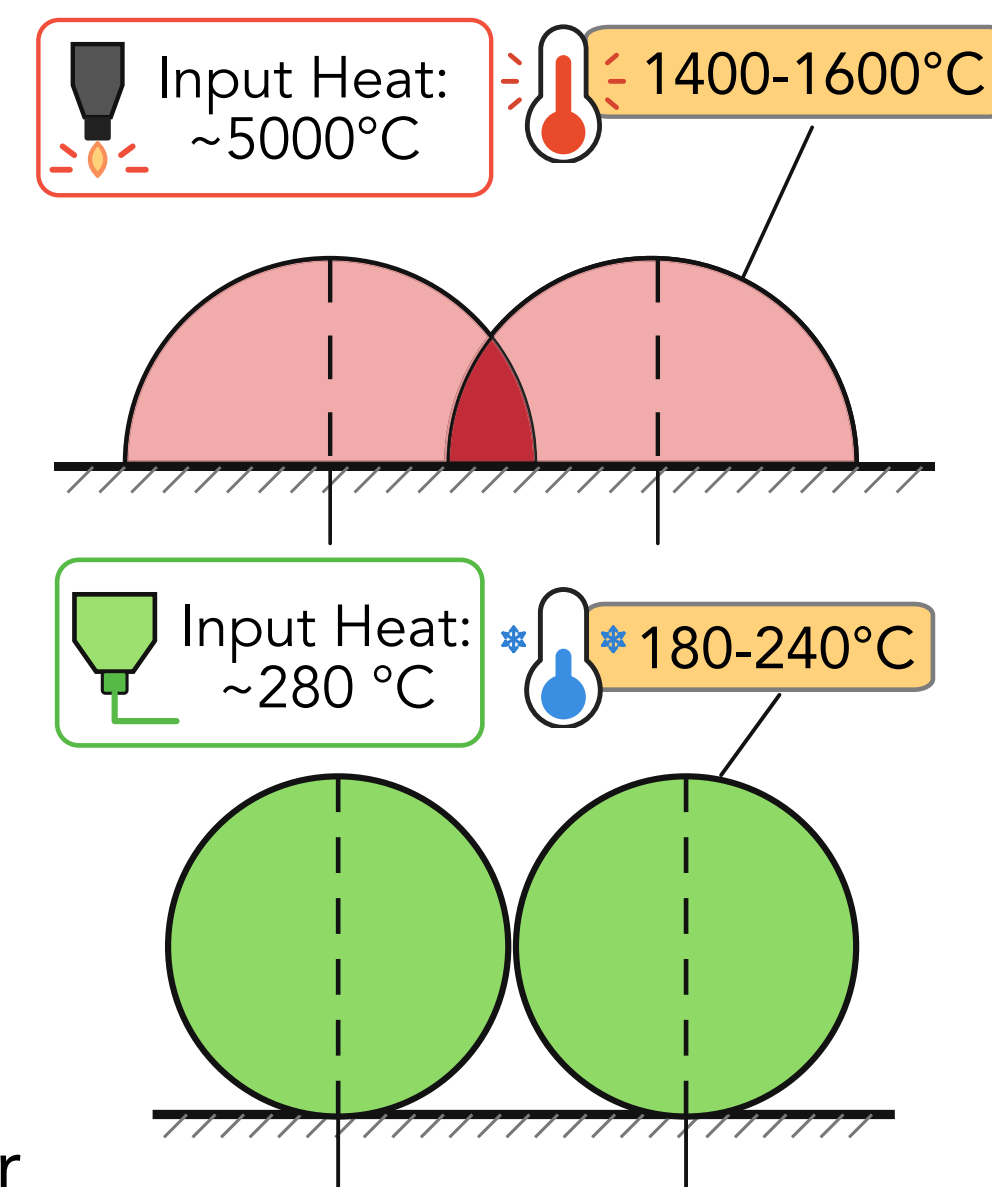


Fig. 1. WAAM vs FDM Process.

Methods

WAAM-Work:

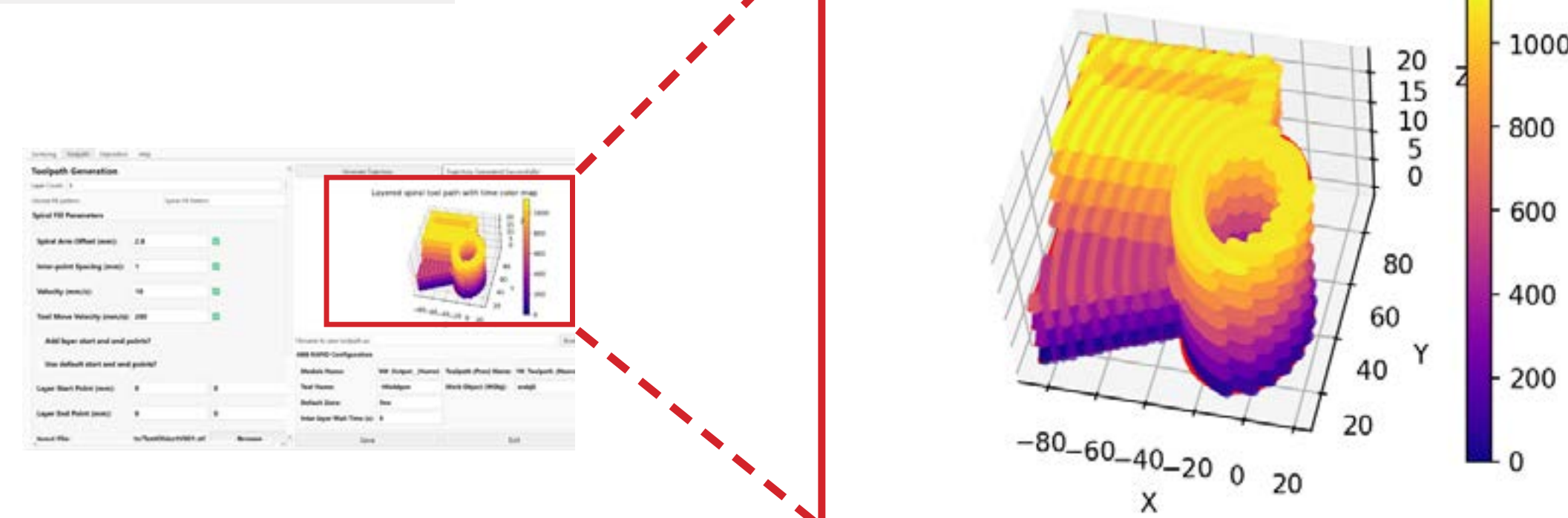


Fig. 2. Toolbox sample.

• We created WAAM-Work, a python-based software tool that **converts a 3D model into robot toolpaths**. It controls the scan strategy, layer height, bead spacing, boundary offsets, path simplification, and deposition sequence.

Build and Scan Hardware:

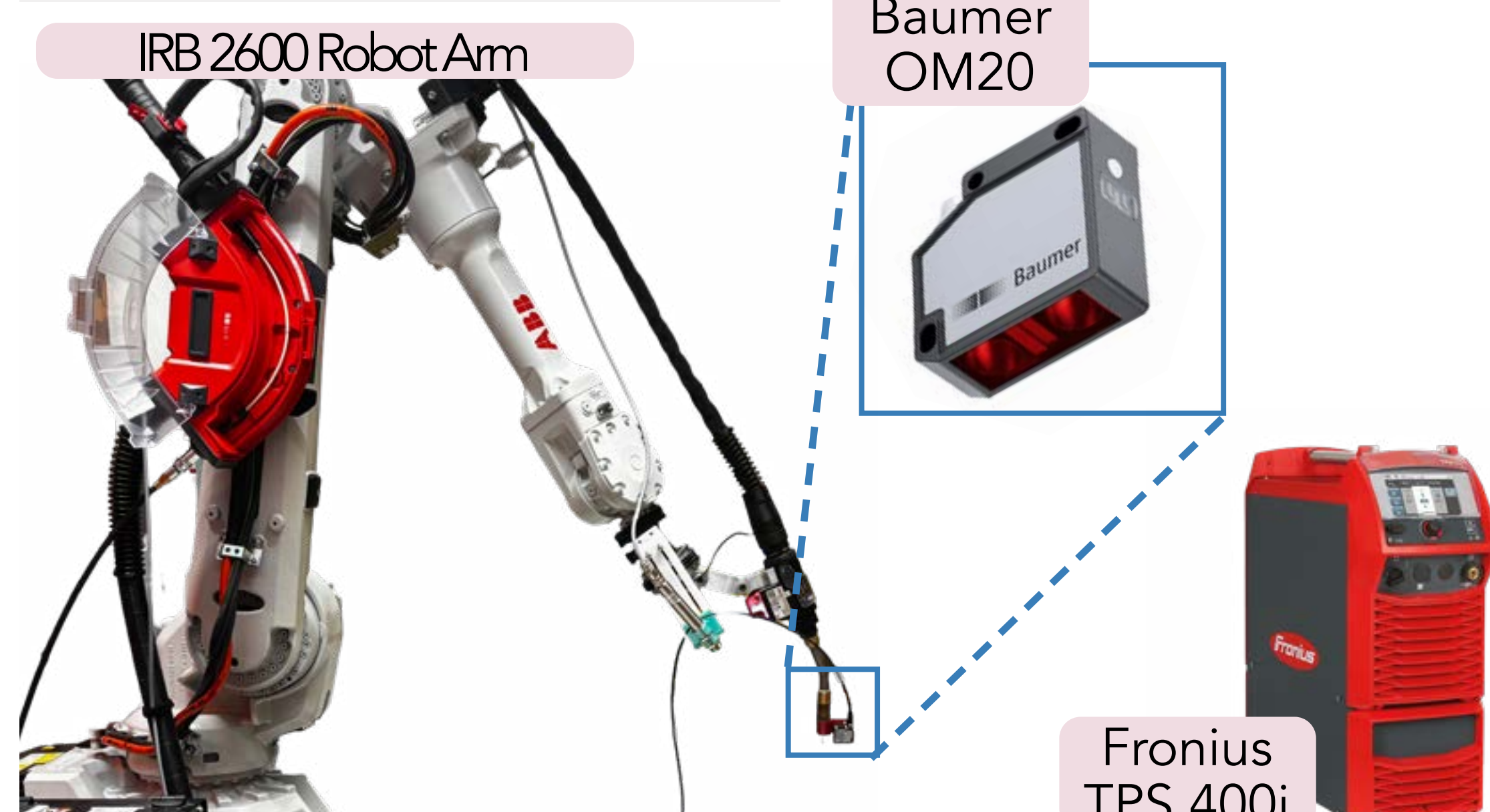


Fig. 3. Robot.

Workflow:

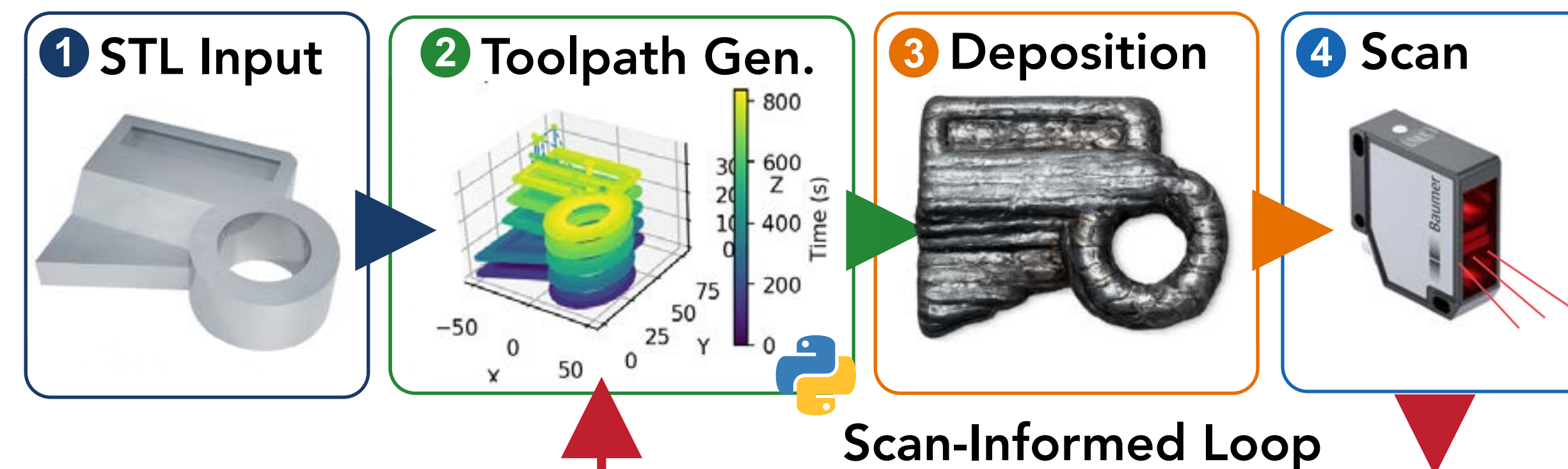


Fig. 4. Simplified WAAM-Work workflow

Results: One Shape, Six Patterns

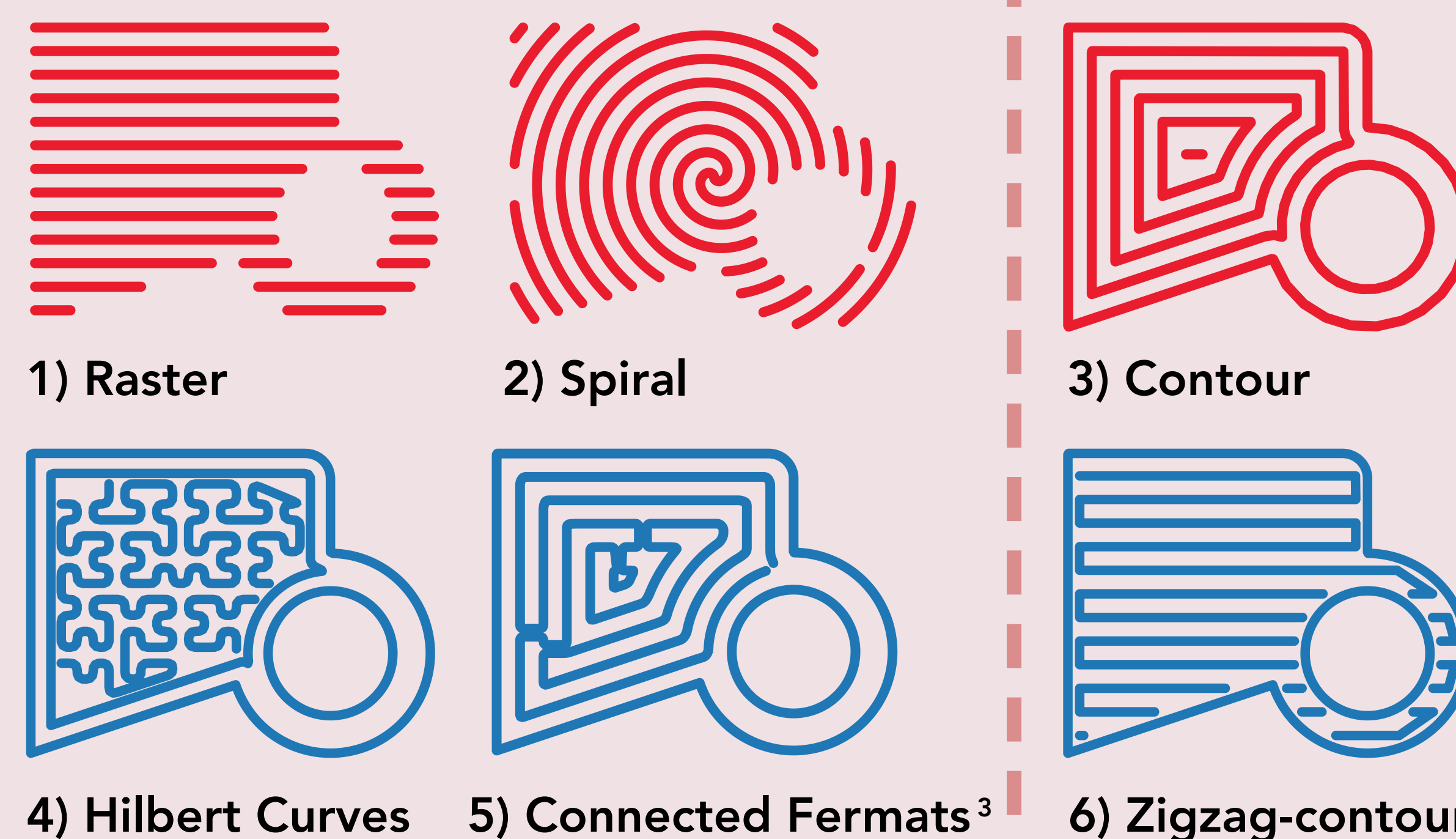


Fig. 5. Example toolpaths, selected patterns studied below (dashed box)

Potential Advantages of Each Toolpath:

• The blue toolpaths generally use fewer ArcStart and ArcStop events, **reducing welding interruptions and associated start-stop transients**, especially as parts grow larger. Their meandering motion may also **distribute heat more evenly, limit localized heat buildup**, and improve continuity across each deposited layer.

Toolpath	Arc Starts
Fermat	16
Contour	29
Hilbert	31
Zigzag	61
Raster	98
Spiral	108

Depositions:



Fig. 6. Contour sample.

Controlled Comparison:

Both samples used the same material and process settings. Only the toolpath changed.

Fig. 7. Zigzag-contour sample.

Did the Robot Fill Inside the Lines?

Fig. 8. Zigzag-contour sample height deviation from the STL.

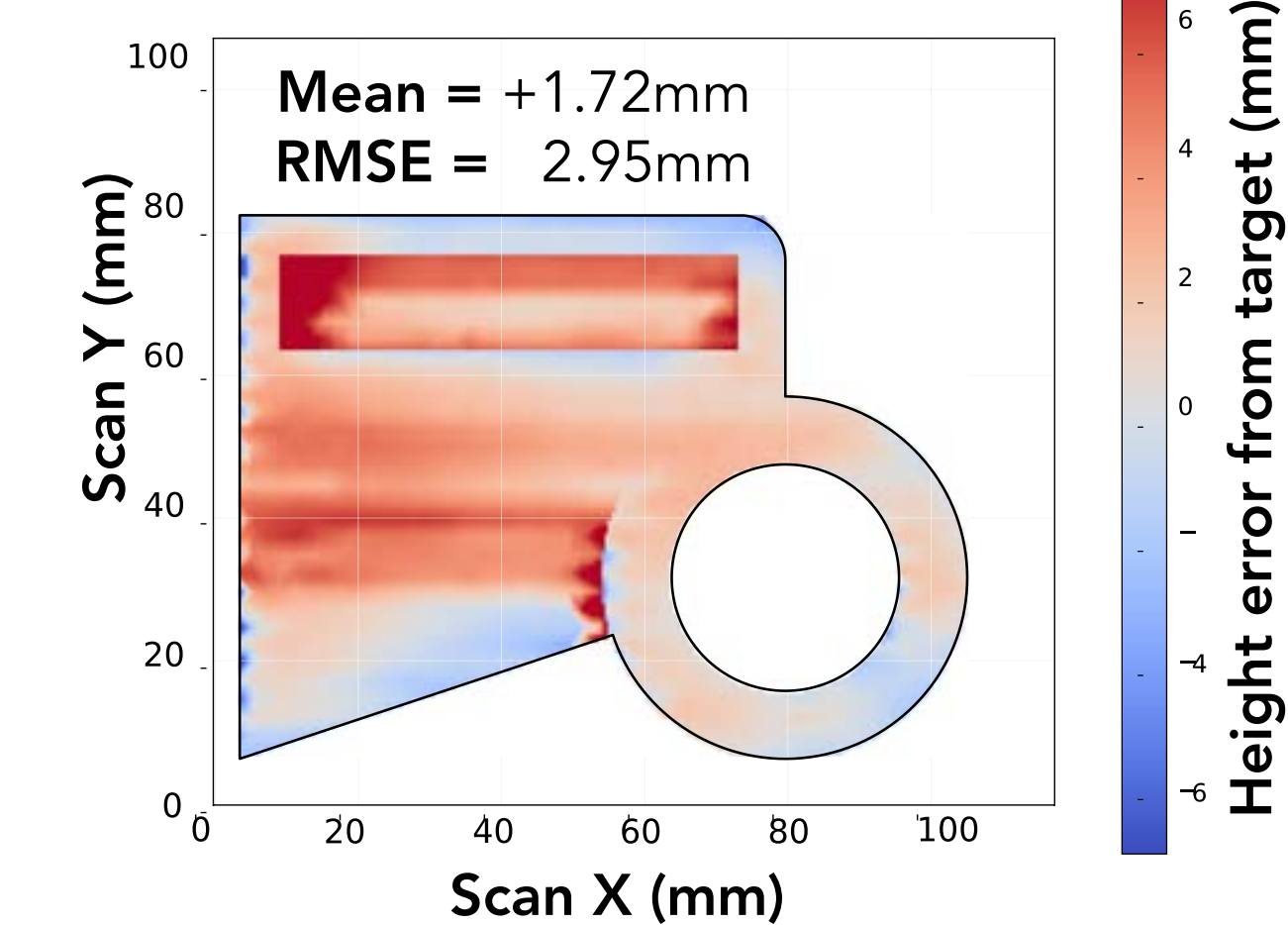


Fig. 9. Deposition tolerance comparison for chosen samples.

Within ±2 mm	Contour 15.9%	Zigzag-contour 53.8%	Difference +37.9
Over +2 mm	Contour 2.5%	Zigzag-contour 42.1%	Difference +39.6
Under -2 mm	Contour 81.6%	Zigzag-contour 4.1%	Difference -77.5

• The surface comparison used 2,870 measurements and is corrected for build-plate tilt.

• **Zigzag-contour placed 53.8% of the measured area within ± 2 mm**, compared with **15.9% for contour**. Underbuild fell from 81.6% to 4.1% while overbuild increased from 2.5% to 42.1%, showing that the new route replaced most missing material with excess material.

This is not necessarily detrimental to metal depositions as **excess material can often be machined away**. Missing material cannot.

Conclusions

- Toolpath selection substantially changed the deposited geometry even though both samples used identical process parameters.
- These results indicate that **toolpath topology and process parameters must be calibrated together**. Path spacing, contour offsets, bead overlap, corners, and local heat accumulation can each introduce systematic geometric error.
- The scan-to-STL comparison provides a quantitative method for locating these errors and guiding toolpath-specific parameter refinement.

Acknowledgments

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References

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