Feedback control of blown-powder additive deposition

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Thanks to Vivien Parker (final year project), Renaux Maxence (summer internship) for experimental work; Richard Harlow for help with the Trumpf

Thanks to the EU AMAZE programme for funding

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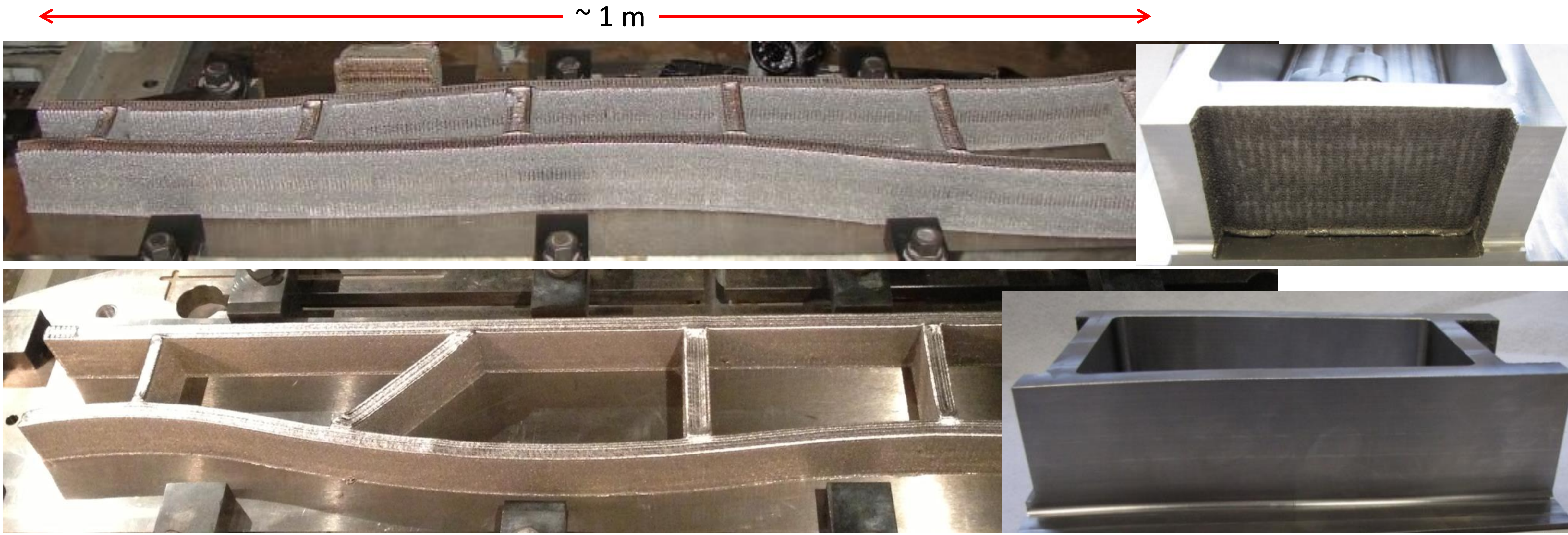
Building large components



Qiu *et al.*, 2014, with BAE SYSTEMS

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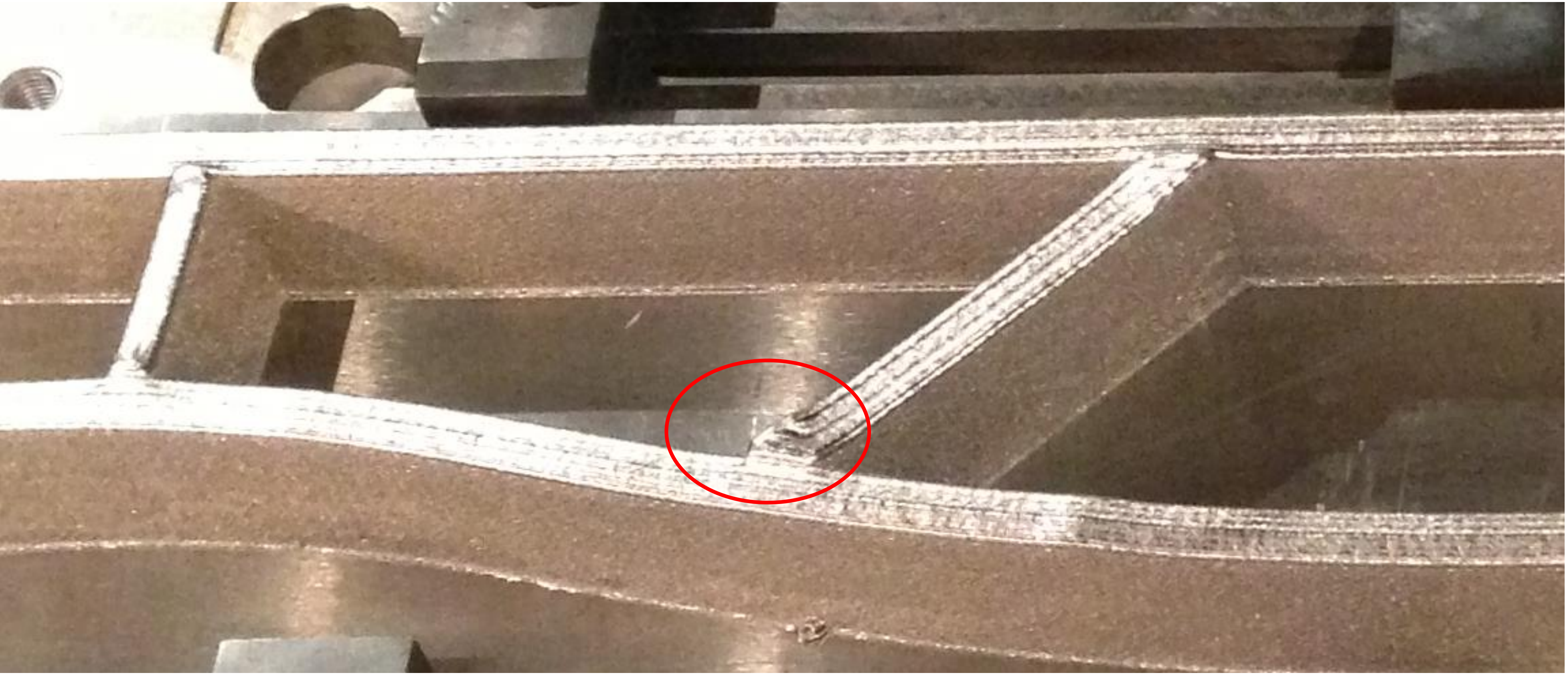
Building large components



Qiu *et al.*, 2014, with BAE SYSTEMS

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Development of DEMD at AMPLab

Measuring → ***Understanding*** → ***Controlling***

	Measuring	Understanding	Controlling
Structure	Optical, SEM, TEM, EBSD etc.	Microstructural development	Choosing the path + conditions
Shape	Optical sensors		Closed-loop control of speed, power etc.
Cost	Recycling	Speed	Complexity

Powder
Morphology
Properties

Modelling
FE (global) : overall strain + shape
FV (medium) : temperature + structure
FV CFD (micro) : detailed local results

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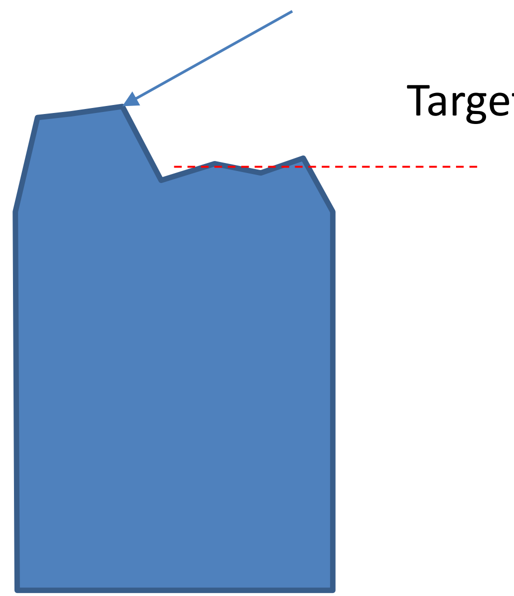
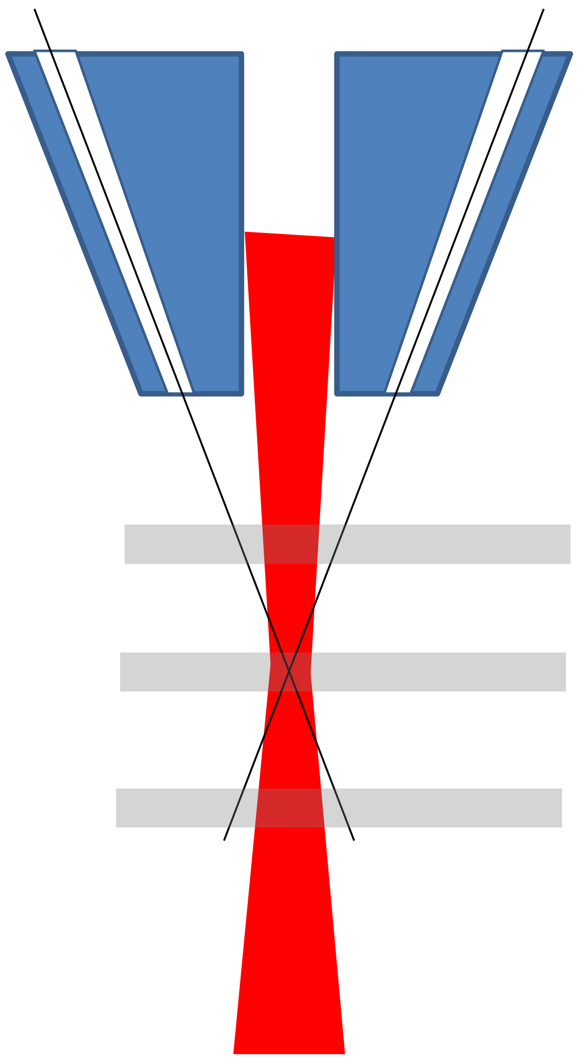
Introduction: Active control

- Automatically control object shape during laser metal deposition by modifying the build path parameters.
- For each layer:
  - scan the object $\Rightarrow$ top surface Z coordinates
  - if it is too high somewhere, deposit less material there in the next layer
  - if it is too low somewhere, deposit more material there in the next layer
- It can run continuously if needed, without stopping the laser between layers



Passive control



If we deliberately build here we should have some automatic passive control of build height

Overbuild => move up to lower capture level

Low powder capture at this level

Underbuild => move down to higher capture level

High powder capture at this level

Low powder capture at this level

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Comparison of control methods

	Active	Passive
Powder capture efficiency	+++	
Build height accuracy	+++	
Record of the build development	+++	
Hands-off	+++	
Simple (no control system)		+++
Simple (no scanner)		+++
Speed	Can be +++ too	+++

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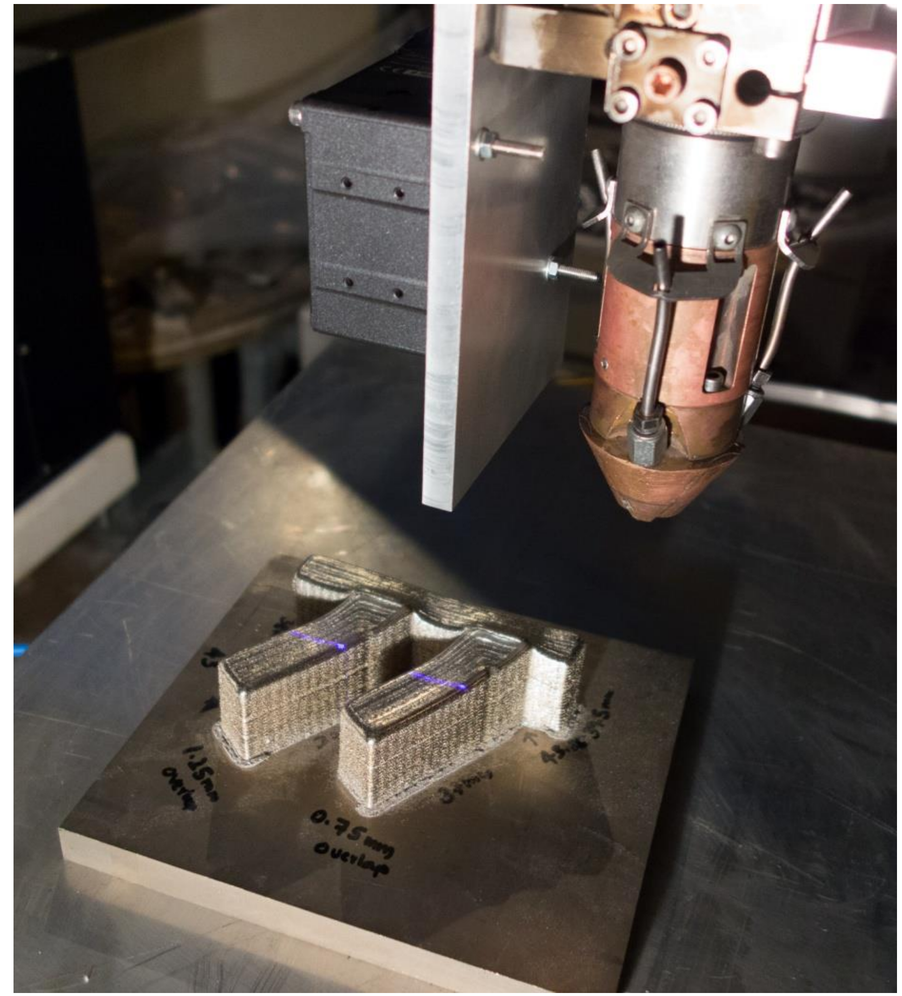
Measuring with a linescanner

- High accuracy and resolution
- Either additional time needed or an additional manipulator



Measuring with a linescanner

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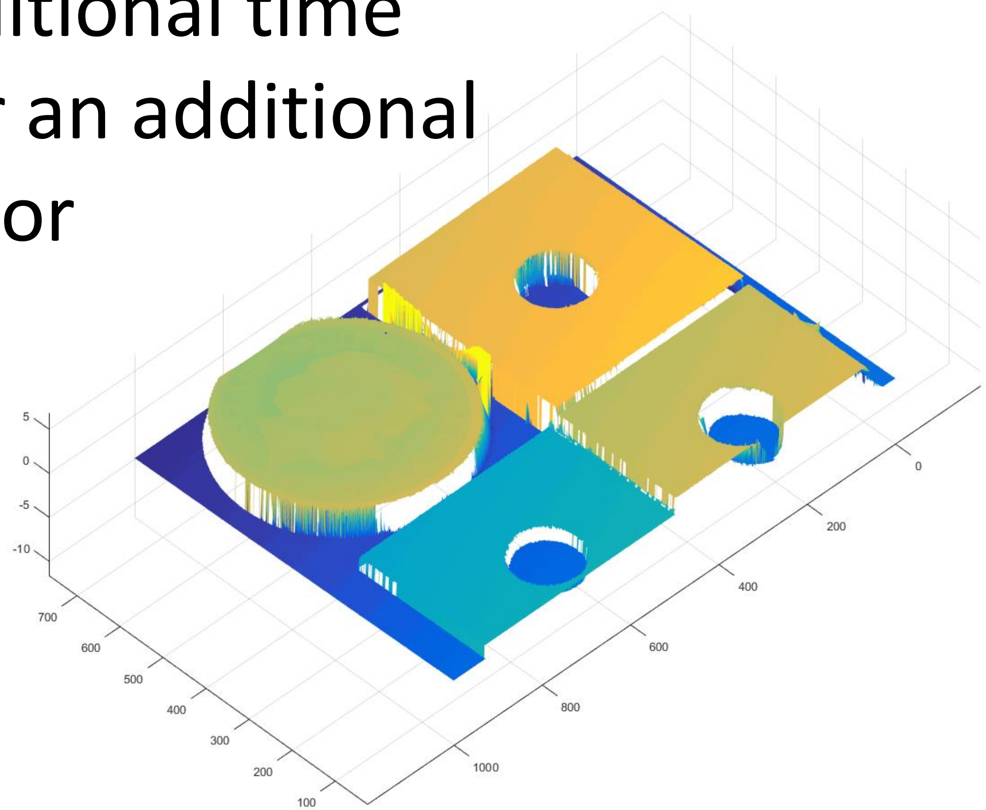

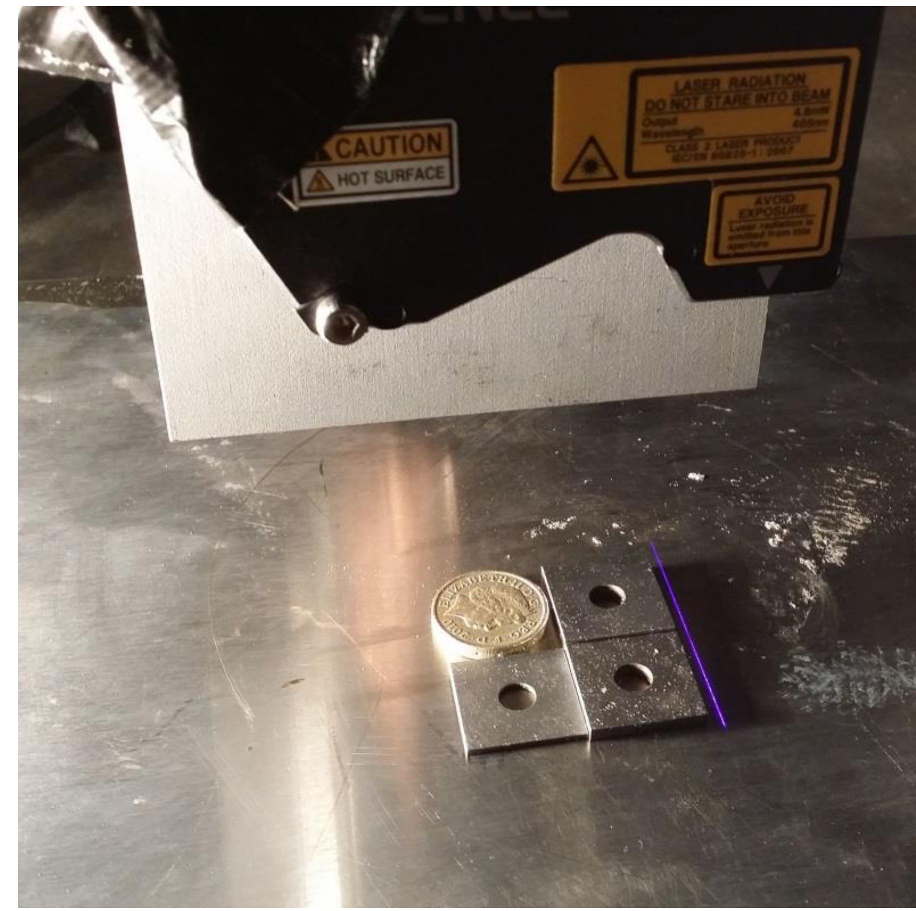

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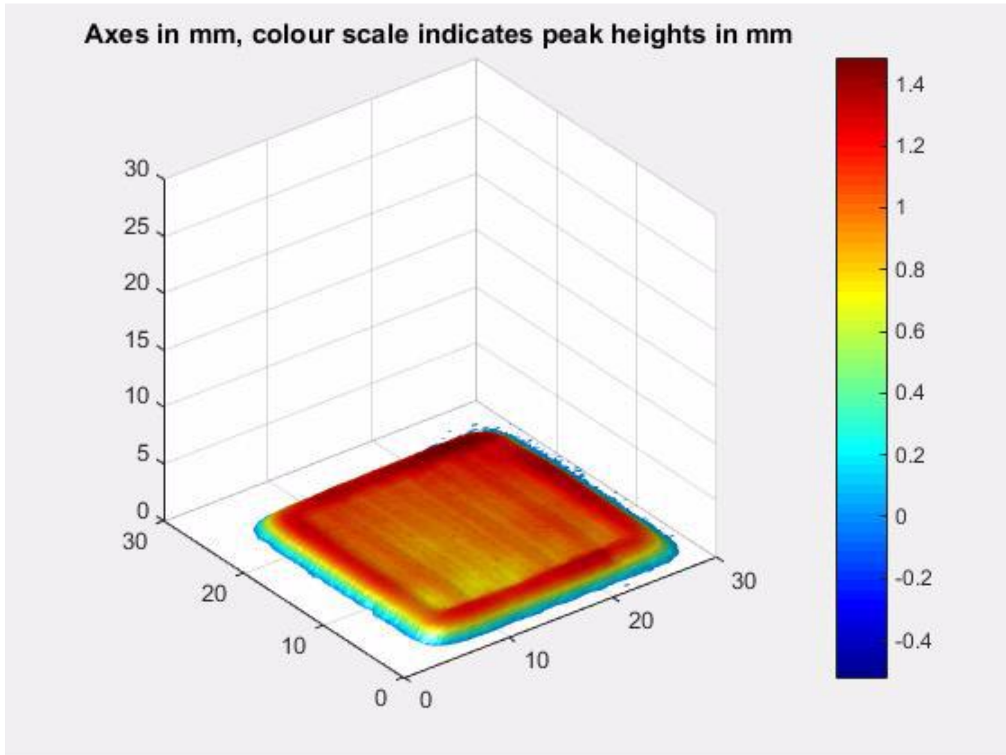
Measuring with a linescanner

- High accuracy
- Either additional time needed or an additional manipulator
- Dense points covering the whole build



click to play

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Measuring by triangulation

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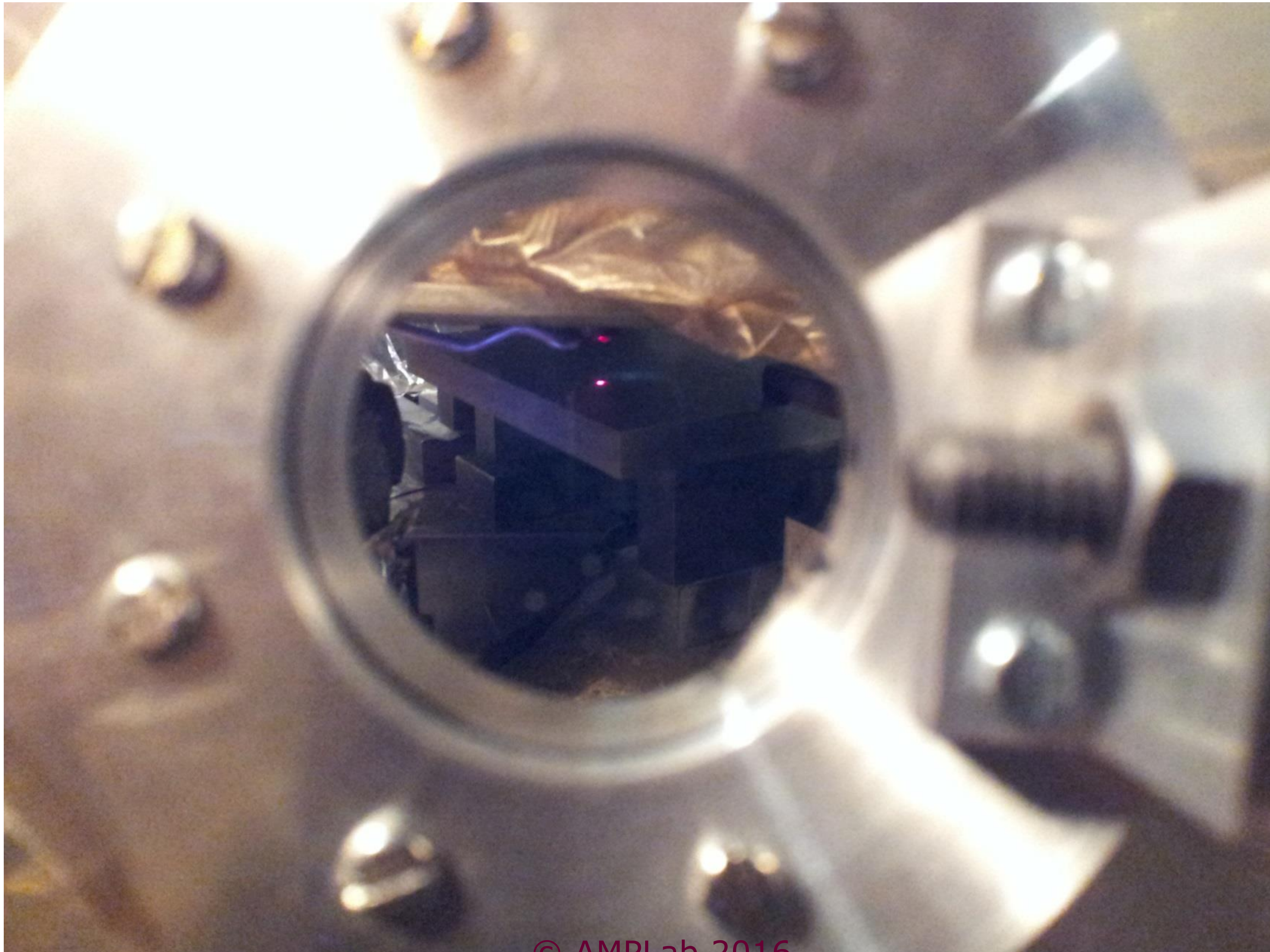
Measuring by triangulation



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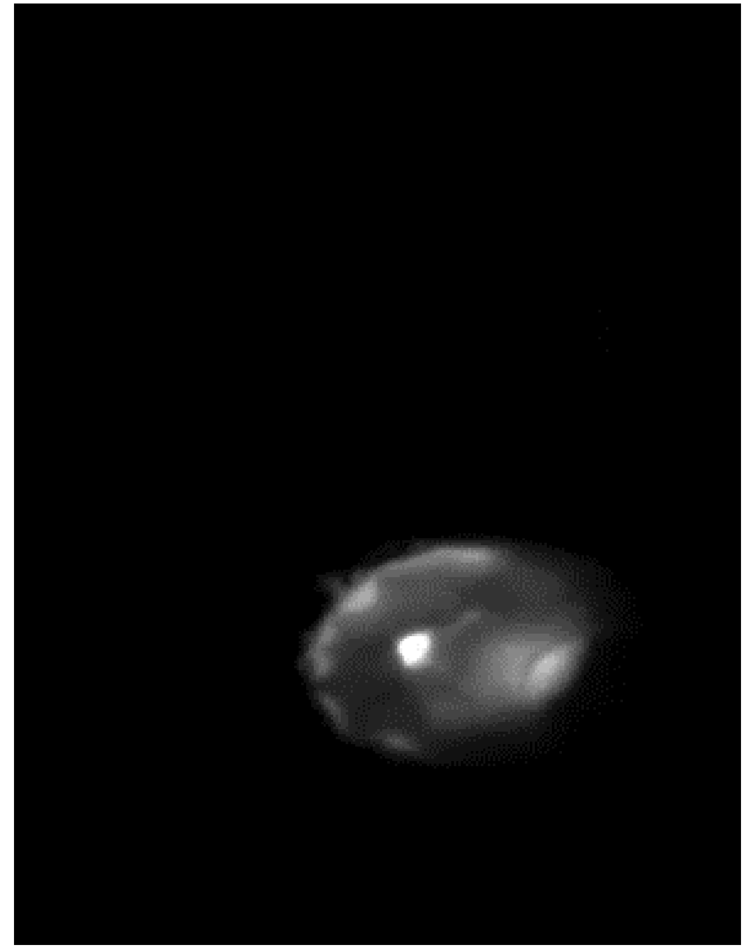
Pool image moves in Z

1. Calibrate and turn y-location of laser spot in image into z-location relative to camera.
2. Combine with camera (head) position to get x,y,z location of spot in space



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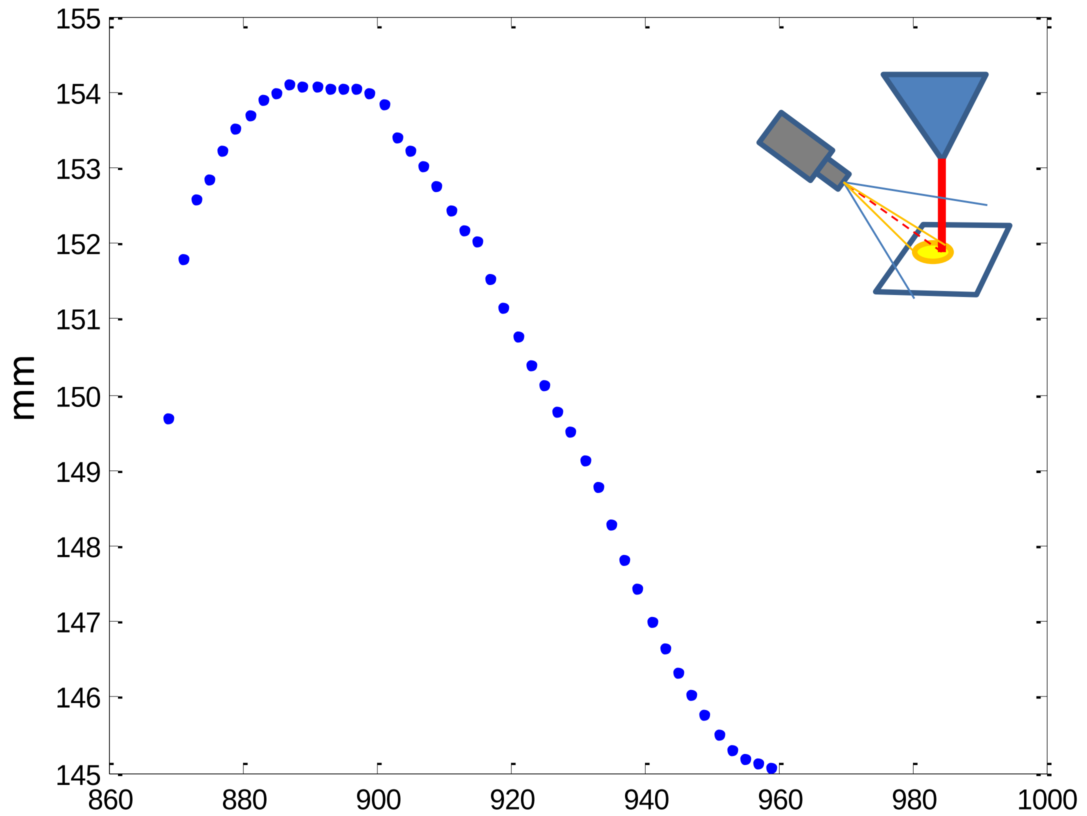
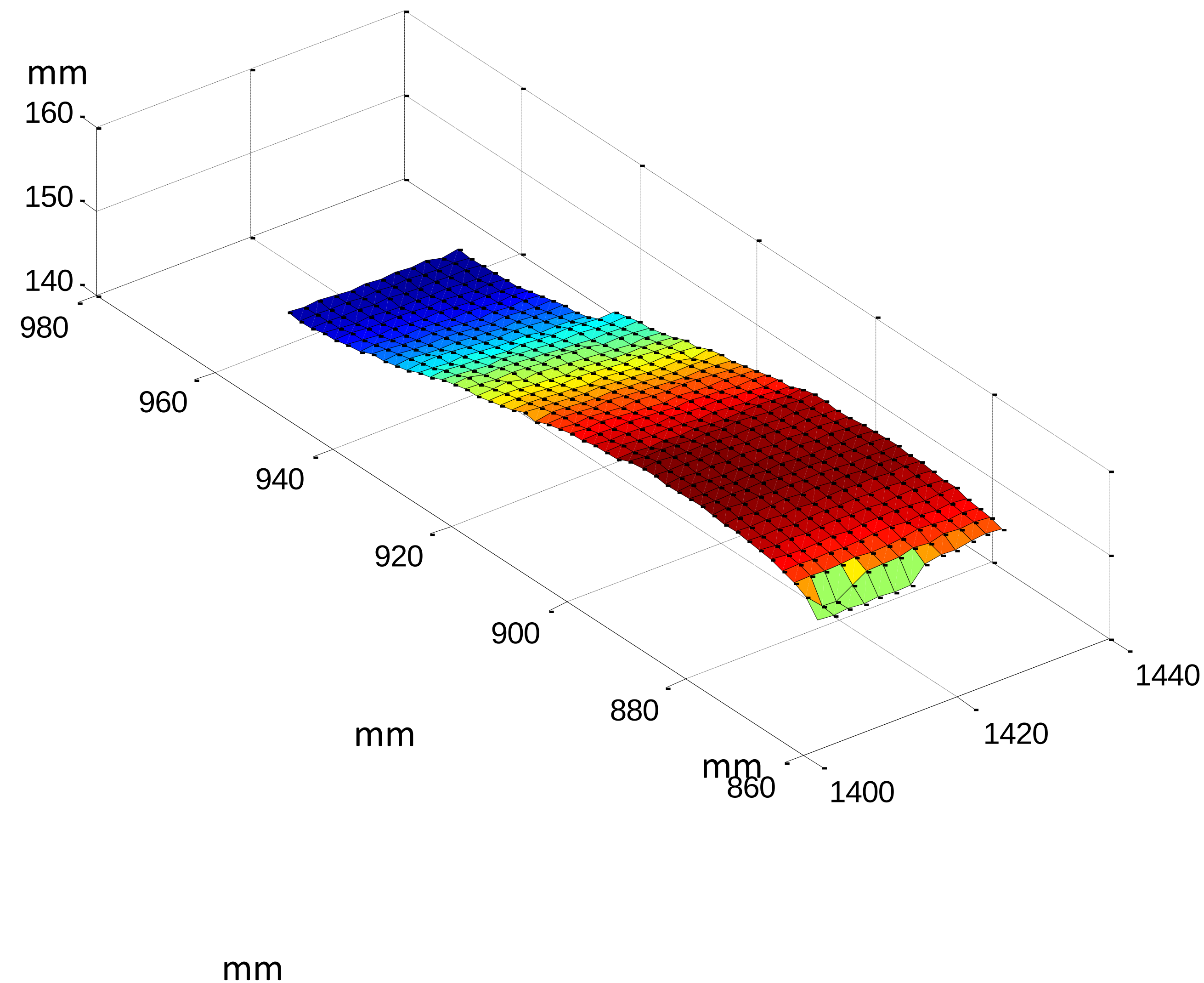
Results from real-time height measurement system (triangulation)





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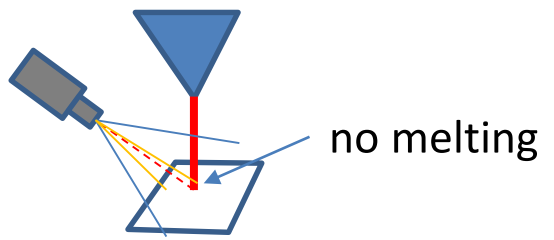
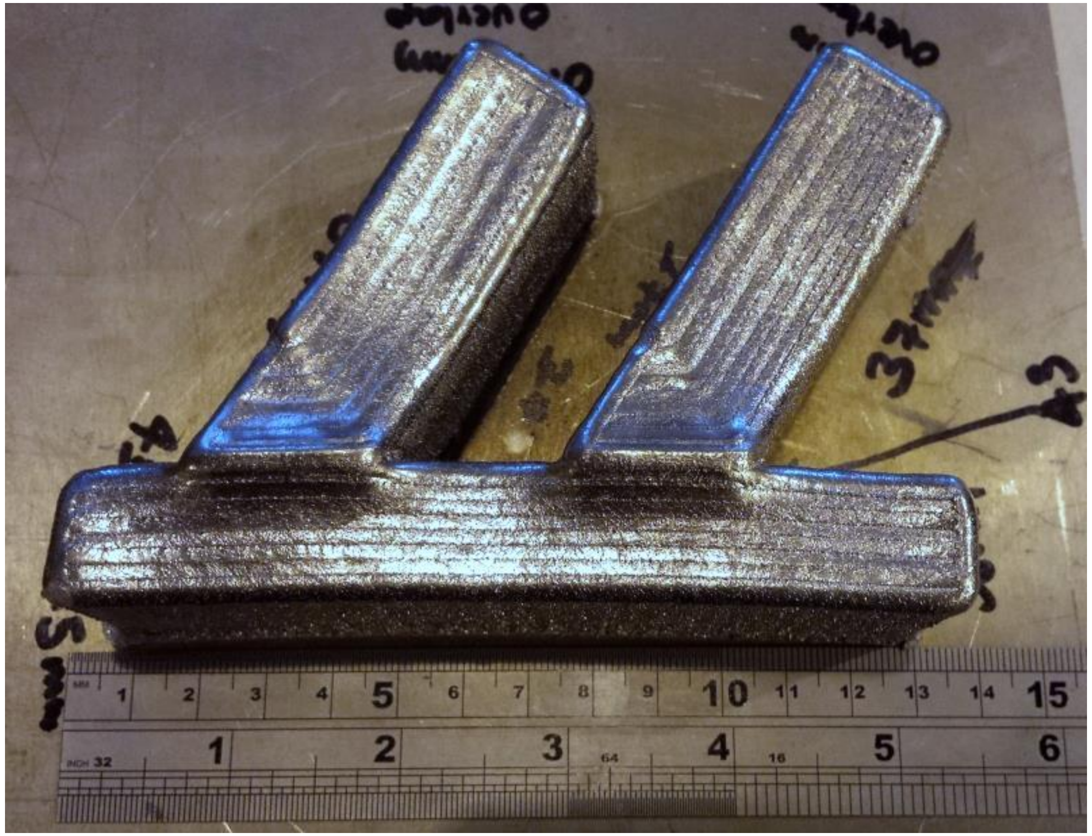
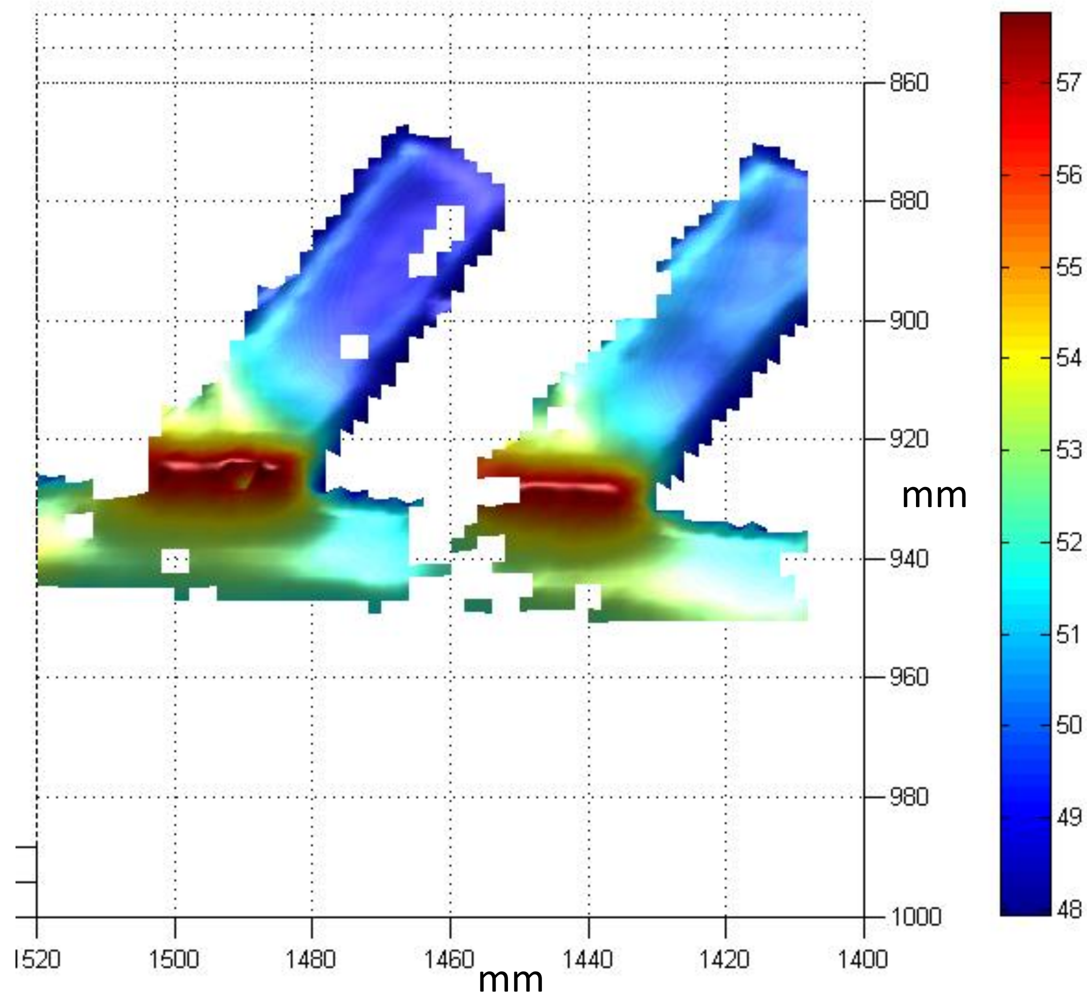
Note: these were taken at very low power, with no melting. The data quality improves when there is melting as it reduces the effects of specular reflection.







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Measurement system methods

	Linescanner	Spot triangulation
No extra time needed	+++ is possible for large builds	+++
Accuracy and resolution	+++	+
Coverage of the whole build area	+++	+

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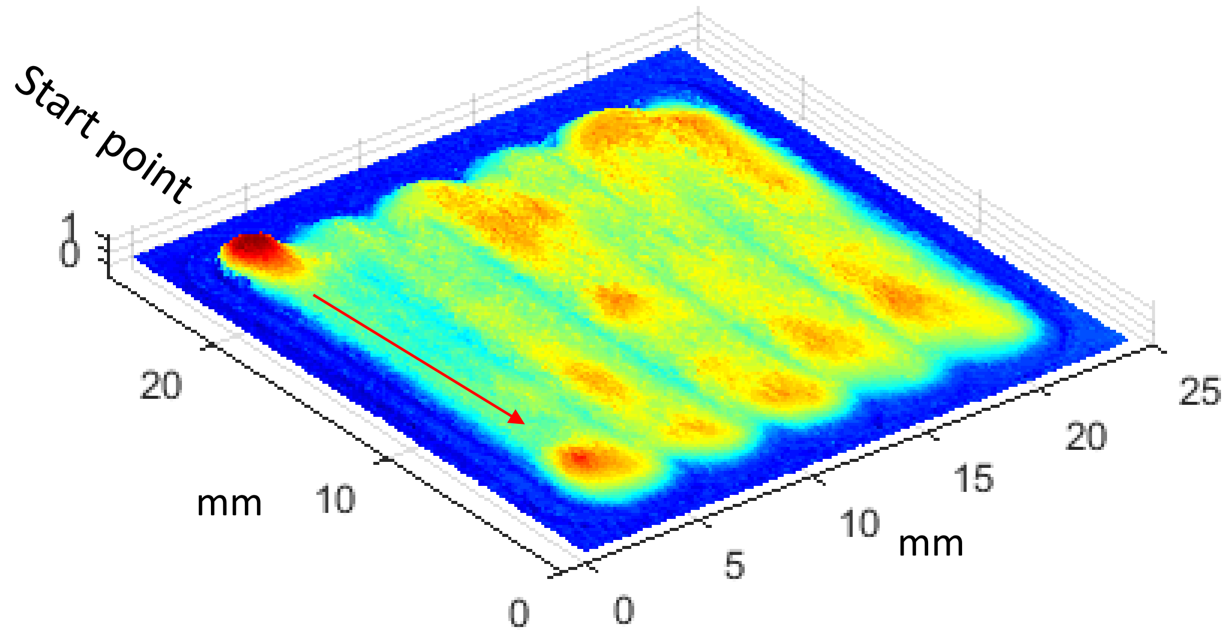
Method

A build program was used that was deliberately not ideal.
- powder flow takes time to start per layer, creating an underbuild

The height everywhere within the cube slice boundary should be 0.6 mm, but it can be seen that the uncontrolled (open-loop) build is already uneven after just the first layer.



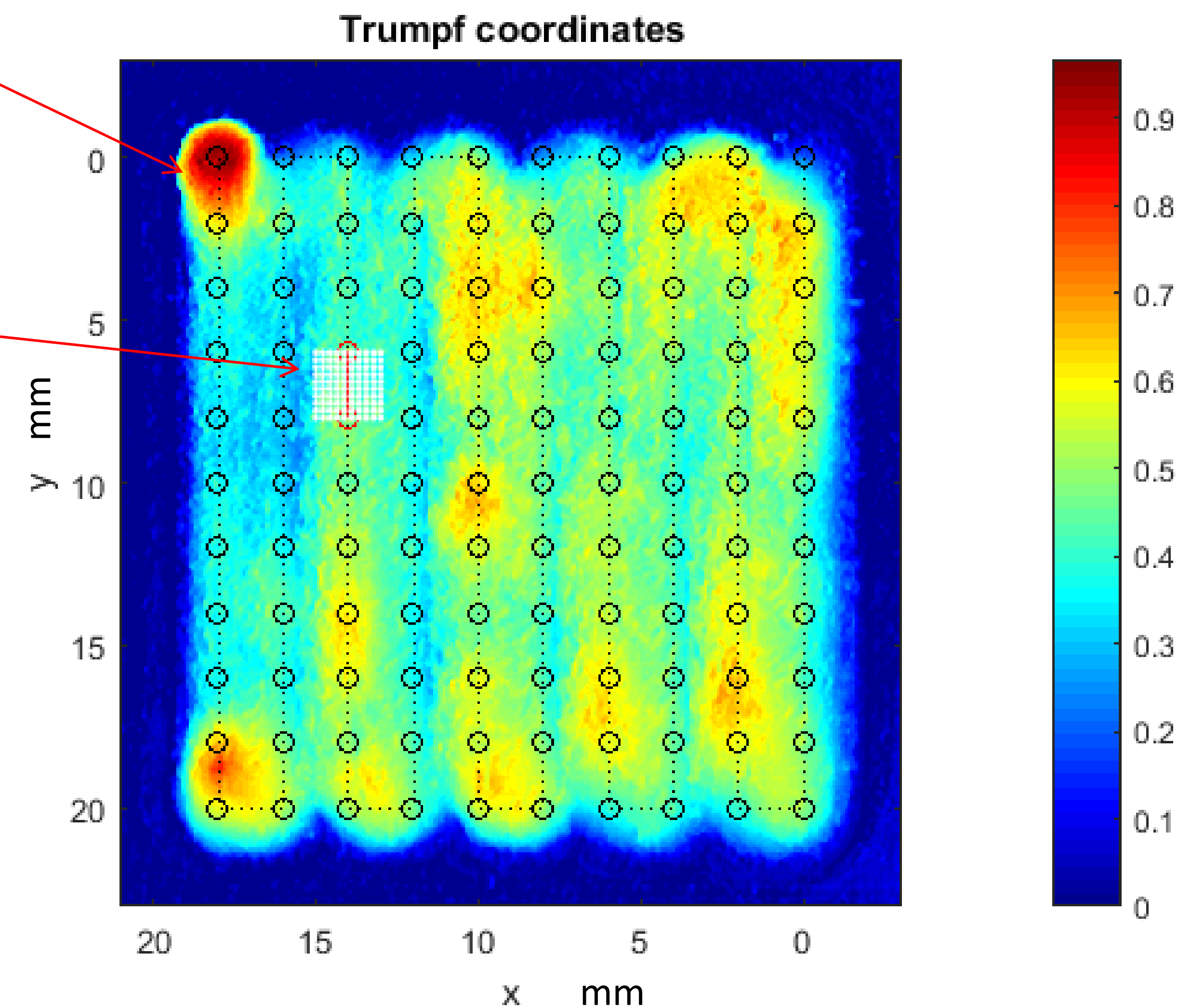
Open loop build first layer

Method

Automatically split the build path into segments,
and for each segment the heights at a grid of points are compared with the desired height.

A build program for the next layer is written to compensate for any differences, transmitted to the Trumpf and built.

The algorithm used is just to control the head traverse speed.
Slower = more deposition



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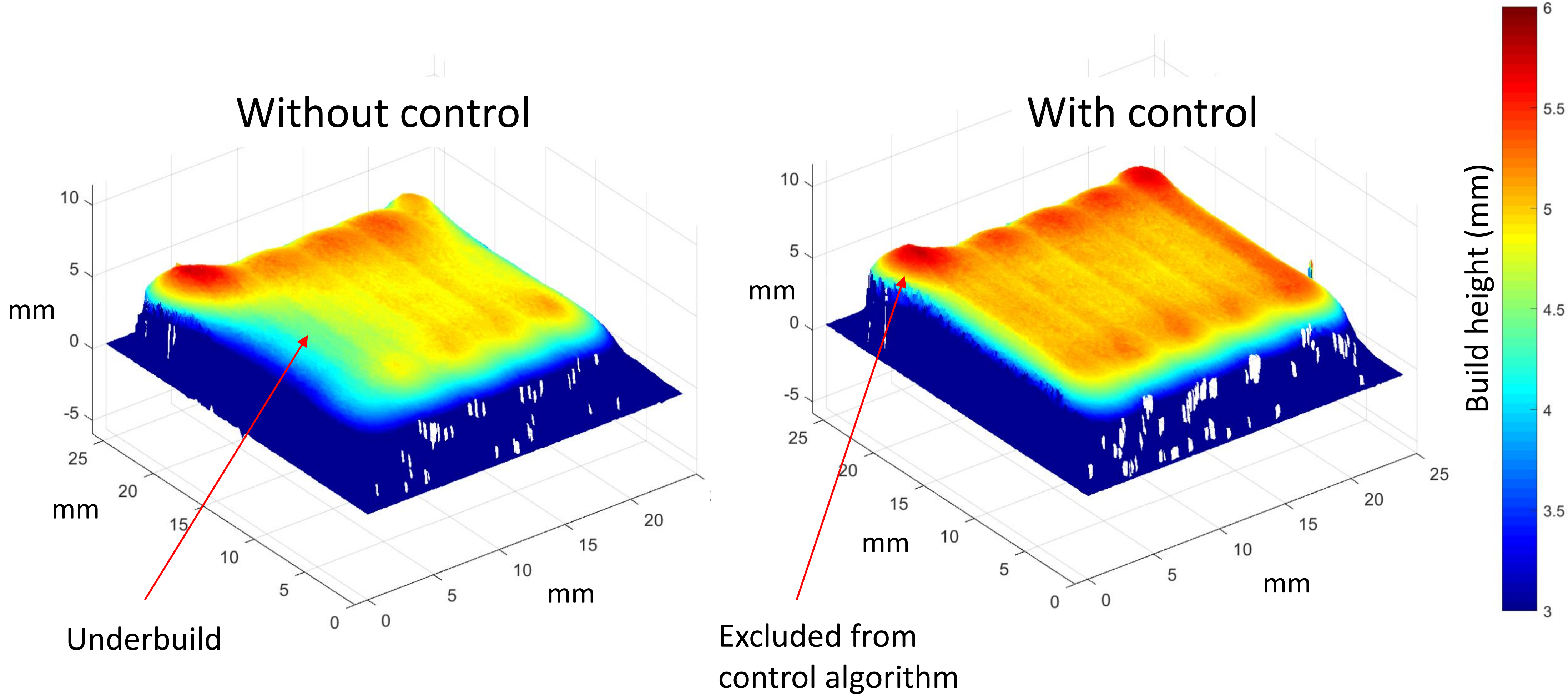
Results for 5 mm desired height



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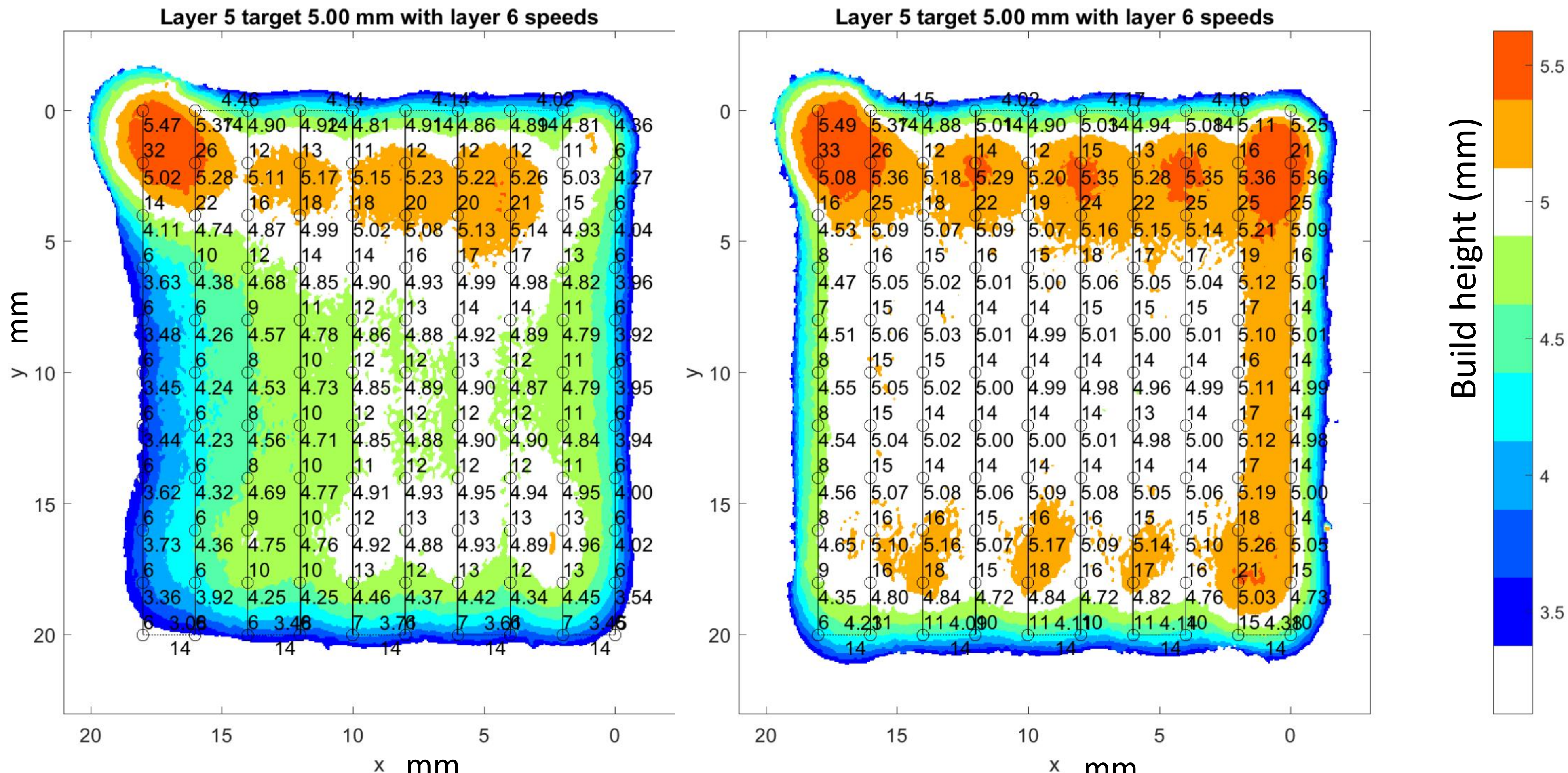
Results for 5 mm desired height



Without control — With control

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Choice of control algorithm

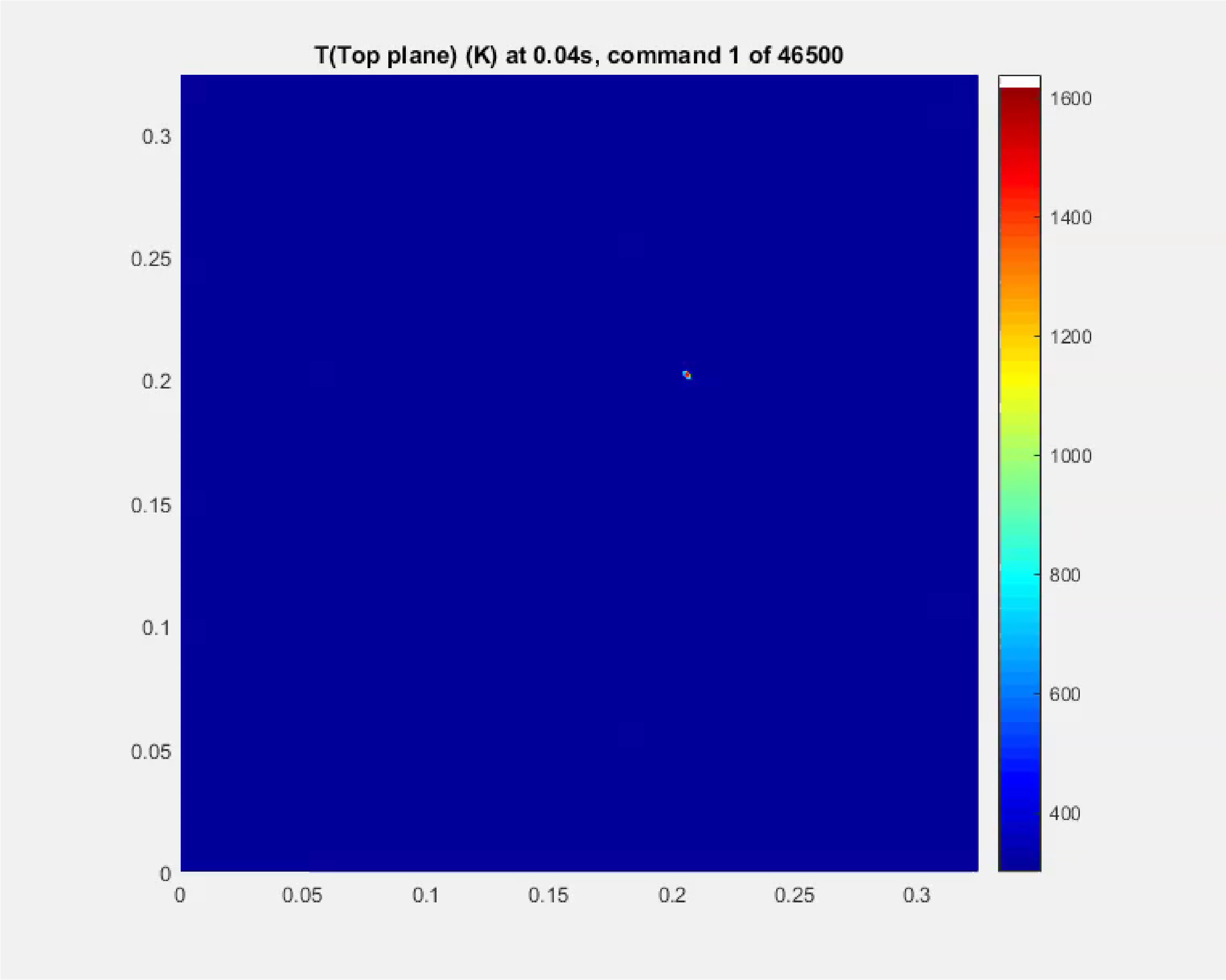
- Manipulate a combination of speed, power, head z position
- Move head up/down as needed to maintain correct standoff
- Control the melt pool size? Is that enough?
  – Maybe use 3d modelling beforehand to roughly set the local power so as to control the LST etc.

Fast thermal modelling of DLF

An example simulation of very rapid building.

IN738
1.6 g s^{-1} 50 mm s^{-1}
2x2x2 mm elements
300x300x9 mm base

Element-by-element simulation is slow compared to layer by layer.
But it lets us predict e.g. locations of unwanted melting etc. in complex shapes. And on a GPU, including post-processing, with this (large) element size it can be faster than real time.



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Fast thermal modelling of DLF

An example simulation of very rapid building.

IN738
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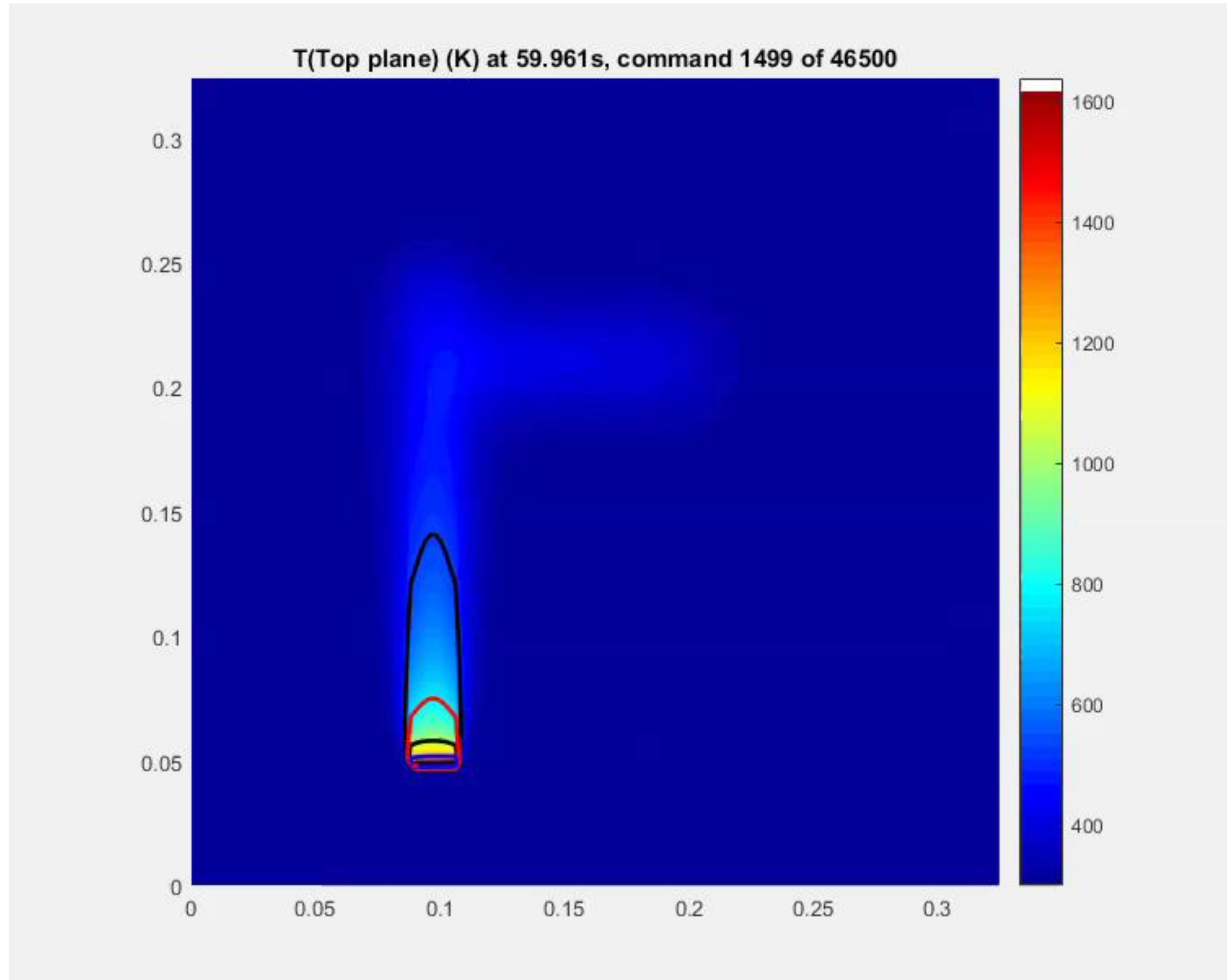
2x2x2 mm elements
300x300x9 mm base

This movie is the top surface temperature at the end of each layer of deposition.



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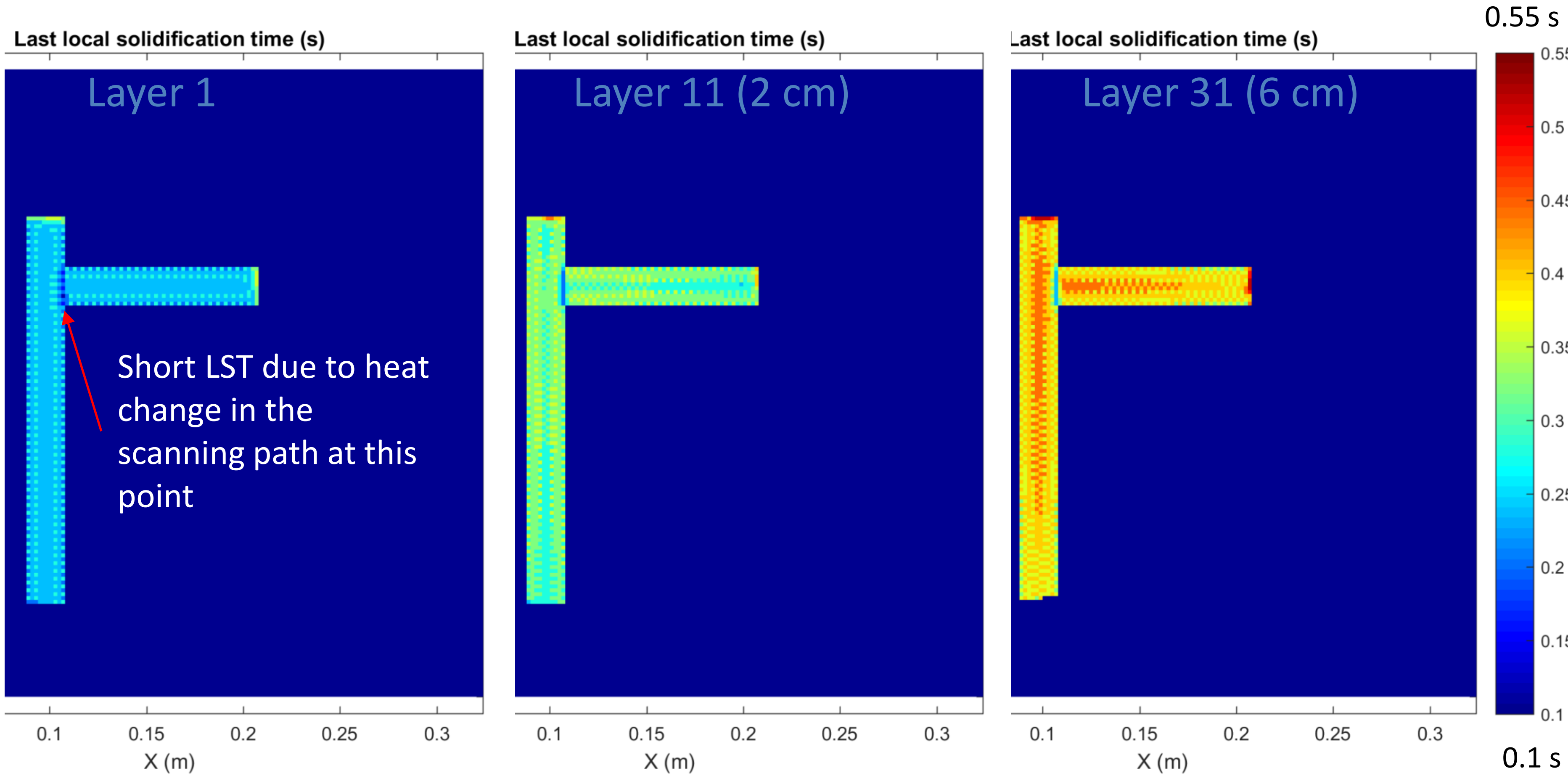
Fast thermal modelling of DLF



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Discussion

- Even controlling just the head speed improves build shape accuracy!
- Monitoring without control may be useful too:
  - build history
  - map of deposition efficiency (process diagnostics)
- but... Microstructure? Porosity?
- Deposition is non-linear: edges, steps etc.
- For large rapid builds with joints etc., also use a model to predict time-varying parameters beforehand to maintain the microstructure? (Surrogate or more physics-based)

Thanks to the EU AMAZE program for funding; Vivien Parker (final year project), Renaux Maxence (summer internship) for experimental work; Richard Harlow for help with the Trumpf

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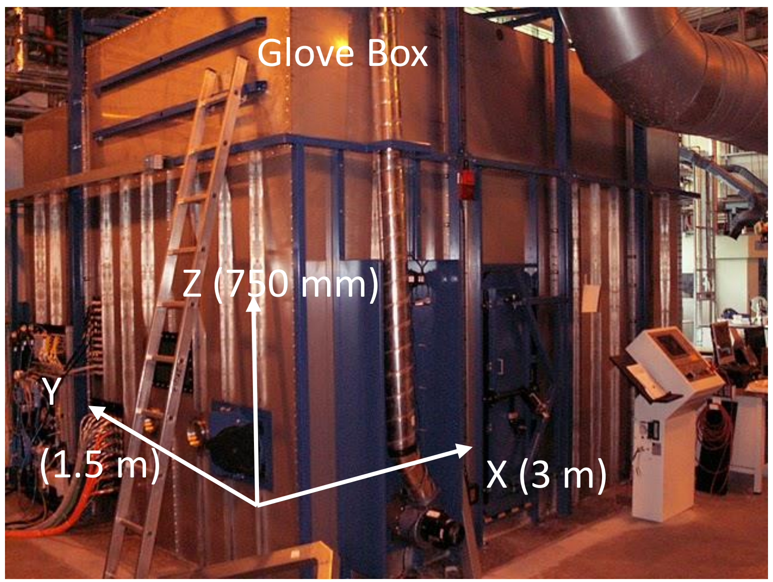
Direct Laser Fabrication facilities

TRUMPF 6.5 Axis DLF system



- ☐ Machine Limit - 1.5x1.0x3.0m
- ☐ Laser system Disk laser 4kW (Continuous and Pulsed Wave)
- ☐ Laser spot size: 0.4 - 6mm

Co-axial Nozzle

- ❑For thin wall builds
- ❑Powder focus ≥ 0.3 mm
- ❑Max. laser power ≤ 2kW

3-Beam Nozzle

- ❑For thick wall builds
- ❑Powder Focus ≥ 1.5mm
- ❑Max. laser power ≤6kW

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