POLITECNICO
MILANO 1863

Video-image data mining for zero-waste additive manufacturing

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mecc

DIPARTIMENTO DI ECCELLENZA
MIUR 2018-2022

VISION 2023

Full Professor - Co-founder of the **AddMe Lab**, **IC Labs and 3D cell Lab**

Politecnico di Milano (since 1863)
Largest technical university in Italy
(45 thousands students)

Manufacturing and Mech Eng (2023)

- 1st in Italy
- 4th in Europe
- **7th worldwide**

Engineering & Technology (2023)

- 1st in Italy
- 7th in Europe
- **18th worldwide**

Senior Editor- Department Editor:
Progress in Additive Manufacturing- Additive Manufacturing Letters
Informs Journal of Data Science – IISE Transactions
Journal of Quality Technology

Member of the European Commission's platform **Manufuture** Member of the SC of the **Vanguard Initiative on 3D Printing** **-** Board Member of the CLC South - **EIT Manufacturing,** Council members of **ASQ**, **Informs QSR** and **Enbis**

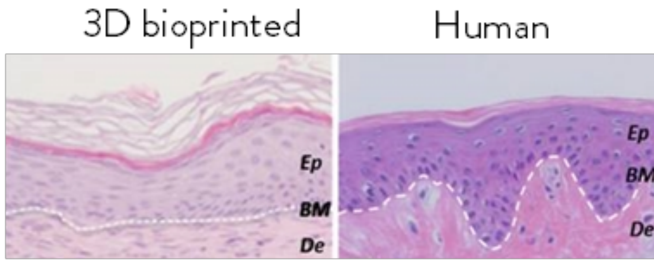
2023 Awards:

- **Royal Swedish Academy of Engineering**
- **2023 ASQ Brumbaugh Award**
- **2023 ENBIS Box Medal Award**

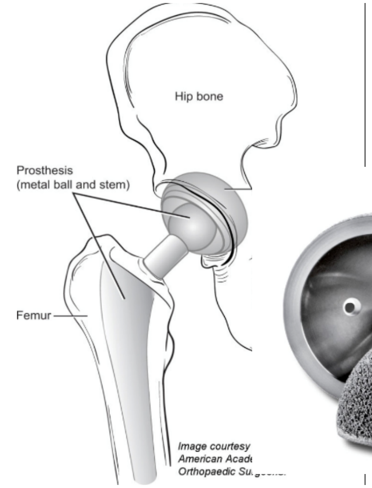
Included among the top 100 Italian woman scientists in **STEM** (https://100esperte.it/)

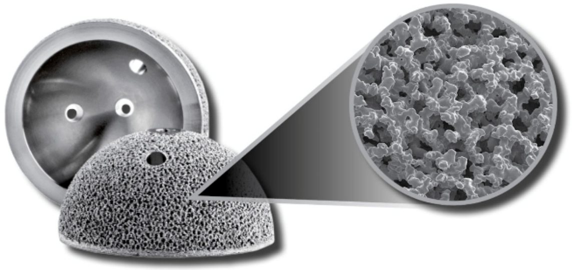
2015 EDAG Light Cocoon *(https://driventowrite.com/2015/03/03/edag-research-into-additive-manufacturing/)*

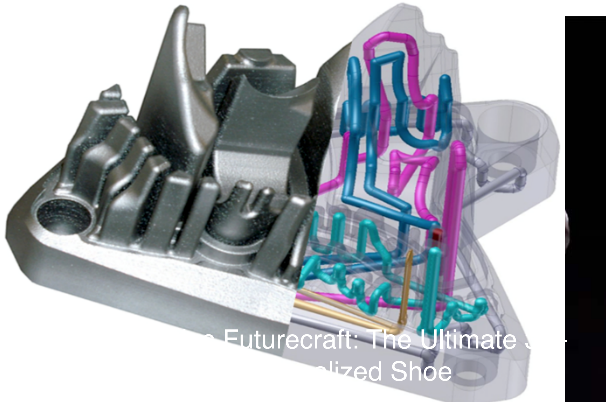
What do they have in common?



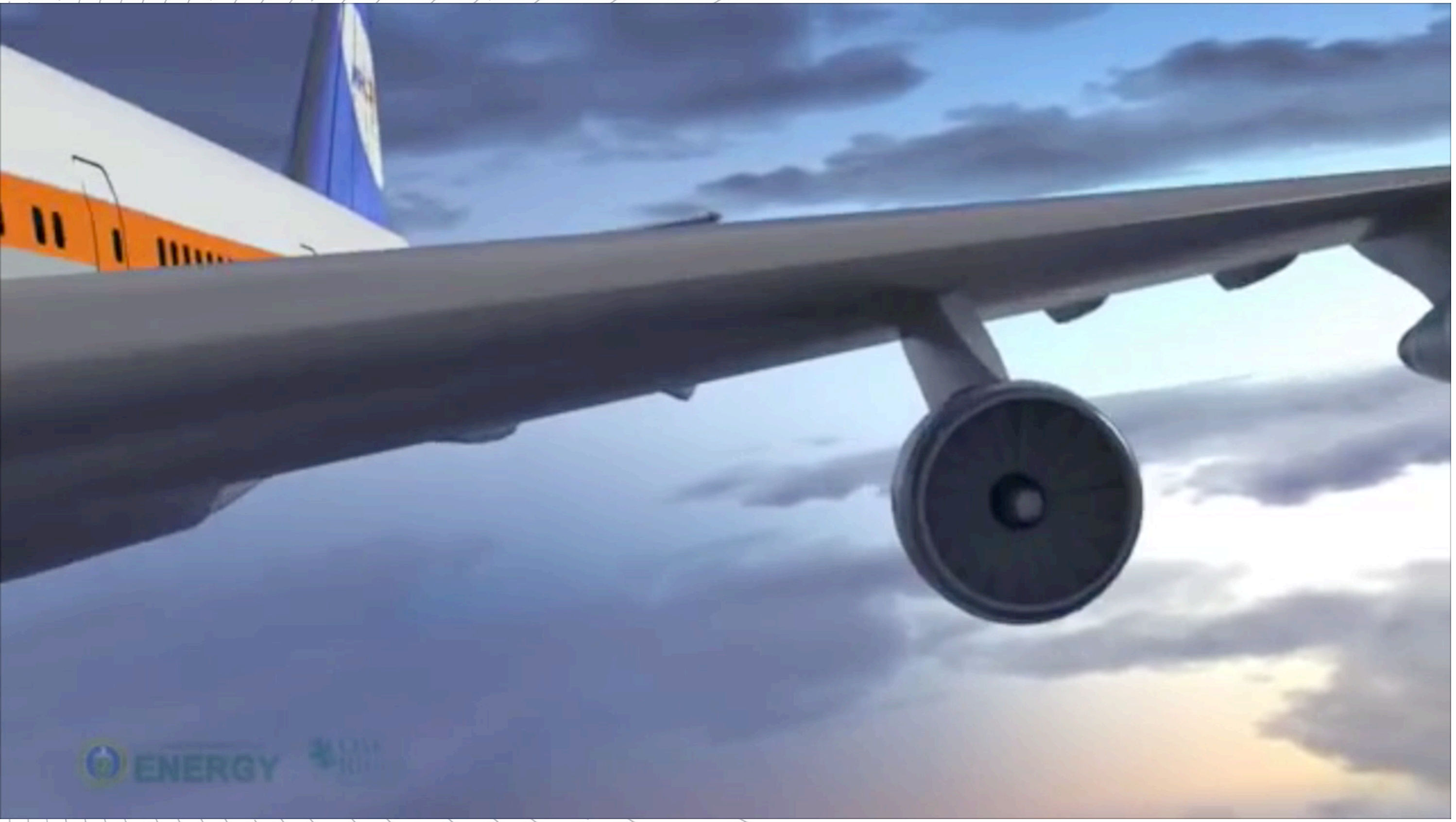
Bioprinted skin



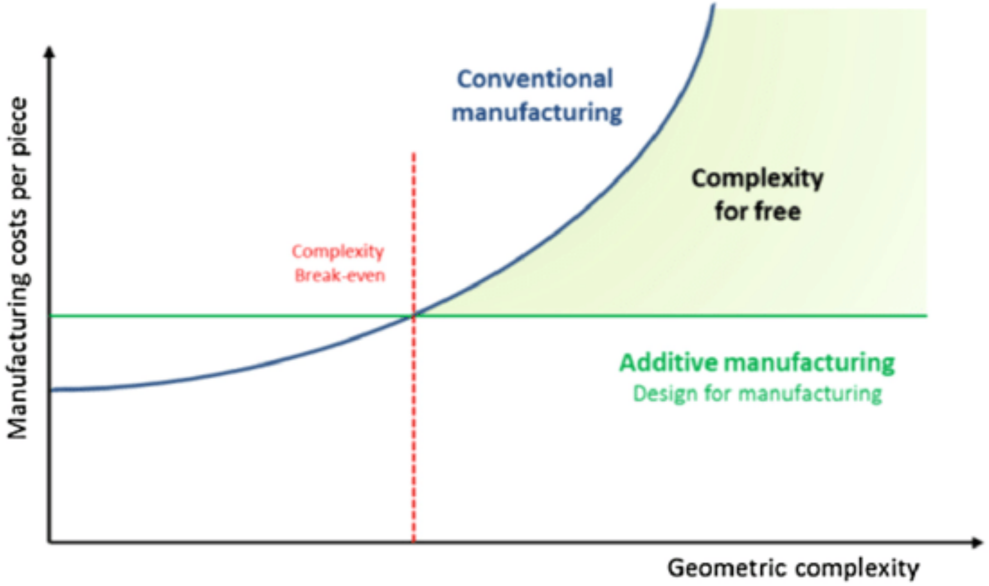




Additive Manufacturing - Complexity for free



An example of metal AM – power bed fusion via EBM



Additive manufacturing:
"the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive and formative manufacturing methodologies."

AM & the green transition

AEROSPACE

Satellites: Bracket

- Weight reduction: - 60 %
- Waste reduction: - 98 %
- Cost reduction: - 53 %

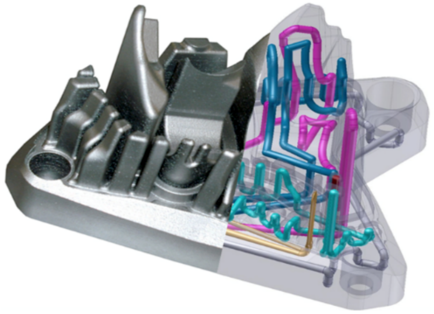
GE Fuel nozzle (Leap jet Engine)

- Reduce # components
- More durable (5X)
- 25% lighter (15% fuel savings)

MACHINERY AND TOOLING

Machinery and tooling

- Extended lifetime
- Reduce defects

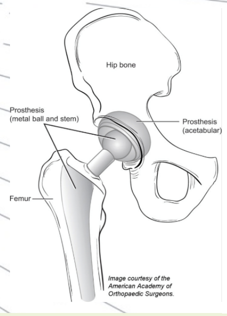


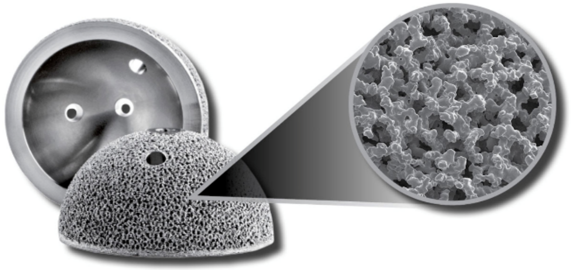
CREATIVE INDUSTRIES

- Material savings

BIOMEDICAL

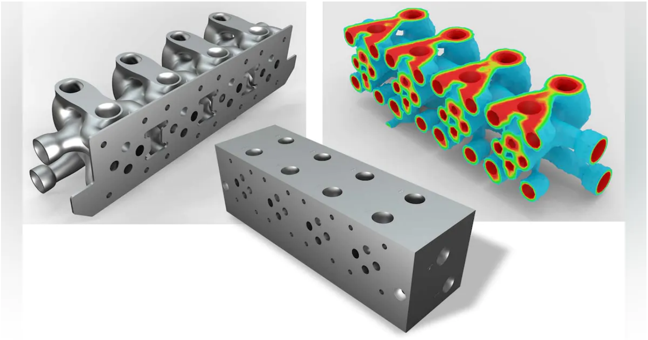
- Customization





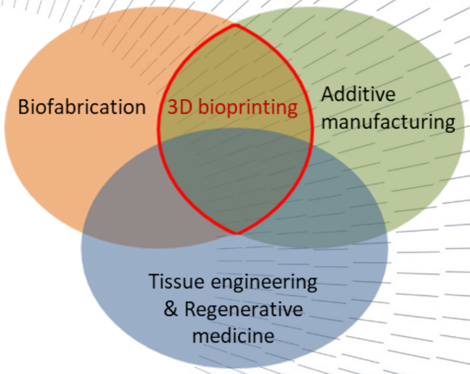
OIL & GAS

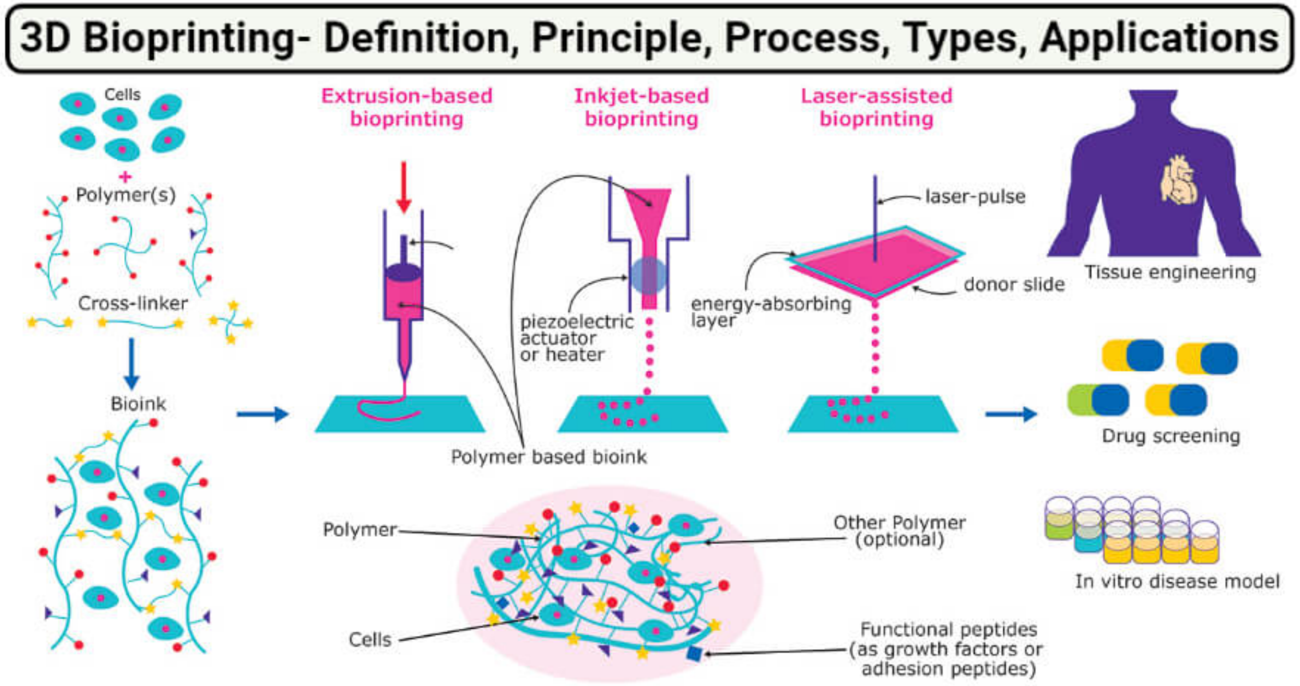
- weight and performances

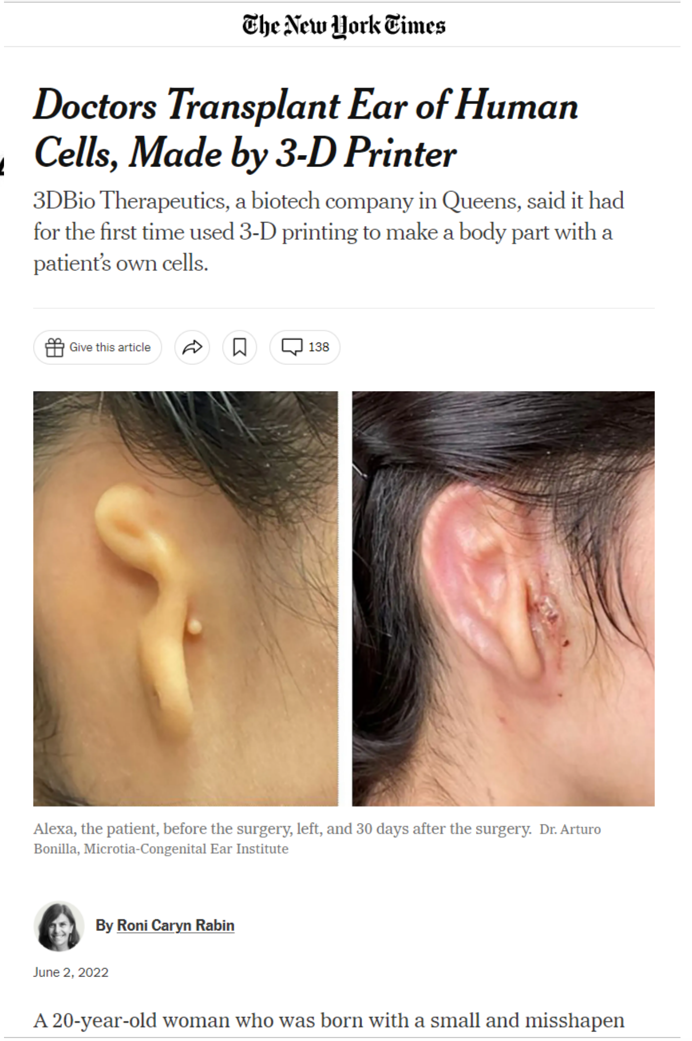


- Green performances
  - lightweight, energy-efficient, small number of components, material just where needed
- First-time-right/Zero-defect
- Circular (extend lifetime, repair, recycle)
- Produce when and where it is needed

From 3D printing to bioprionting







The New York Times

Doctors Transplant Ear of Human Cells, Made by 3-D Printer

3DBio Therapeutics, a biotech company in Queens, said it had for the first time used 3-D printing to make a body part with a patient's own cells.

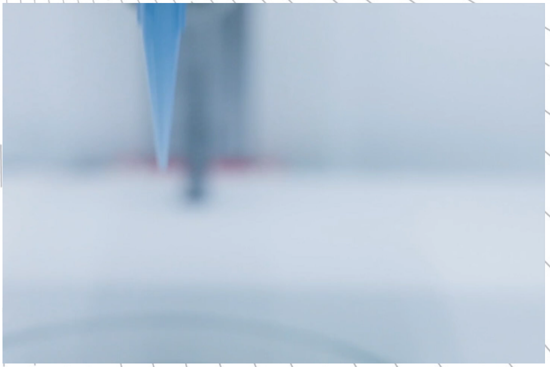
Give this article 138

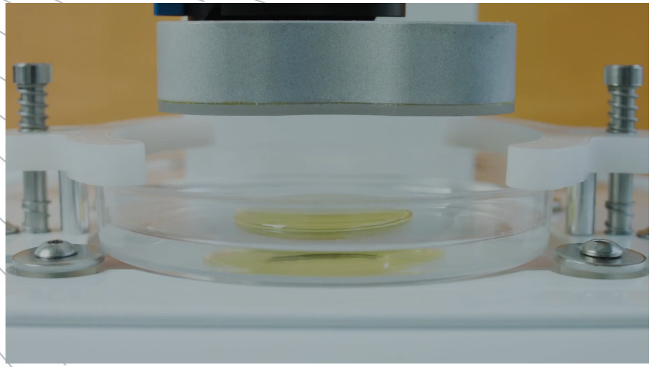
Alexa, the patient, before the surgery, left, and 30 days after the surgery. Dr. Arturo Bonilla, Microtia-Congenital Ear Institute

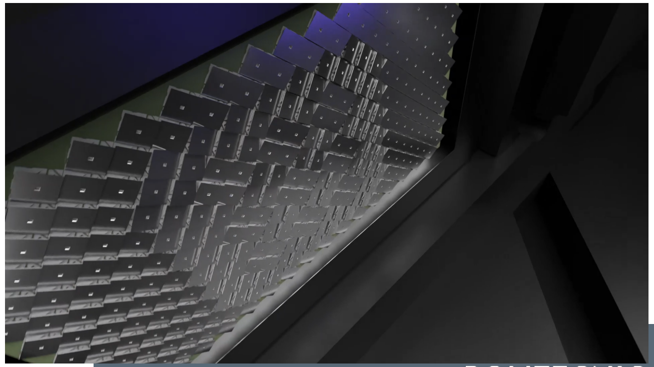
By Roni Caryn Rabin

June 2, 2022

A 20-year-old woman who was born with a small and misshapen





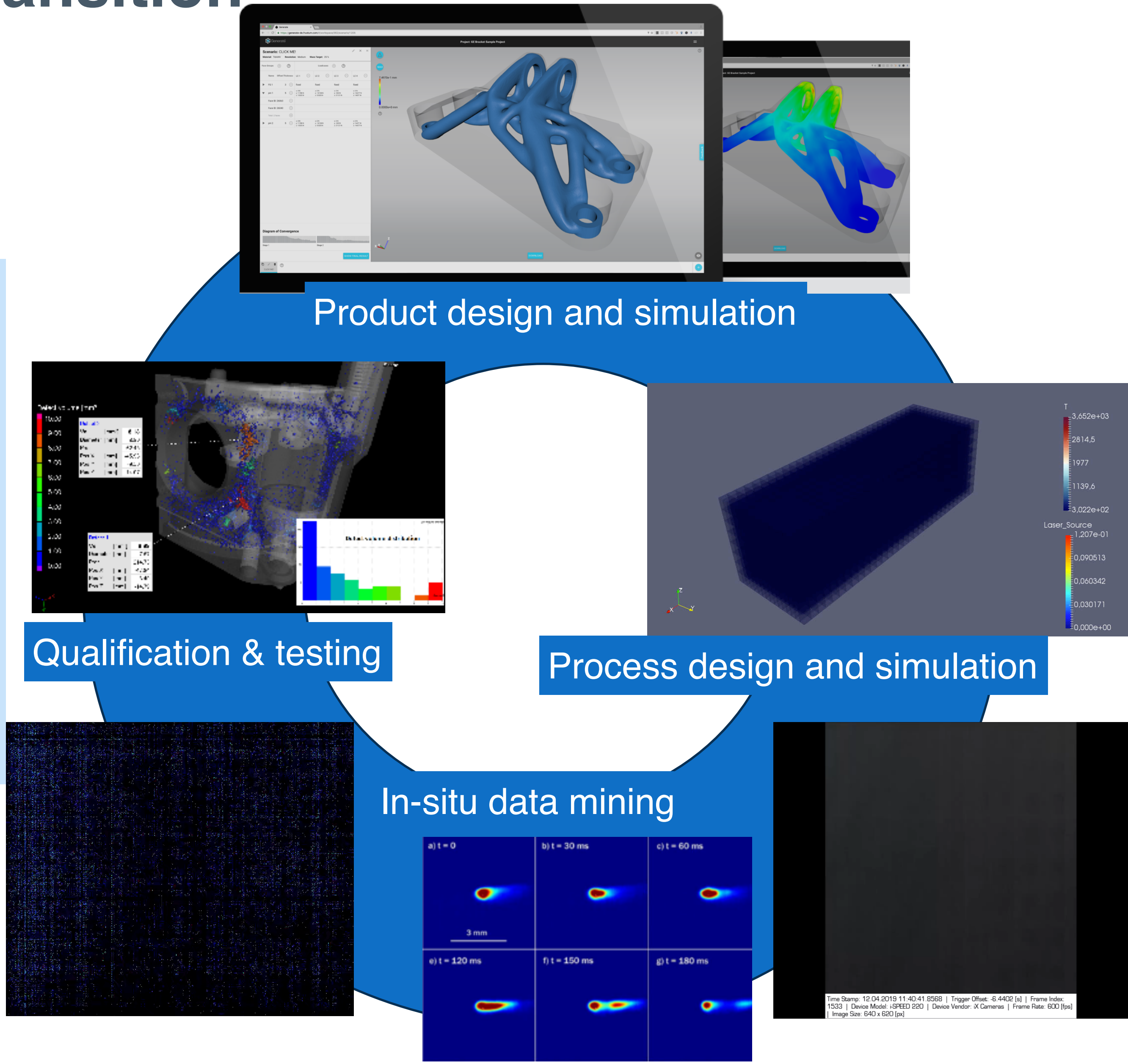


Home / 3D printed brain organoids: Humanitas University and Politecnico di Milano together to research neuronal diseases

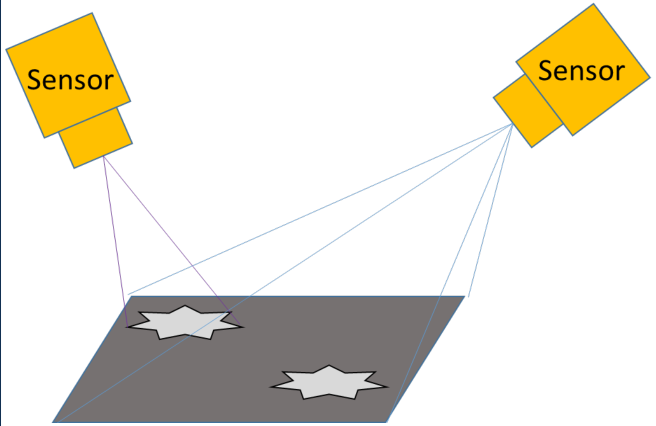
3D printed brain organoids: Humanitas University and Politecnico di Milano together to research neuronal diseases

Additive Manufacturing & digital transition

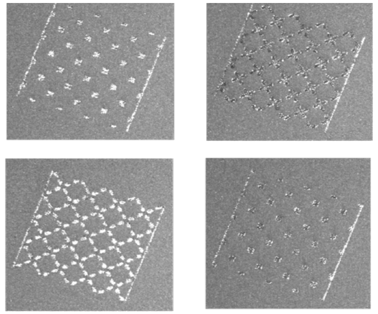
- From physical to digital
- Virtual process & product design (for customization)
- Smart process (real time monitoring and control)
- Digital twin
- IoT
- Cloud computing



Off-axis



Powder bed images

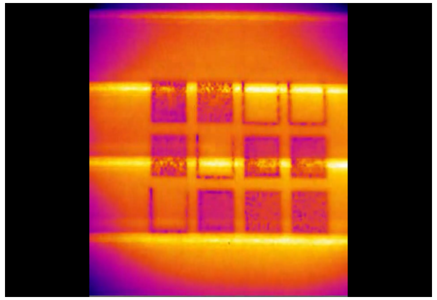


5 - 10 Gbyte

Off-axis high speed video

5 – 10 Tbyte

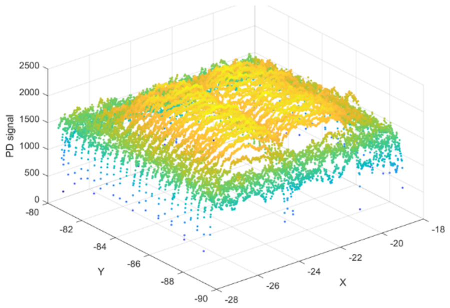
Off-axis high speed IR video



50 – 100 Tbyte

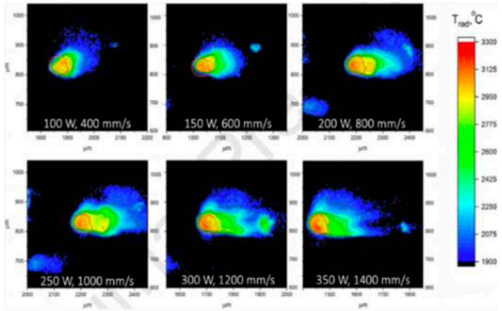
Co-axial

Co-axial photodiode



10 – 30 Gbyte

Co-axial meltpoole



PRODUCT

AddMe.Lab

The intelligent AM machine

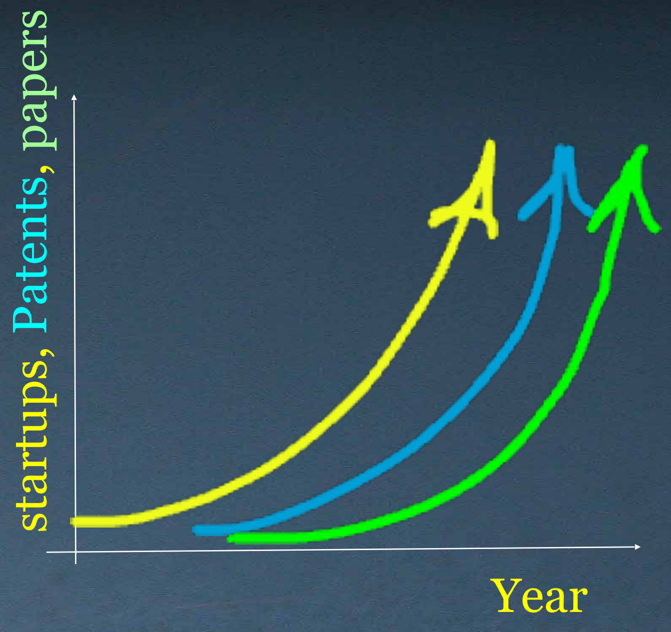
“More 3D printers will have eyes (sensing) and brains (machine learning)”

(Additive Manufacturing trends in 2022)*

In-situ process monitoring:

- First-time-right (&customized)
- Reduce wastes
- From monitoring to control
- Digital twins

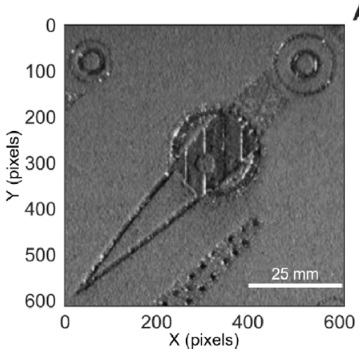
Multistream massive data



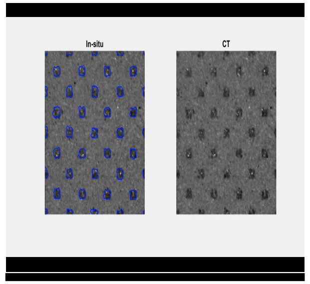
From sensorized to intelligent AM systems

IN-SITU MONITORING IN AM: my agenda today

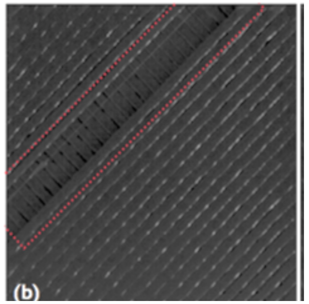
- IMAGES



Free forms



Lattice



Textured surfaces

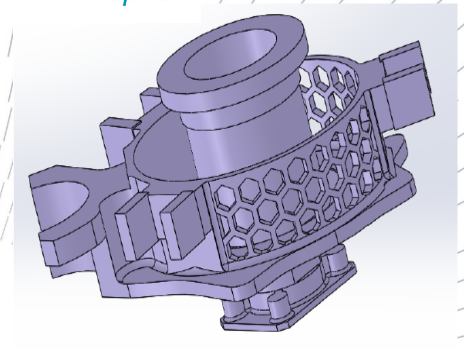
- VIDEO-IMAGES

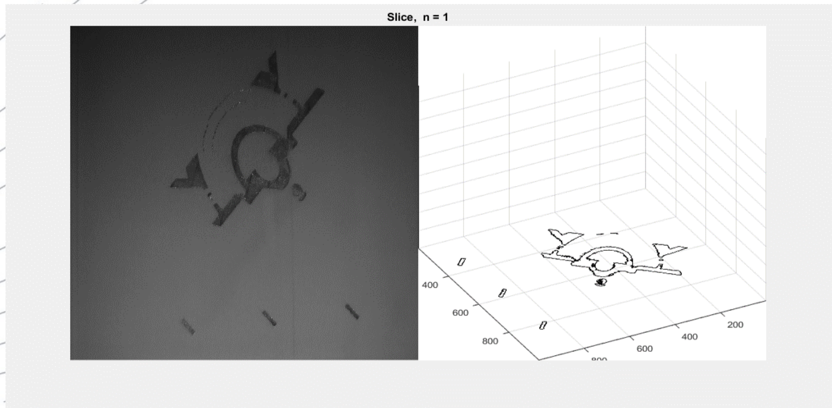
Hot-spots

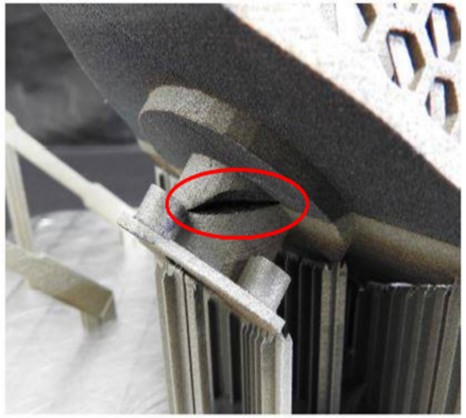
spatters

IMAGES: FREE-FORMS

ThalesAlenia Space







Tested on an EOS M290 by using the powder bed imaging already available in the system.

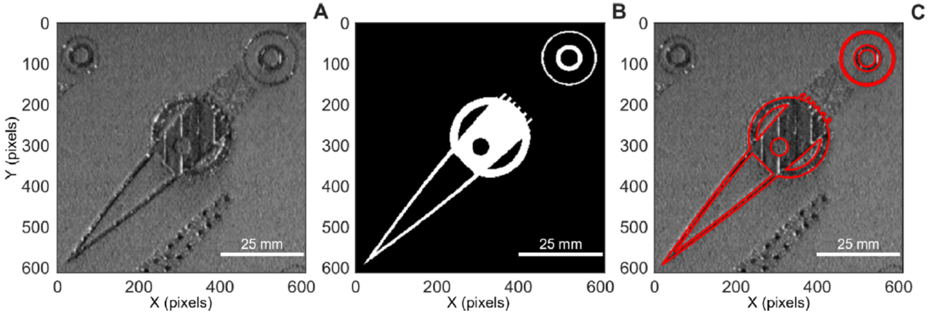
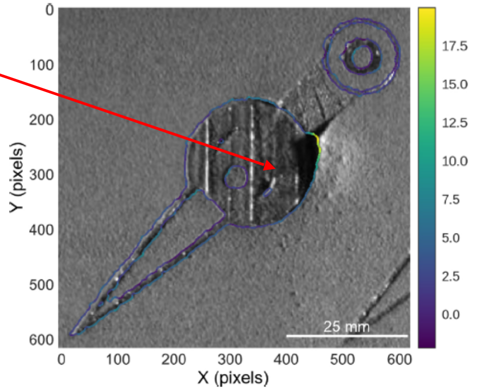
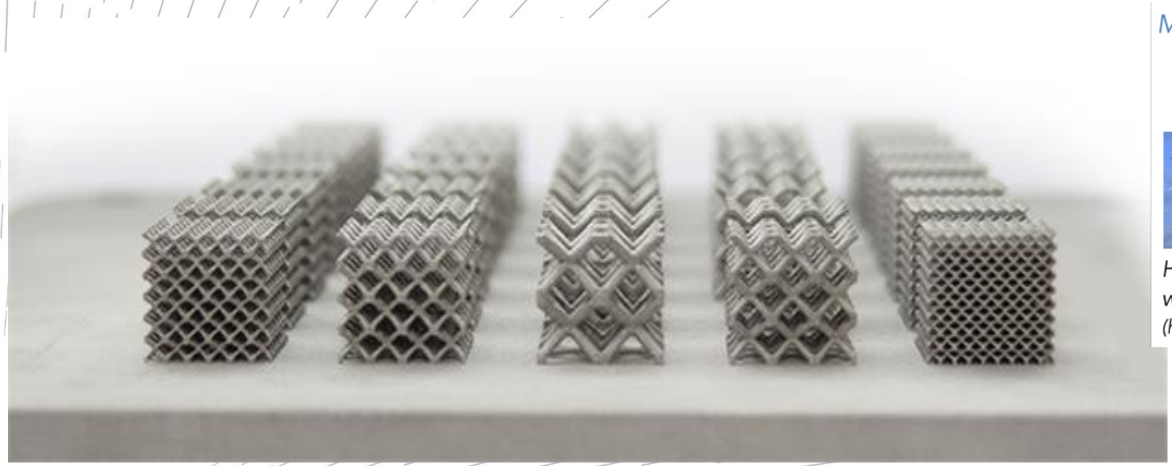


Fig. 5. Example of an acquired image (A) and its nominal mask (B), and the contour of the mask superimposed on the original image (C).

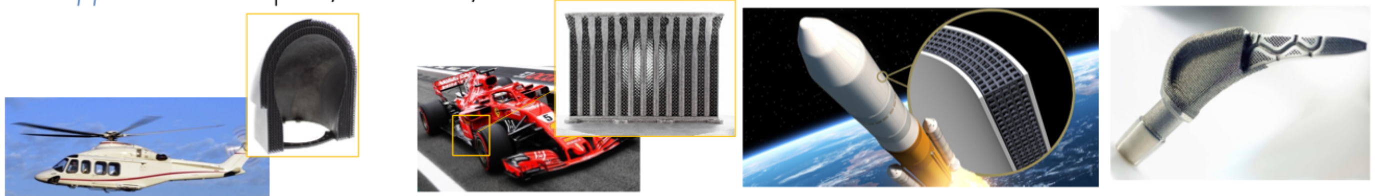


Mask-preprocessing - active contour - pixel intensity correction- Order statistic

IMAGES: LATTICE STRUCTURE



Main application: Aerospace, Aeronautic, Automotive and Defence sectors

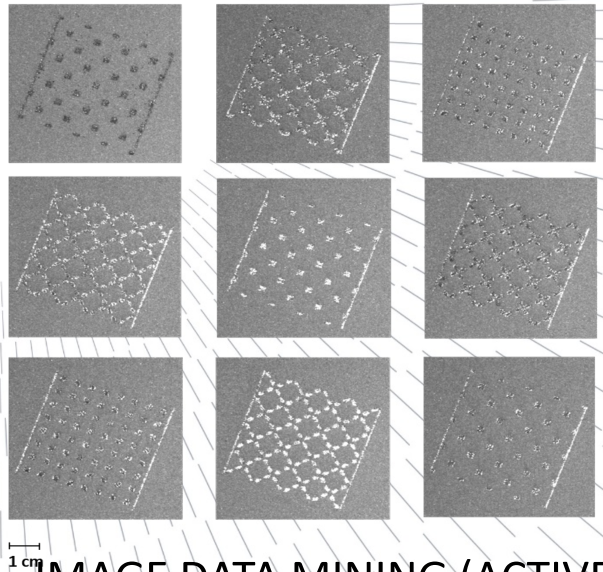


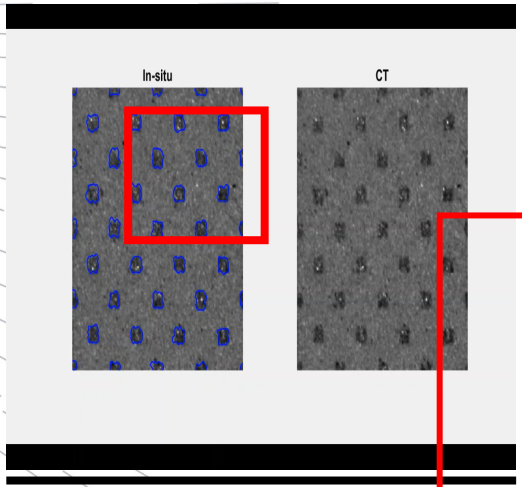
Helicopter exhaust gas nozzle with integral cooling. (https://altairenlighten.com)

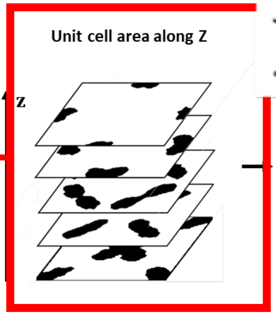
Lattice-filled turbo intercooler for racing car (https://altairenlighten.com)

Vibration absorbers - sandwich panels filled with a lattice core. https://powerandmotionworld.it/

Hip implant with cavities fo[r] medicinal deposits (https://www.fraunhofer.de/)







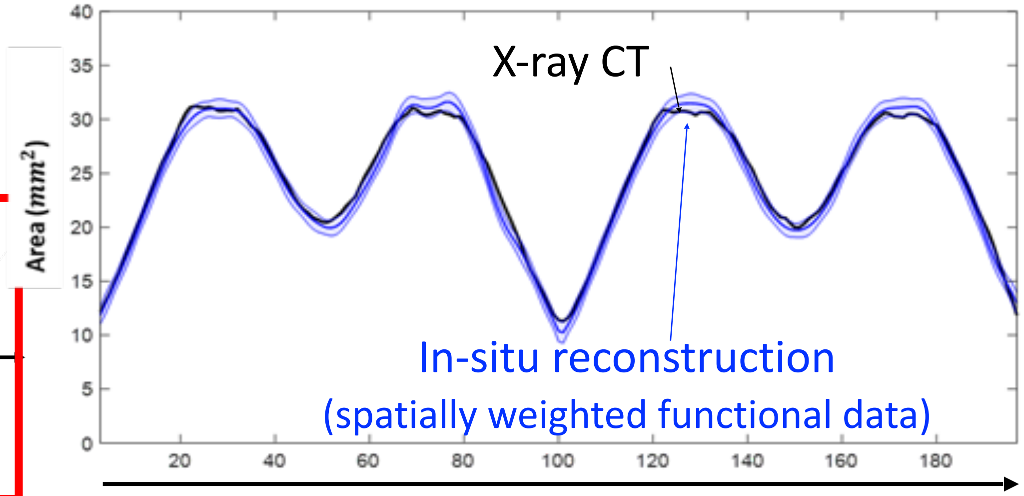


IMAGE DATA MINING (ACTIVE CONTOUR)+WEIGHTED LINEAR MODELING

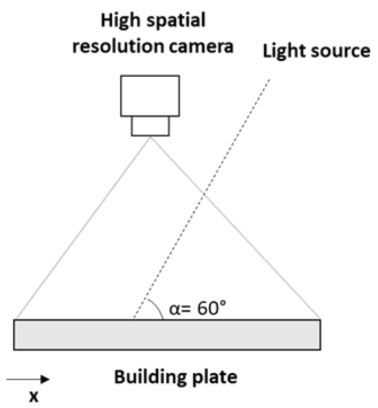
DEVIATION FROM THE NOMINAL SHAPE OF ONE CELL ALONG z (layer number)

95% Prediction Interval based on in-situ reconstruction

X-ray CT reference (as built)

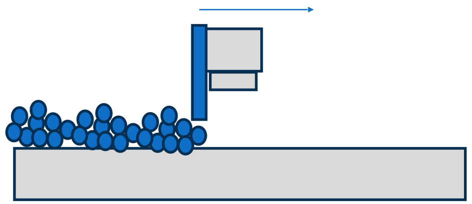
IMAGES: OUR NEW PATENTED SOLUTION
The intelligent recoater

From external camera

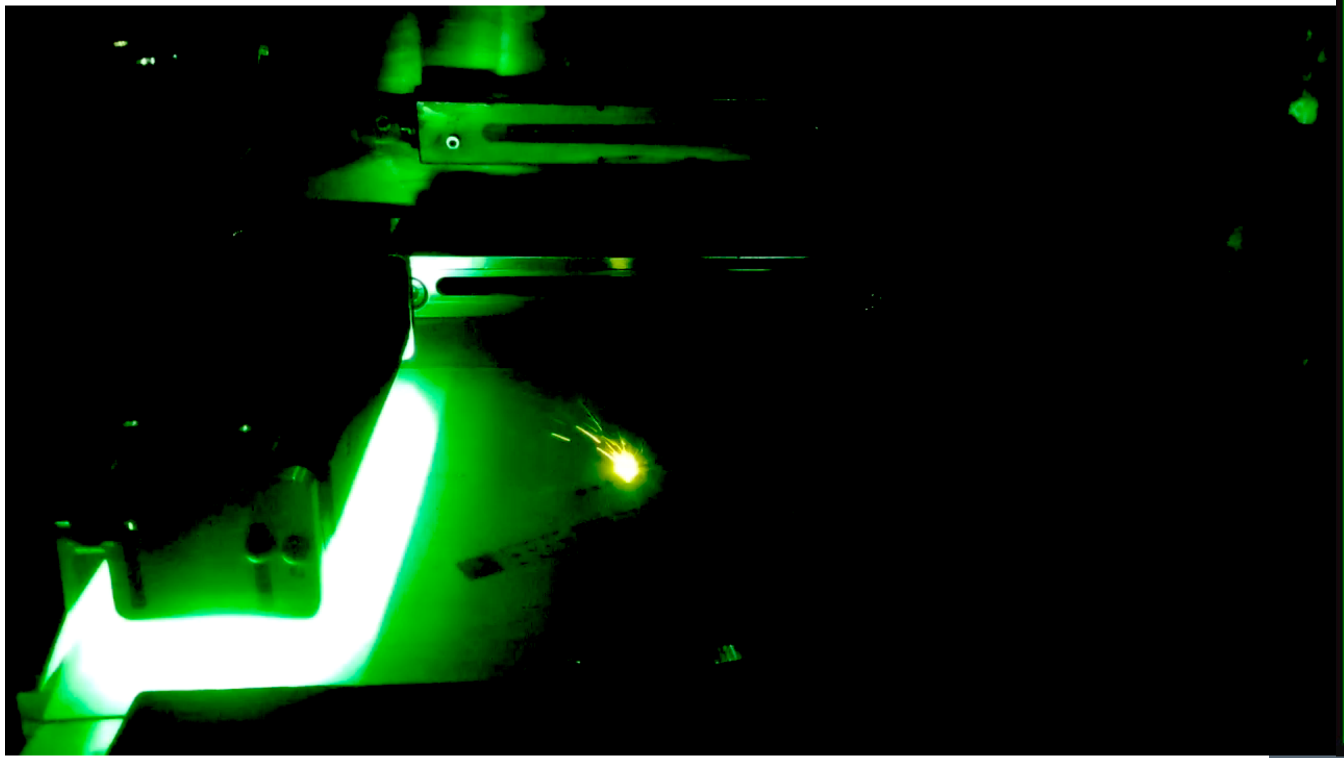


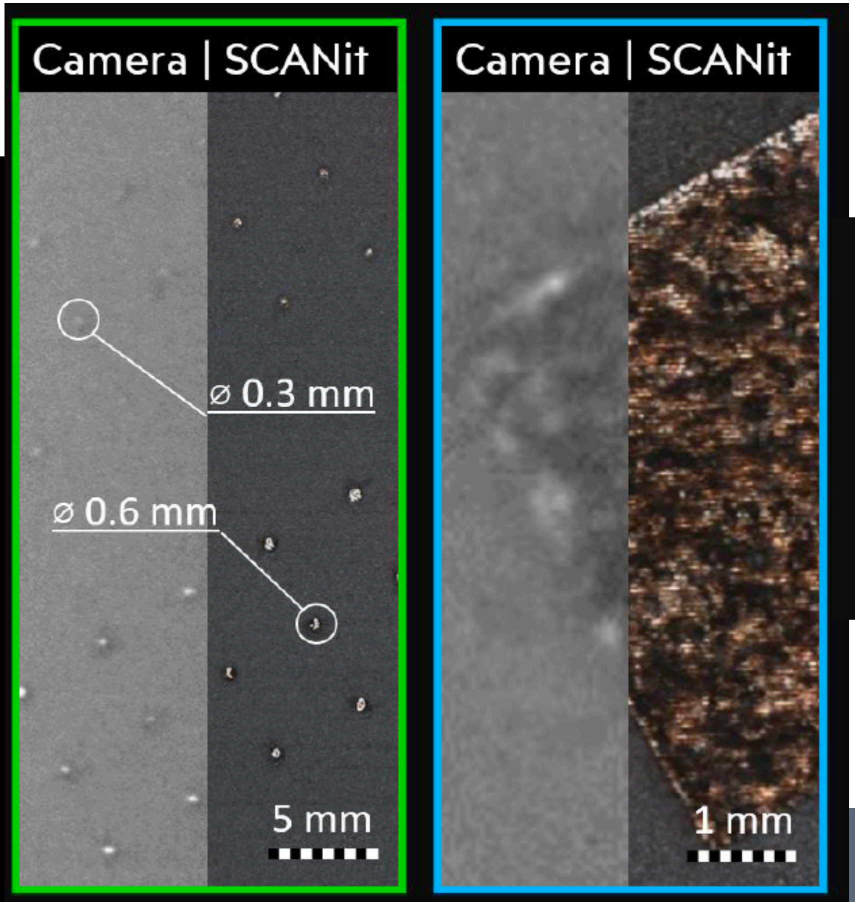
To our SCANIT: scanner on the recoater

Travelling with the recoater during powder spreading with internal lighting system



- High resolution (5x better than camera)
- On-board intelligence
- Insensitive to Illumination
- Easy to use





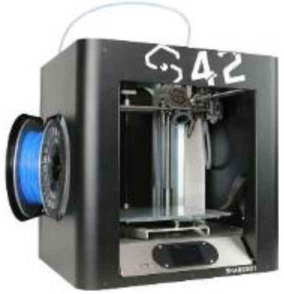
SCANit

- 20 µm/px
- Integrated illumination
- Mono/Color

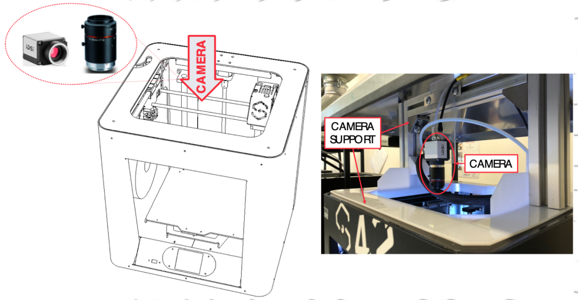
EXTERNAL CAMERA

- 100 µm/px
- External illumination
- Mono

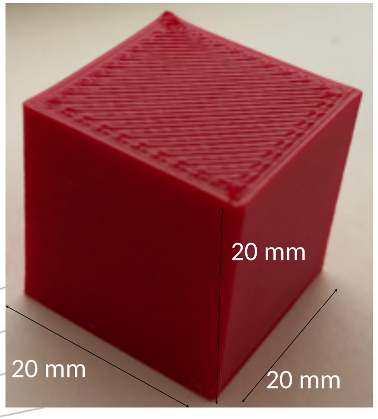
IMAGES: TEXTURED SURFACES



Sharebot 42
Nozzle diameter = 0,4 mm

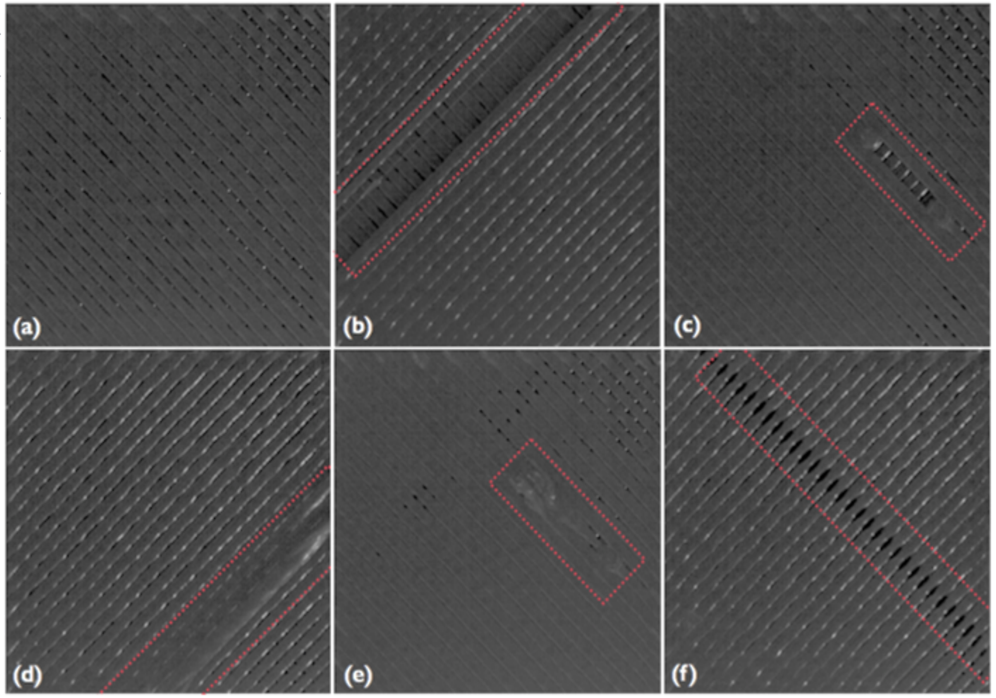


- 10.55 Mpix IDS UI-5490SE-C-HQ camera mounting a 25 mm lens
- Spatial resolution =0,02 mm/pixel



- Textured images
- Image’s contrast is changing layerwise-because of road rotation (
at each layer)

Material: PLA
Filament diameter =1,75 mm
Parallelepiped with 100% infill
Filament Temperature =220 °C
Bed Temperature = 50 °C

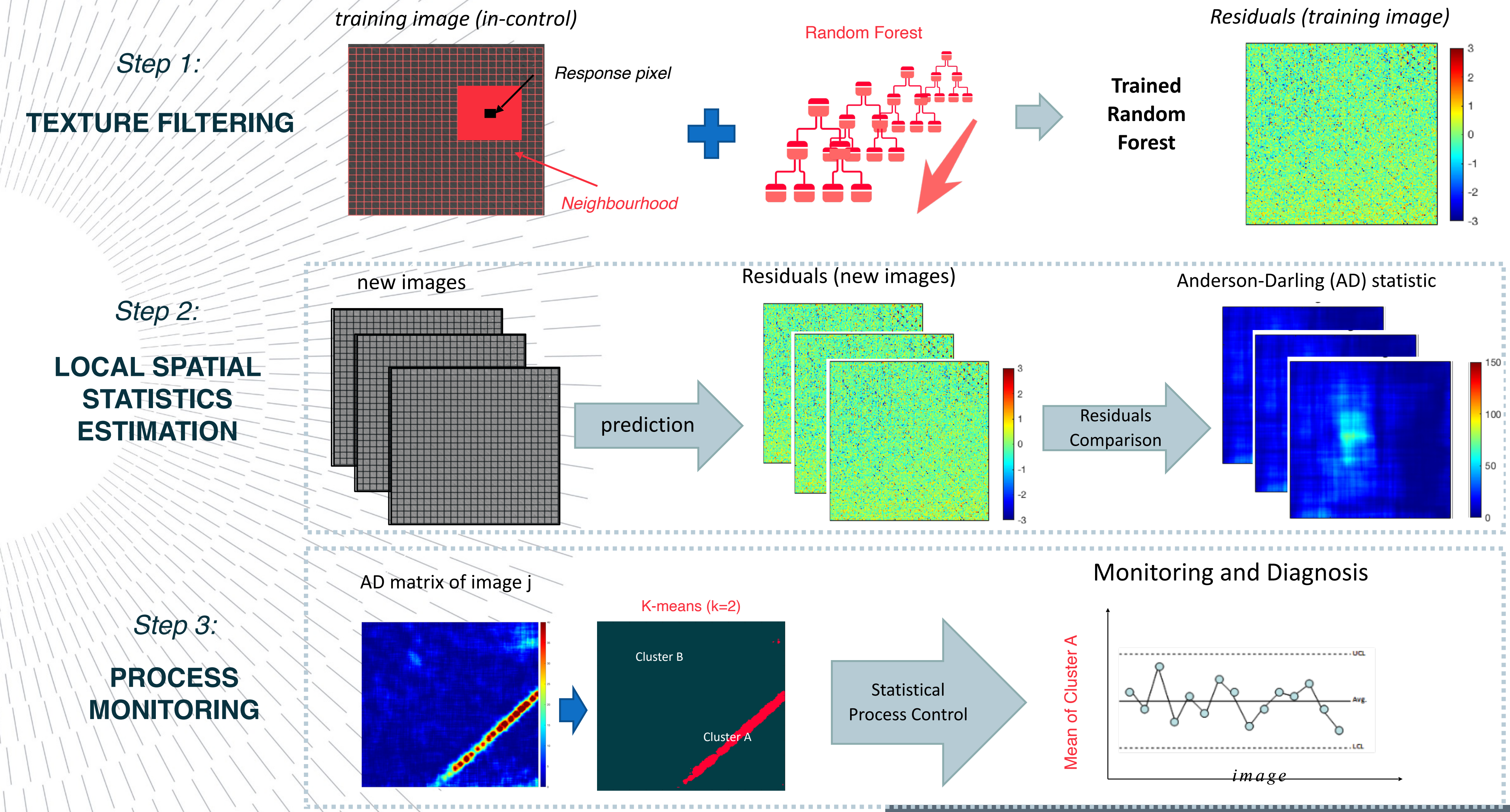


Different defects typologies

(a) In-control.
(b) Under-extrusion of the track.
(c) Partial under-extrusion of the track.
(d) Over-extrusion of the track.
(e) Partial over-extrusion of the track.
(f) Under-extrusion between tracks.

IMAGES: TEXTURED SURFACES

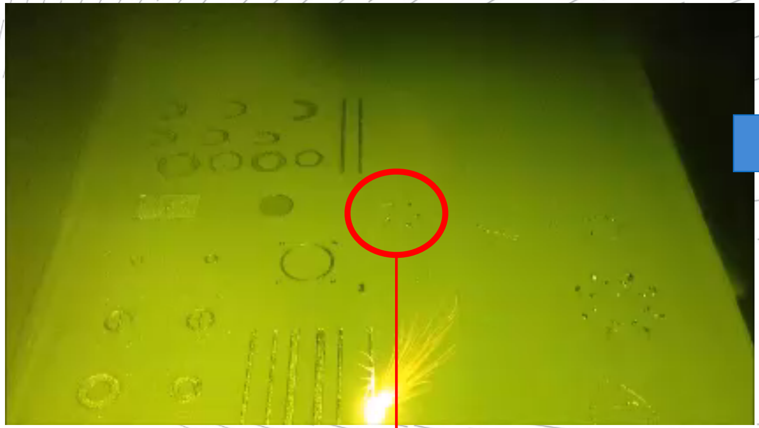
Inspired by Bui & Apley Approach (2018)

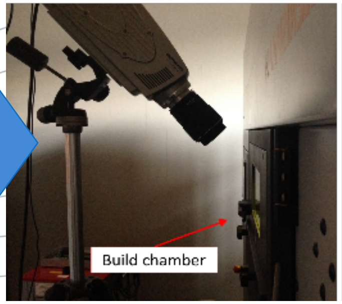


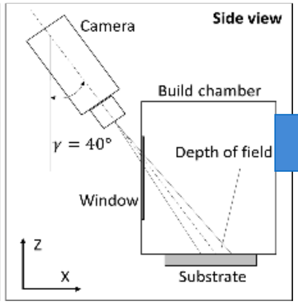
VIDEOIMAGES: HOT-SPOT

Colosimo and Grasso (2018), Journal of Quality Technology
Grasso et al. (2016), Journal of Manufacturing Science and Engineering

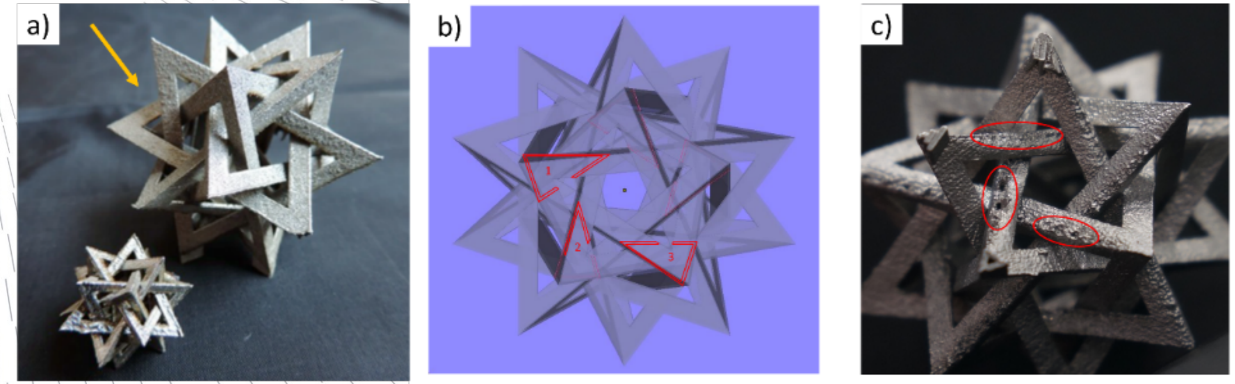
Example of local over-heating in down-facing acute corners (AISI 316L steel)





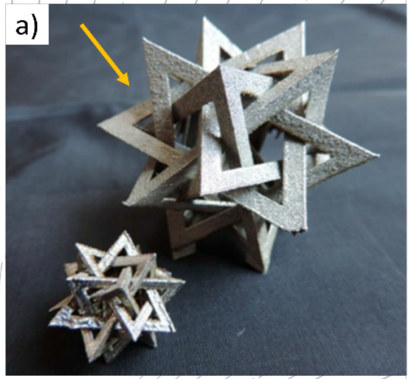


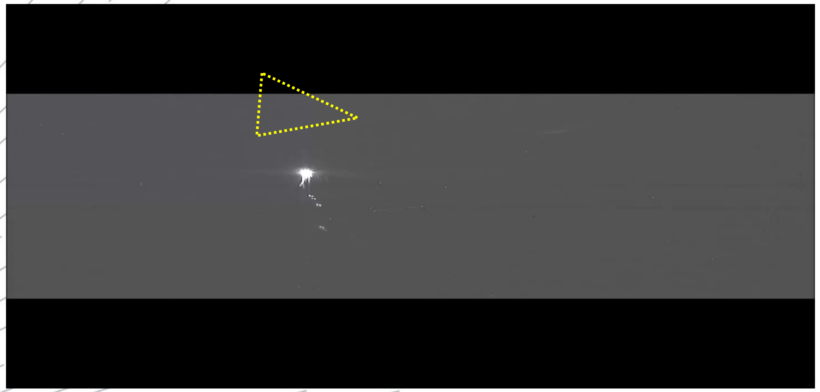
High-speed image acquisition (300 fps)



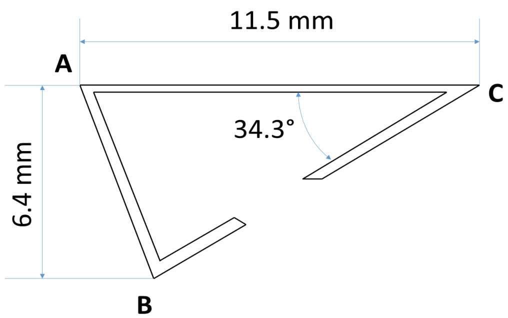
A hot-spot is a local over-heating caused by a dimished heat flux towards surrounding material

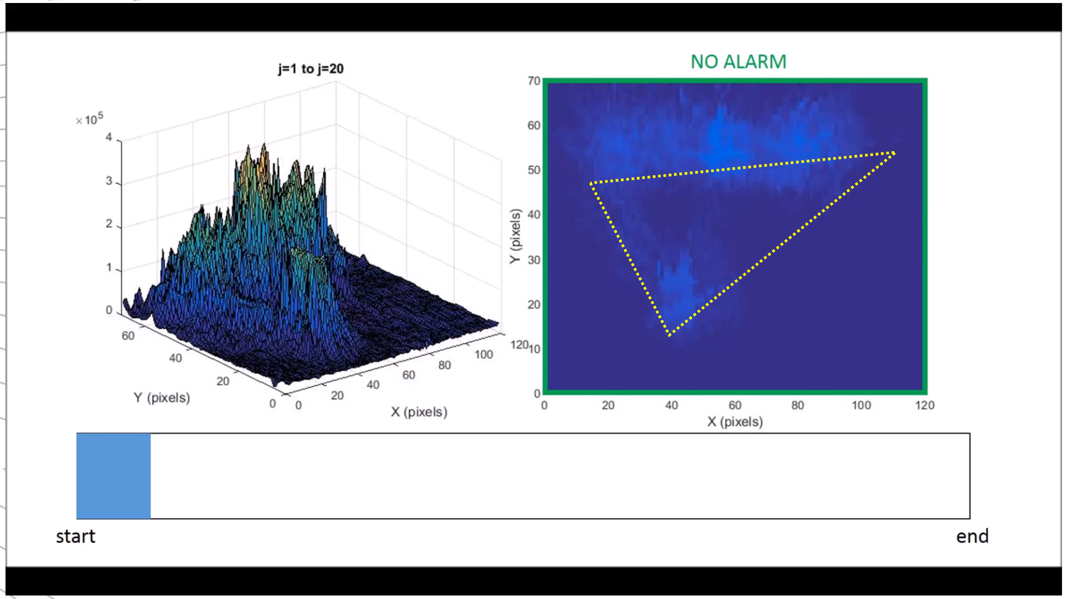
VIDEOIMAGES: HOT-SPOT



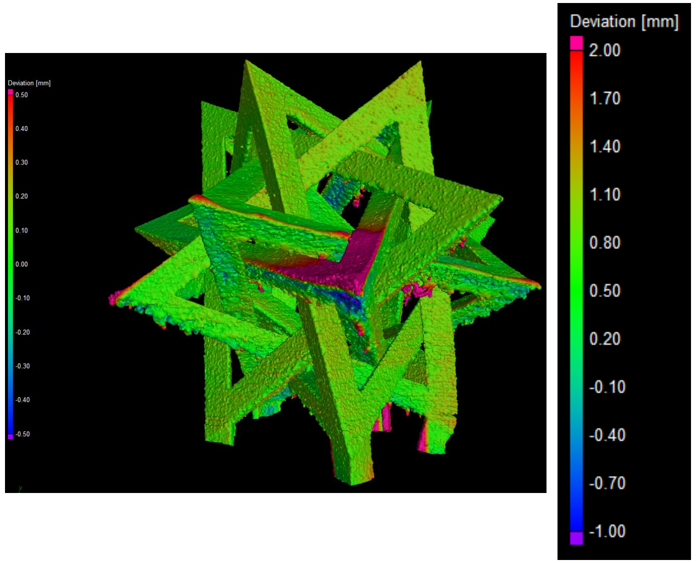


300 fps, visible range, Renishaw AM250





EX-SITU (XRAY CT)

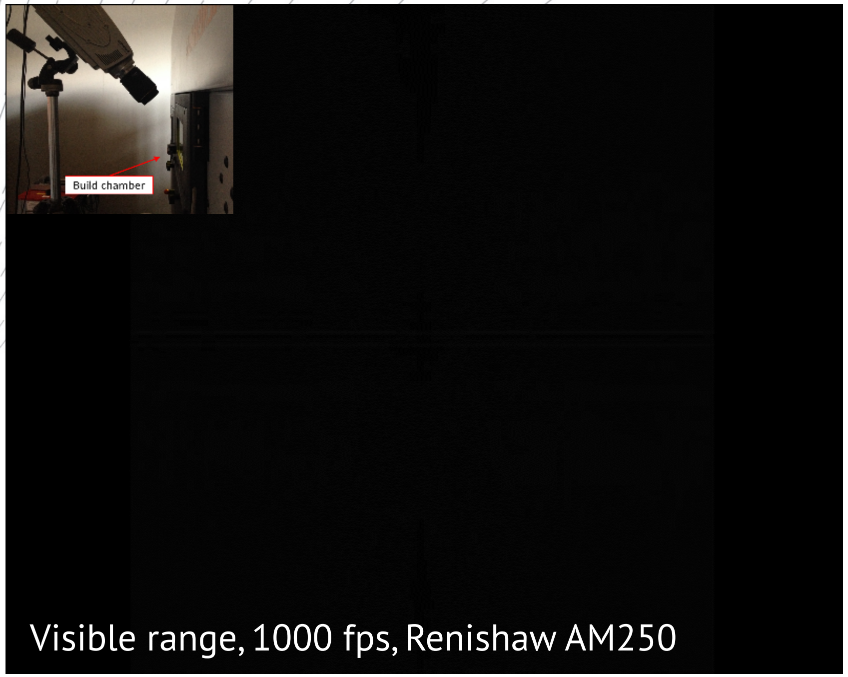


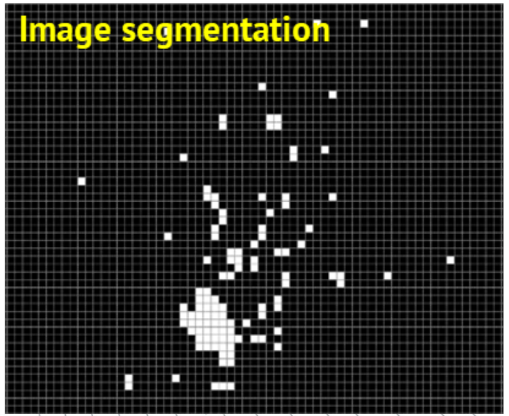
Spatially weighted PCA - Colosimo and Grasso, 2018 JQT **(data available!)**

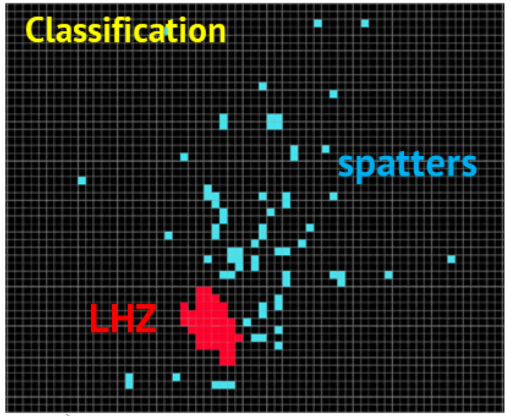
Spatio-temporal statistical process monitoring - Yan, Grasso, Paynabar & Colosimo - IISE Trans, 2022

Fast detection via NN and SVM - Bugatti and Colosimo - Journal of Intelligent Manufacturing, 2022

VIDEOIMAGES: SPATTERS



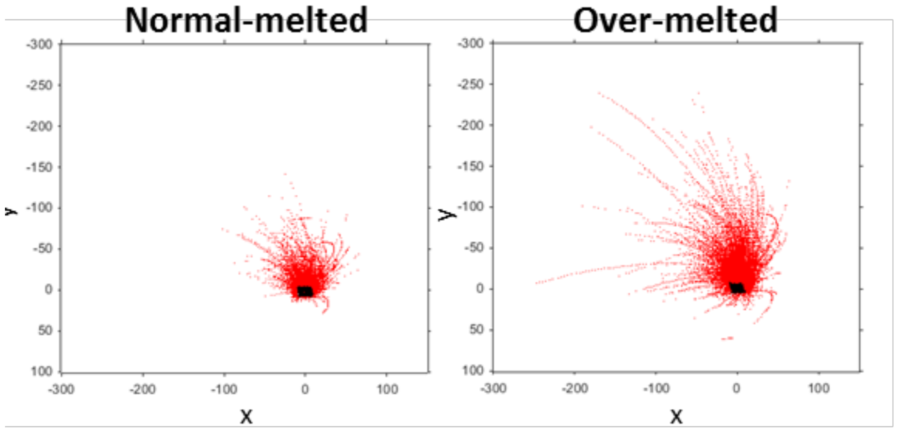


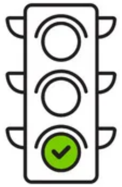


Repossini et al. (2017)

Spatter signature & part quality

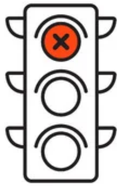
RED: spatters
BLACK: Laser

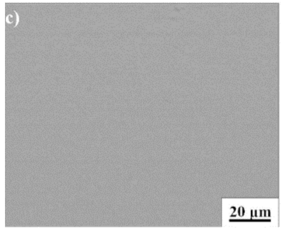


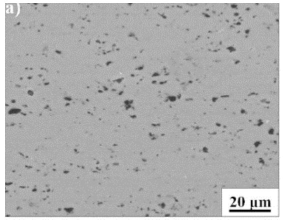


Good quality of the final part (fully dense)

Bad quality of the final part (keyhole porosity)



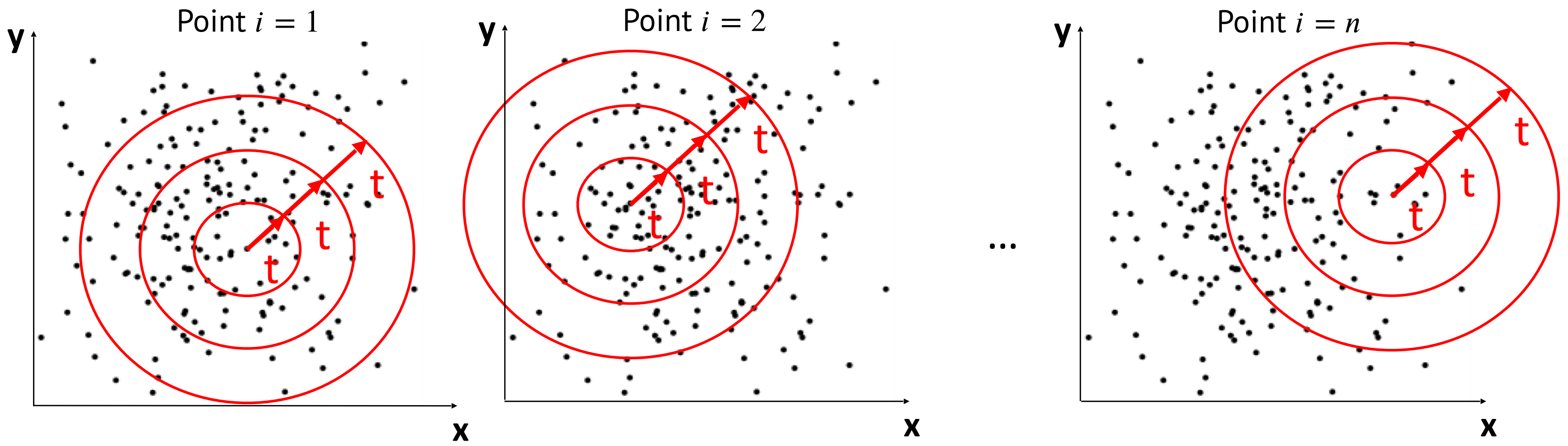




Colosimo et al, 2022
Journal of Intelligent Manufacturing

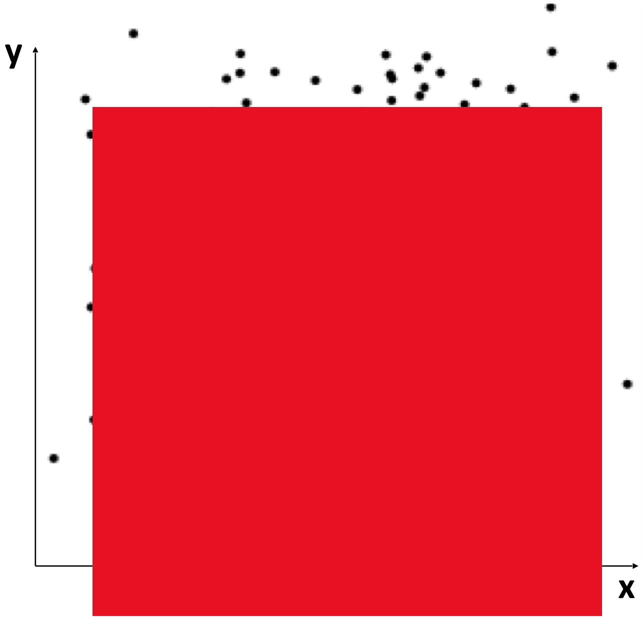
VIDEOIMAGES: SPATTERS
Modeling Spattering via K-functions

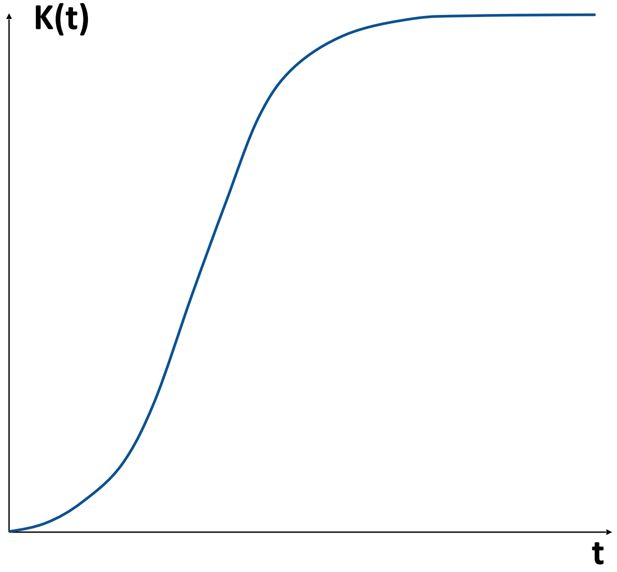
Ripley 1977,
Diggle et al. 2005



$$K(t)=\frac{1}{\lambda}\mathrm{E}\left(\begin{array}{l}\text{#extra points within}\\ \text{distance } t \text{ of a}\\ \text{randomly chosen point}\end{array}\right)$$

λ is the spatial density of points,
i.e., the number of points per unit area.



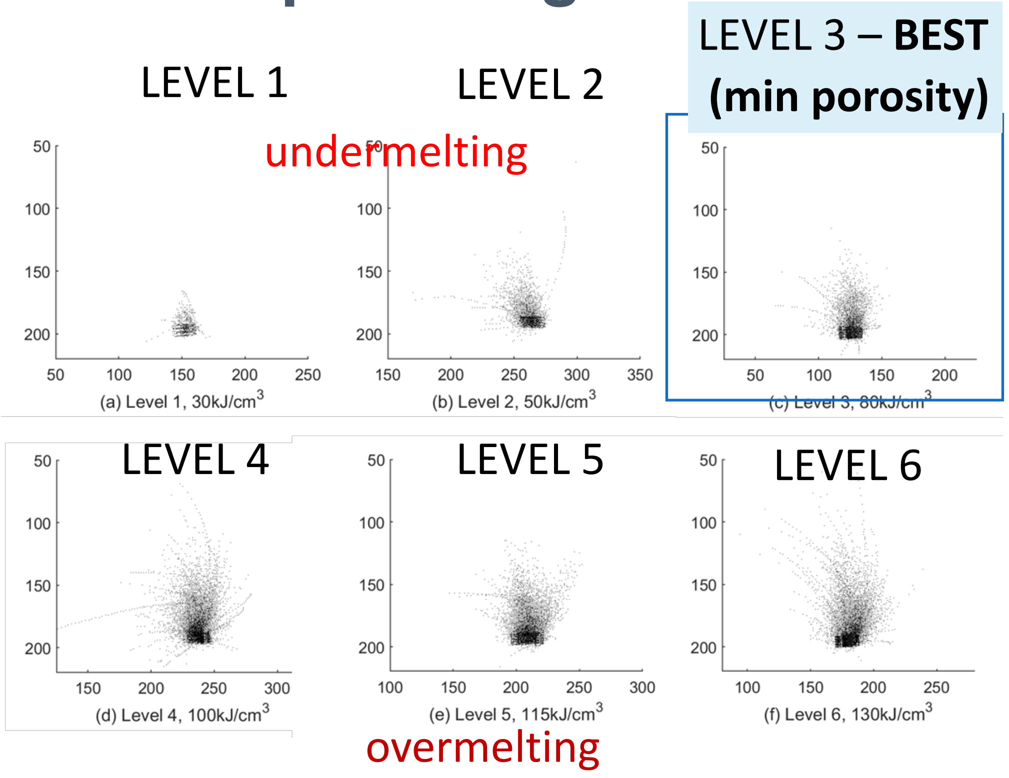


$$K(t)=\frac{1}{n^2}\sum_{(x,y)\in U}\mathrm{I}\big(0<d(x,y)\le t\big)$$

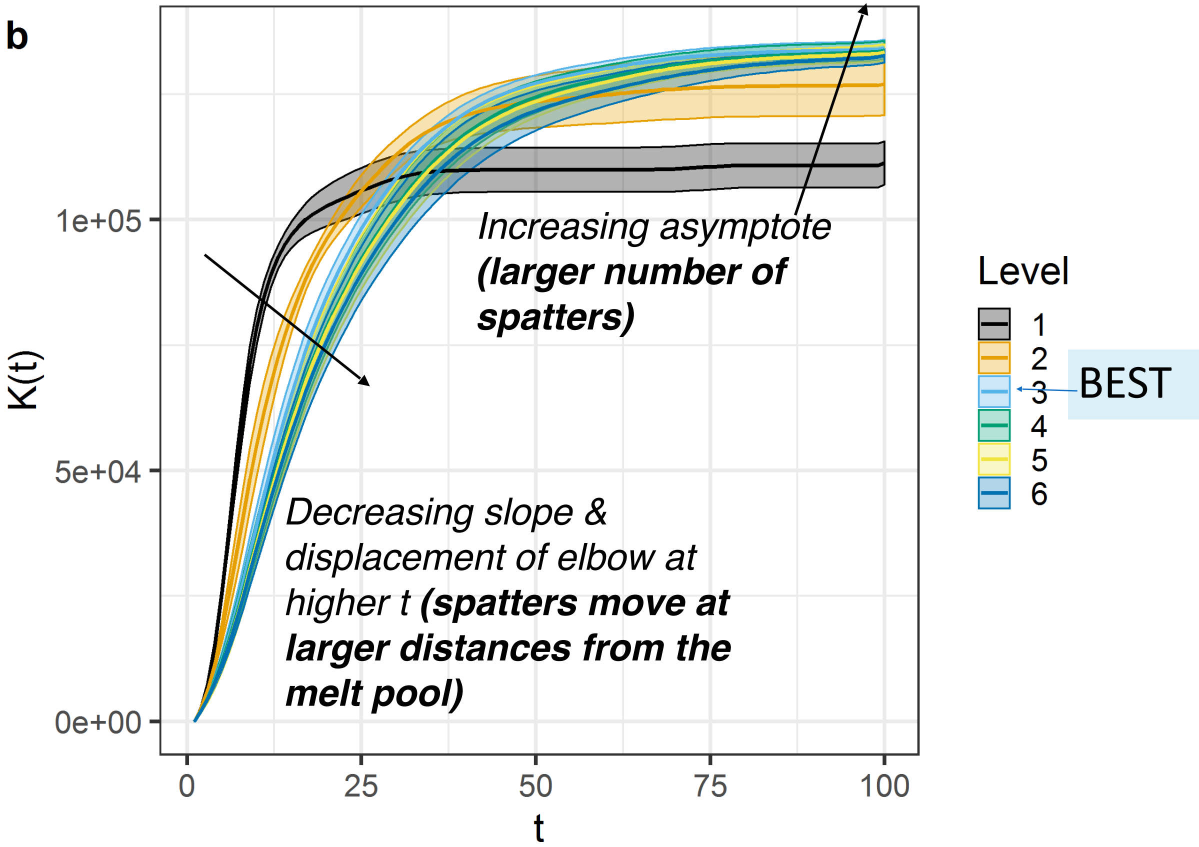
$$K(t)=\frac{1}{n^2}\sum_{(x,y)\in U}w(x,y)\mathrm{I}\big(0<d(x,y)\le t\big)$$

Edge correction (to cope with circles that may be not fully inside the domain U)

Spatter signature



K-function modelling



K-function fitting

A parametric model for ***non-decreasing*** functions was applied in the form:

$$K(t) = \beta_0 + \beta_1 \exp\left\{ \int_{t_0}^{t} W(u)du \right\}$$

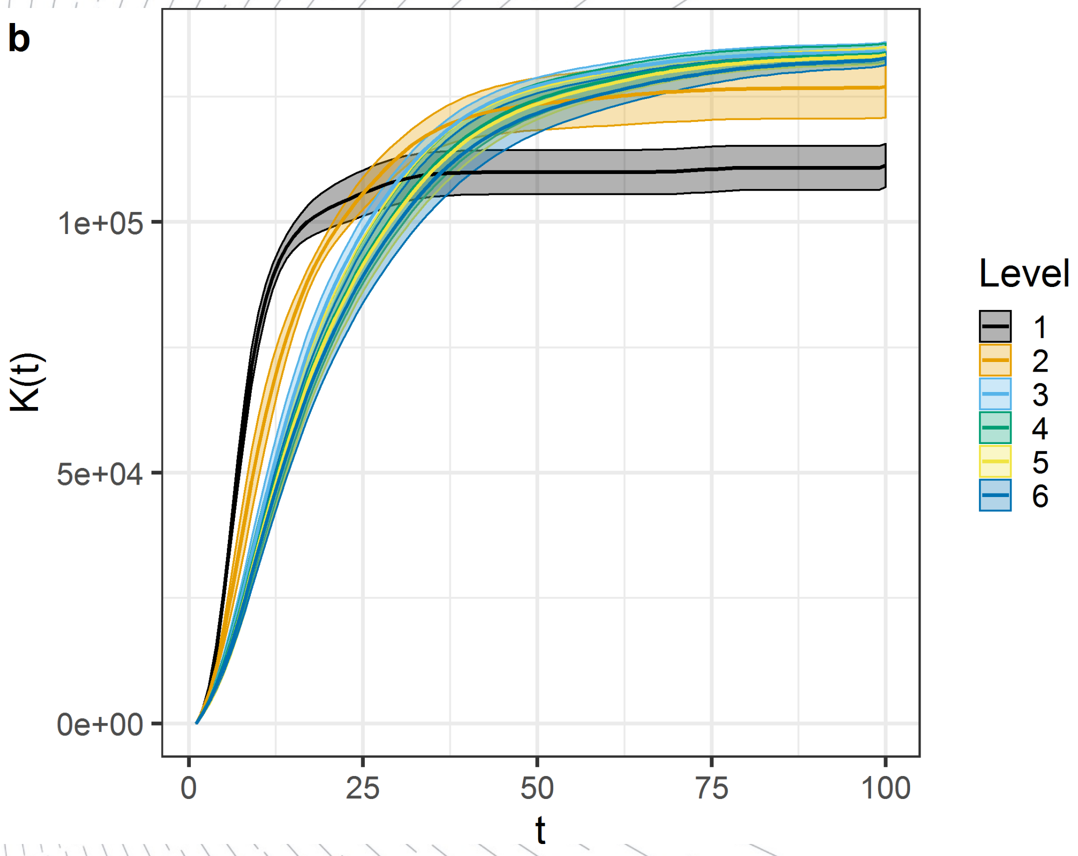
with $W(u) = \boldsymbol{\alpha} \boldsymbol{f}^T(t)$, where $\boldsymbol{f}(t)$ was fitted by means of 3° degree B-spline basis (equispaced knots)

Functional ANOVA (Ramsay, 2004)

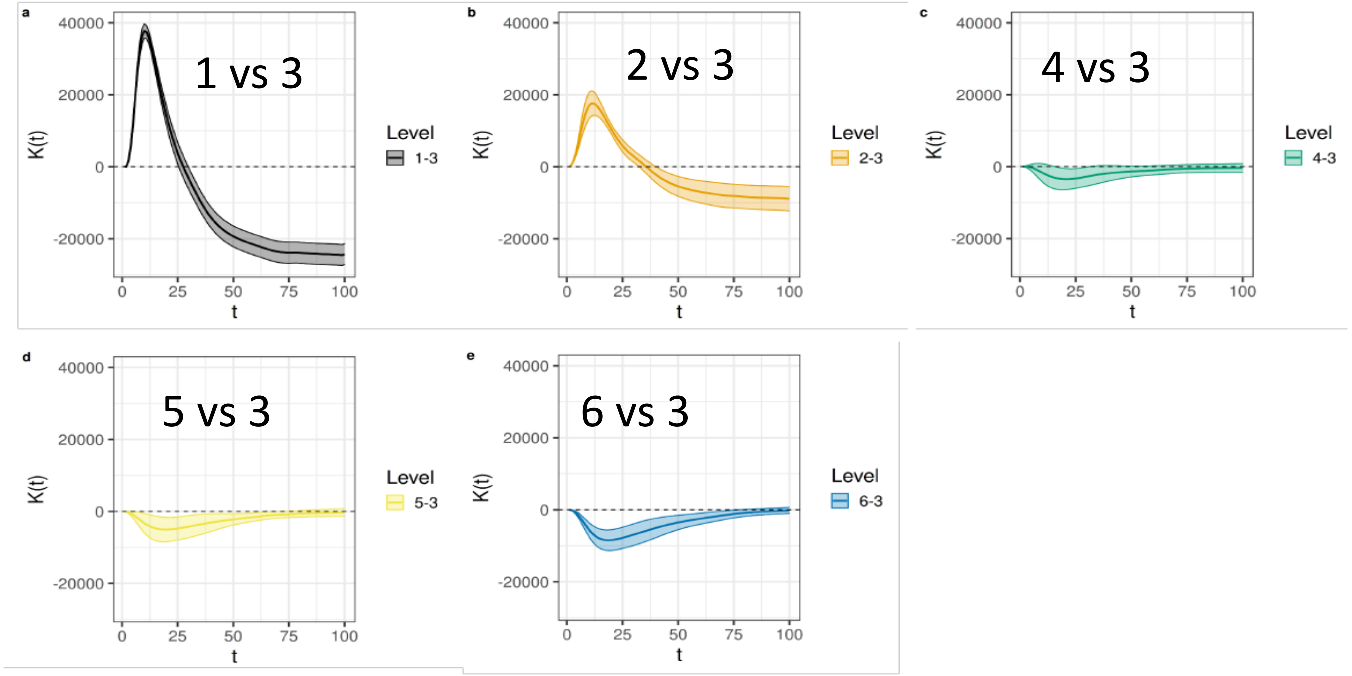
$$\begin{cases} H_0: \mu_1(t) = \mu_2(t) = \ldots = \mu_l(t), t \in T \\ H_1: \exists (i, j): \mu_i(t) \neq \mu_j(t), t \in T \end{cases}$$

where $\mu_1(t), \mu_2(t), \ldots, \mu_l(t)$ are the **functional mean responses** (mean K-functions)

Results



Contrast plot of k-functions (level 3 as reference)



The spatial signature of spattering (via **k-functions**)
to detect **all the departures** from the optimal condition

CONCLUSIONS

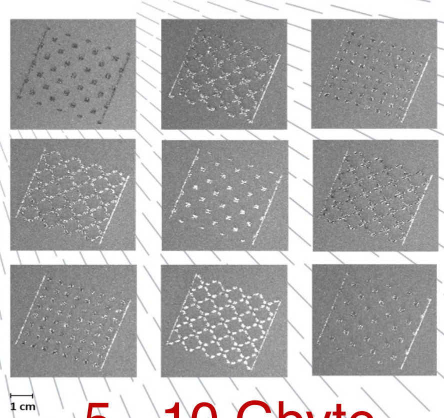
BIG DATA MINING and the twin transition

1. Digital vs GREEN:

Sensing, data storage, computation and data modeling are energy consuming tasks

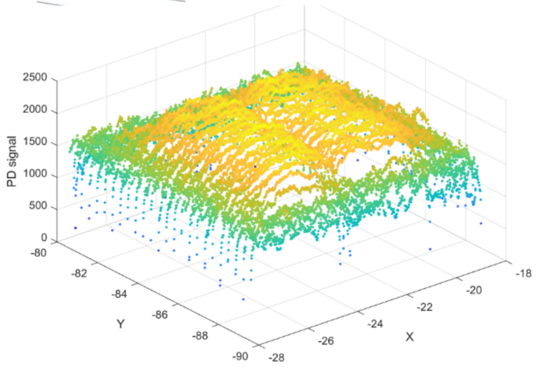
Example: data storage need for in-situ monitoring of a 24h build (2000 layers)

Layer Images



5 - 10 Gbyte

Co-axial photodiode

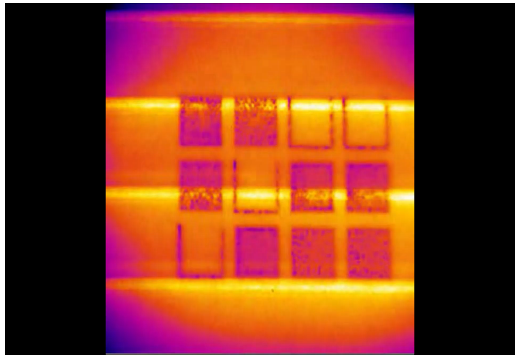


10 – 30 Gbyte

Off-axis high speed video (8 bit)

5 – 10 Tbyte

Off-axis high speed IR video



50 – 100 Tbyte

BIG DATA MINING and the twin transition

2. "BIG" DATA …. opportunity not the goal

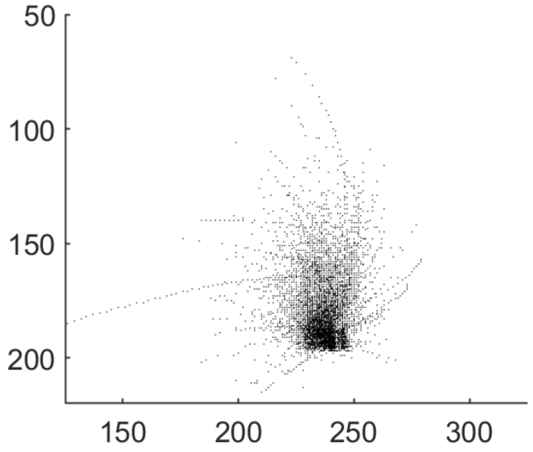
- Data reduction- Sensor and variate selection
- the simpler the better (Edge computing)
- Data fusion

The spattering example

High-speed video

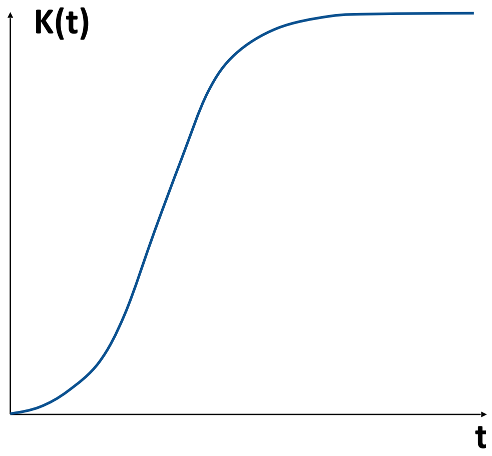
3.12 Gbyte

Spattering image from superimposed frames



432 Mbyte

K-function modeling



<1 Mbyte

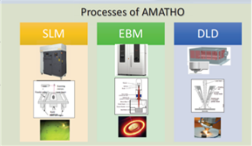
(txt file with fitted function + estimated coefficients)

BIG DATA MINING and the twin transition

3. DATA IS NOT INFORMATION, INFORMATION IS NOT KNOWLEDGE

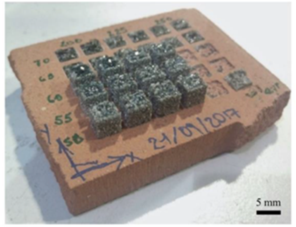
- Embedded out-of-control rule
- Robustness
- Interpretability
- Physics-based data modeling (e.g., multifidelity)

ESA benchmarck center – on structural integrity and in-situ monitoring



AMATHO - *A.dditive MA.nufacturing T.iltrotor HO.using* - https://www.amatho.org H2020- CleanSky 2 -

3D PRINTING OF LUNAR REGOLITH



Funded by the Italian Space agency

Some of our current research partners (running research contracts):

TRUMPF · LimaCorporate · Avio Aero · Baker Hughes · INGERSOLL Machine Tools

THANK YOU!

POLITECNICO
MILANO 1863

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@meccpolimi

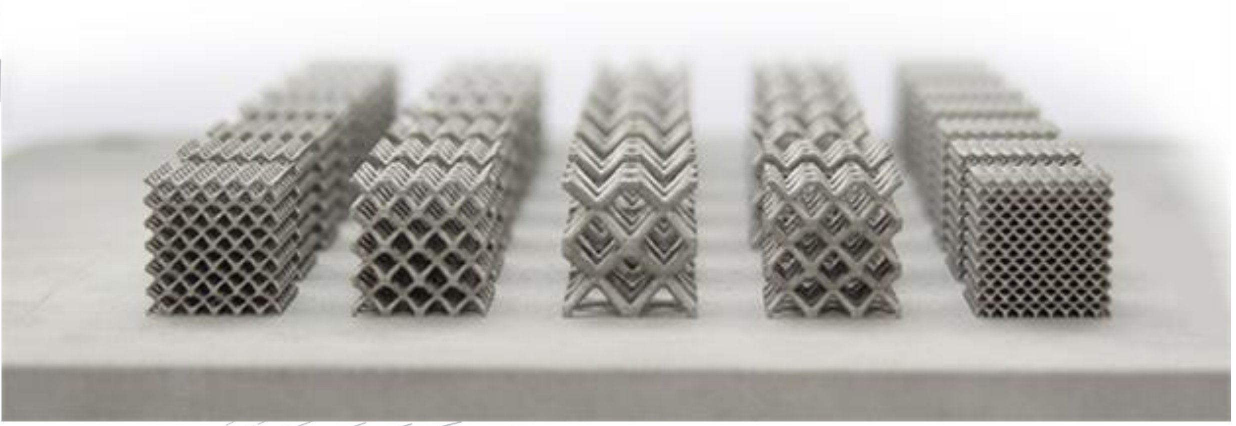
mecc

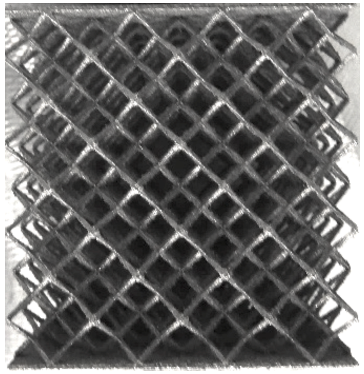
DIPARTIMENTO DI ECCELLENZA
MIUR 2018-2022

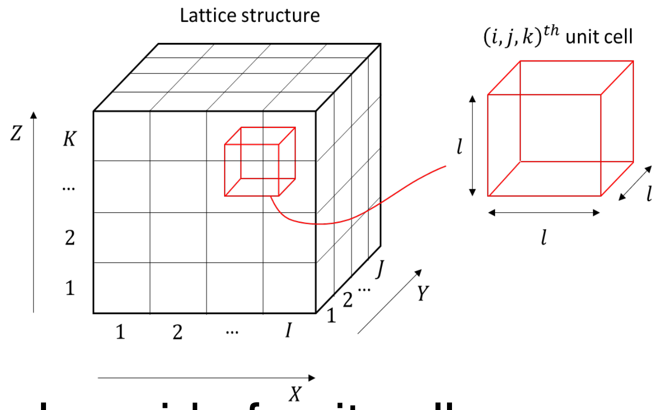
Additional slides

Product complexity: metamaterial or lattice structures

Colosimo and Grasso, JQT 2022 -ASQ Brumbaugh Award



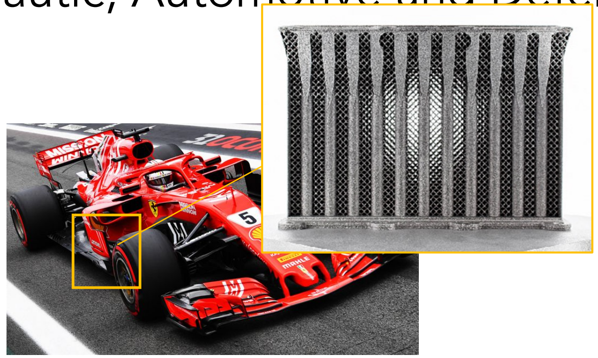




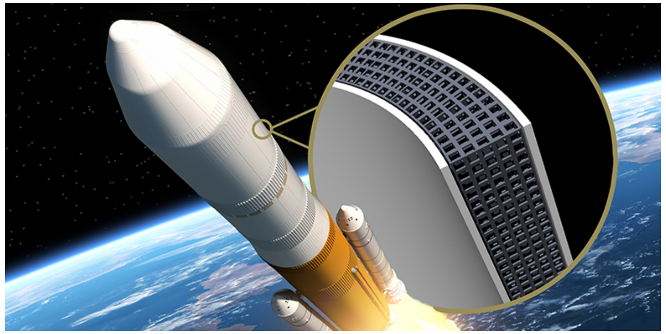
Lattice – a regular grid of unit cells

Main application: Aerospace, Aeronautic, Automotive and Defence sectors

Helicopter exhaust gas nozzle with integral cooling. (https://altairenlighten.com)



Lattice-filled turbo intercooler for racing car (https://altairenlighten.com)



Vibration absorbers - sandwich panels filled with a lattice core. https://powerandmotionworld.it/

Hip implant with cavities f medicinal deposits (https:/ www.fraunhofer.de/)

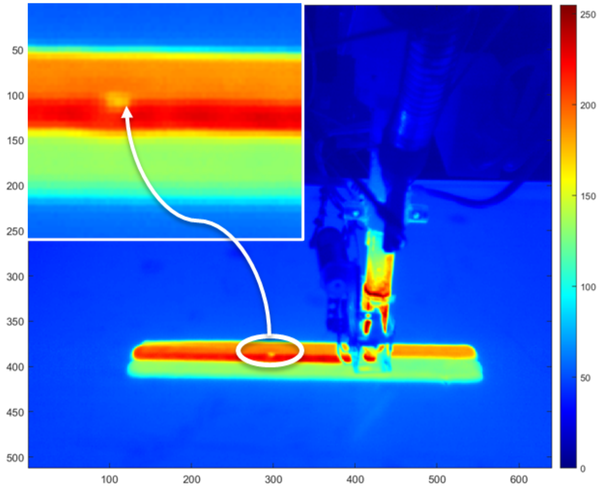
Ex3: Spatio-temporal modeling in thermal video imaging

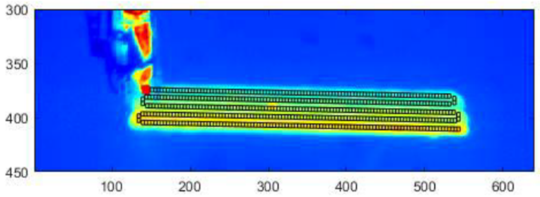



In collaboration with:
John Anastasios Hart , Gregory Dreifus

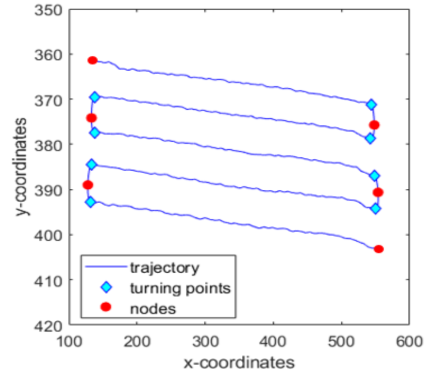
ABS +20% of carbon fibers; acquisition frequency Hz; temperature range: 20-250 °C

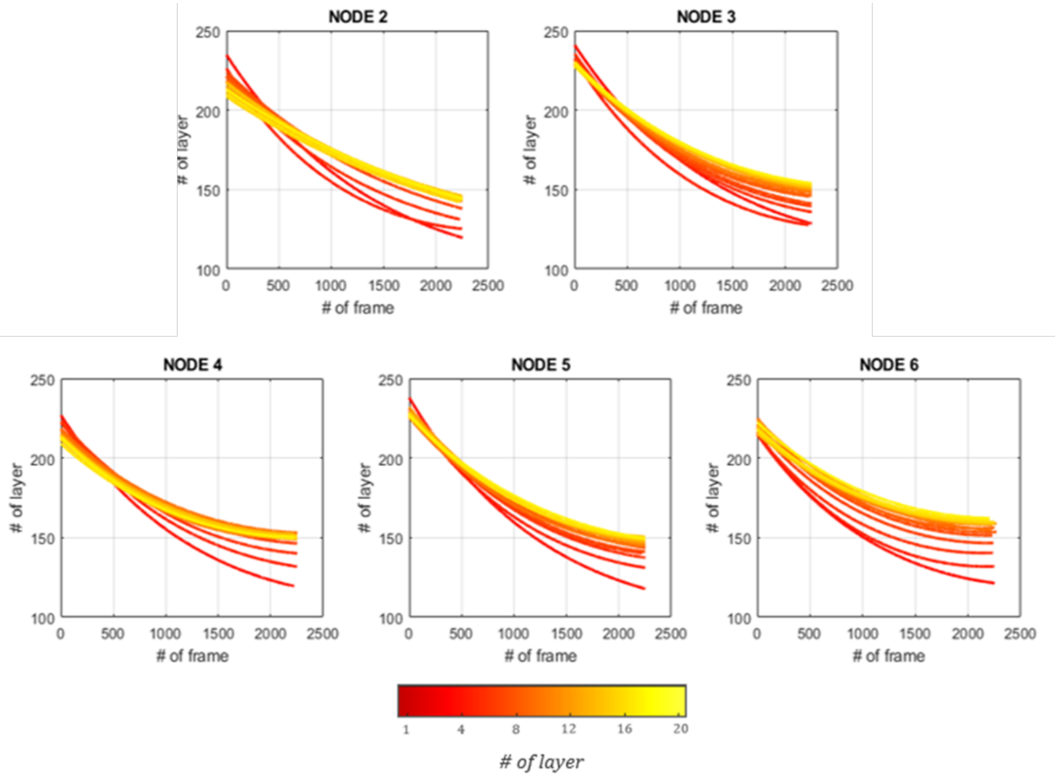
Potential lack of material bonding
(layer 3)





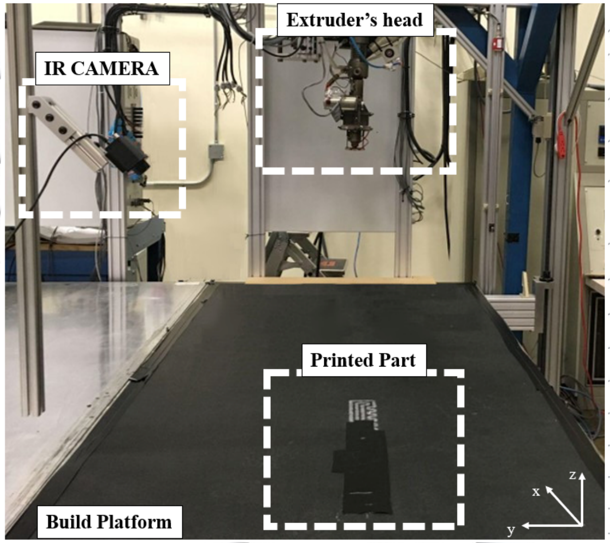
Spatial arrangement of temporal profiles (i.e., time series)

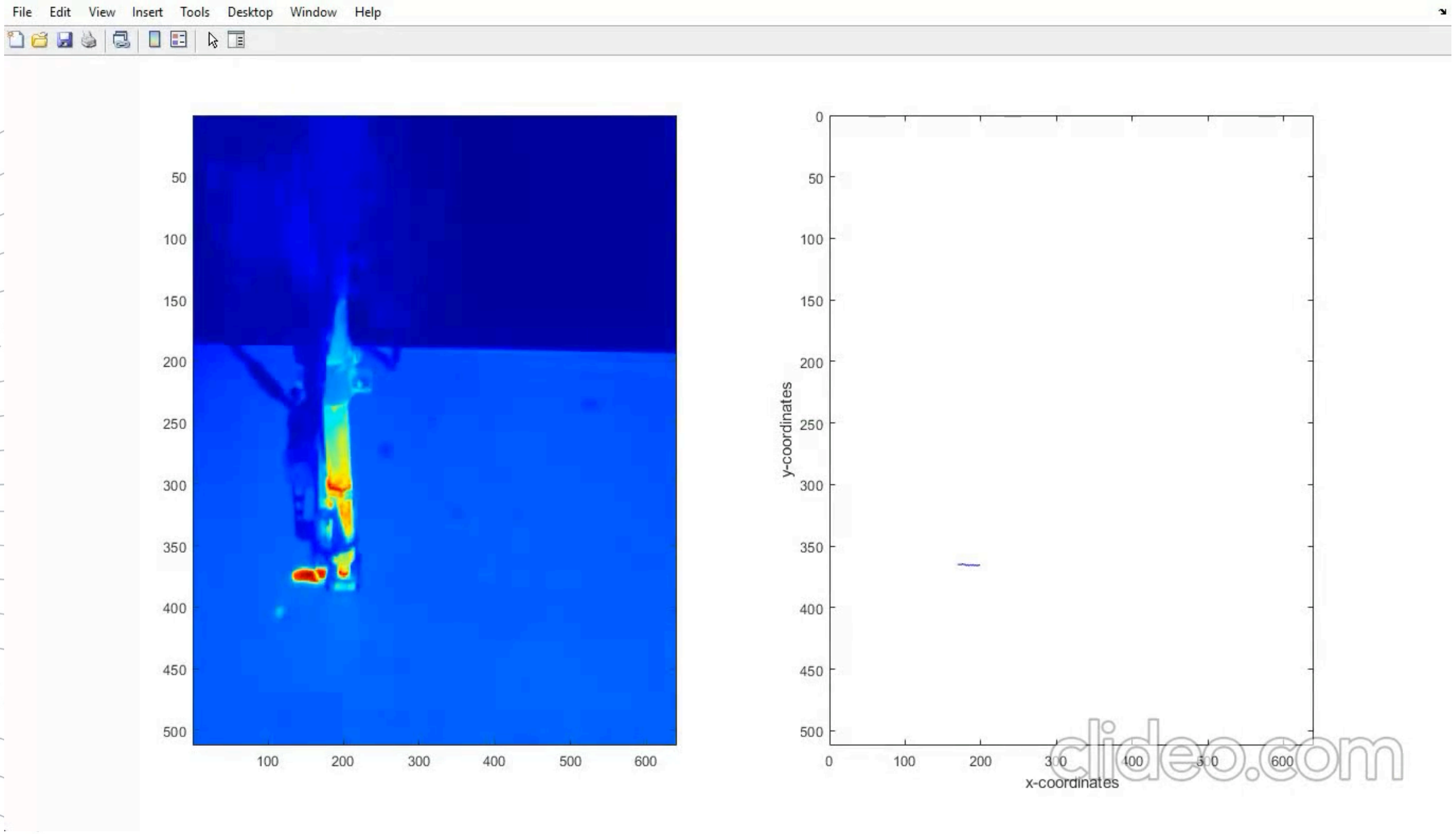




OBJECTIVES:
- Thermal profiles (as a function of location and time)
- In-line Cold/hot spot detections

In-situ thermal monitoring for Big Area Additive Manufacturing (BAAM)

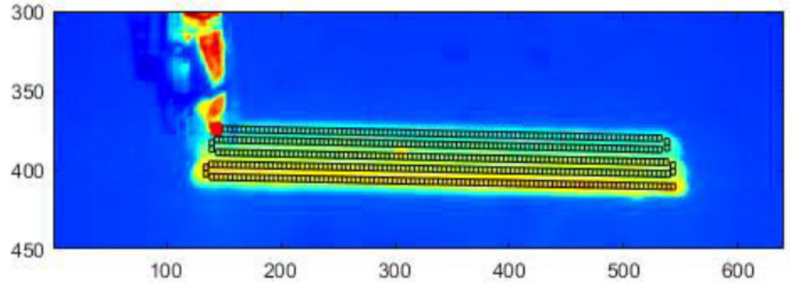




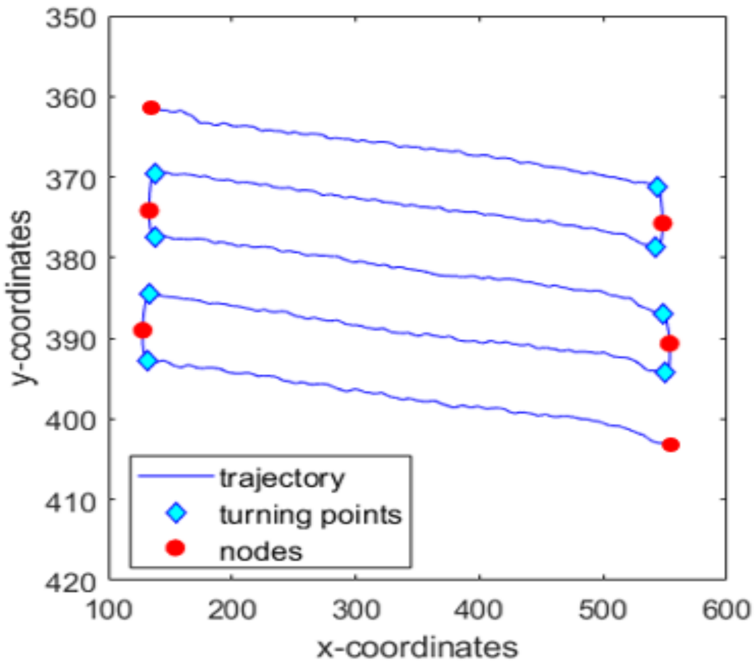
- Camera model: FLIR A35 (FLIR® Systems Inc)
- Acquisition frequency: 30 Hz;
- Temperature range: 20-250 °C
- Optics focal length: 25 mm
- Temperature accuracy: 5°C
- Spatial resolution: 3 mm/pixels

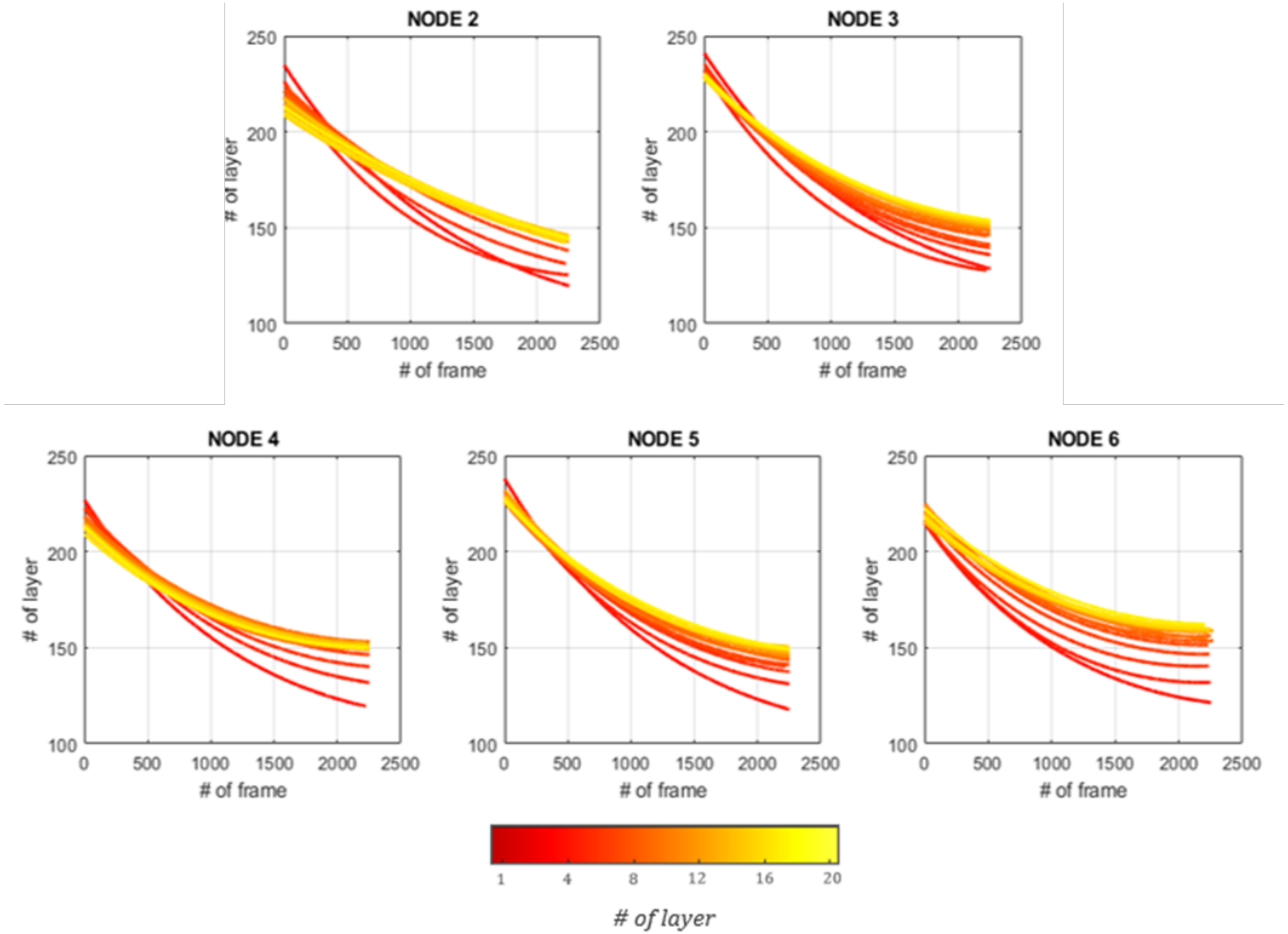
Collaboration among:

Cooling profiles change as a function of the location

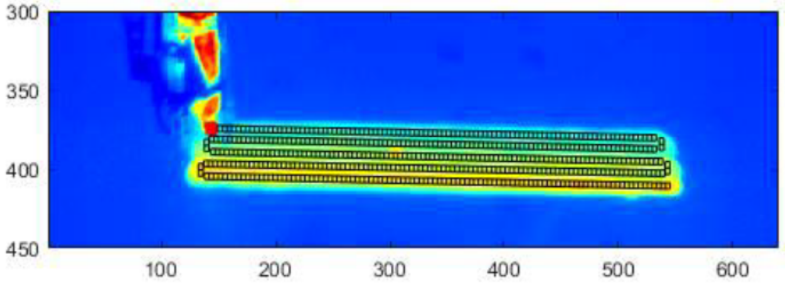


Spatial arrangement of temporal profiles
(i.e., time series)

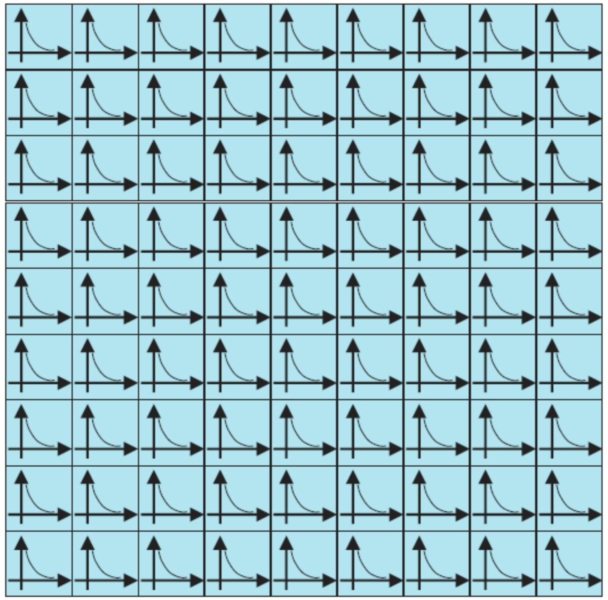




Spatial-temporal indicator

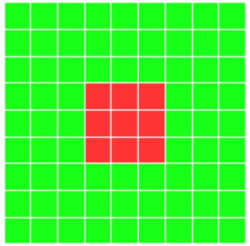


Spatial arrangement of temporal profiles

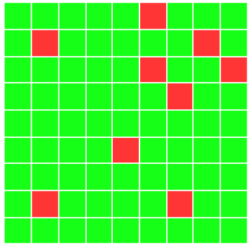


9x9 Matrix of
Temperature profiles

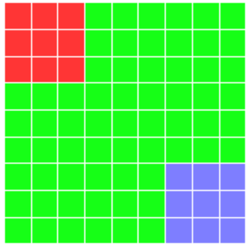
3 defective scenarios:



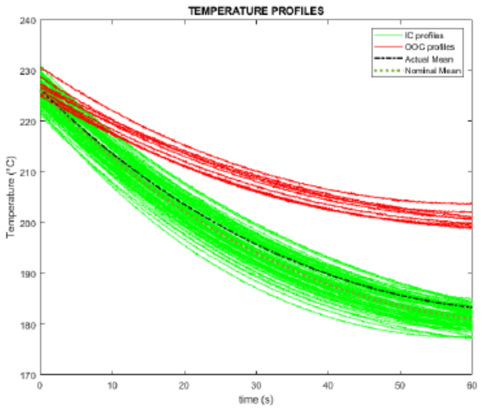
Single cluster



Sparse Defects



Two Clusters



Defect = alteration of cooling rate

Sensitivity analysis

Alteration intensity: Low — Medium — High

Number of defects: One — Few — Some — Many

Moran index (spatial association) for profiles similarities

Colosimo, Caltanissetta, Carraro, 2022

Z index (Gao 2019)

Expresses deviation of a profile from average profile

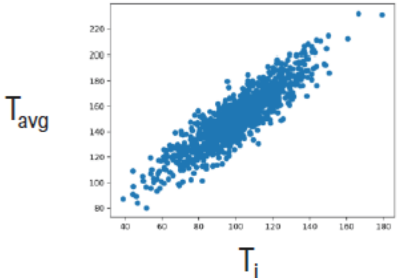
$$Z_i = \boxed{\varphi\left(CORT(\vec{T_i}, \overrightarrow{T_{avg}}) \right)} * \boxed{(area(\vec{T_i})\text{-area}(\overrightarrow{T_{avg}}))}$$

Deviation in terms of profile shape

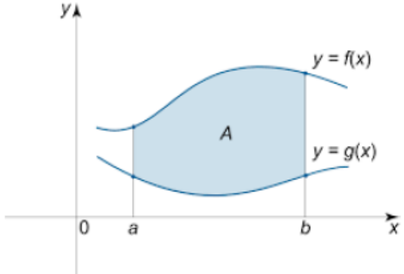
"CORT component"

Deviation in terms of magnitude

"Area difference component"



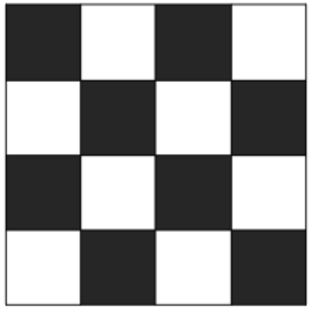
Similarity of profile pattern



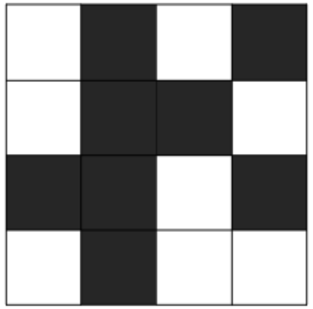
Similarity of profile location

Local Moran's I (Anselin 1995)

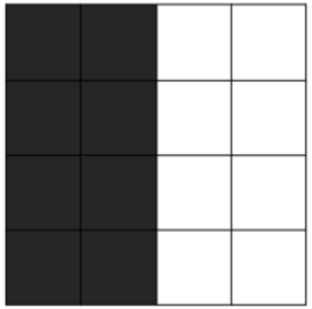
Expresses association between neighboring elements



Moran's I < 0



Moran's I ≈ 0



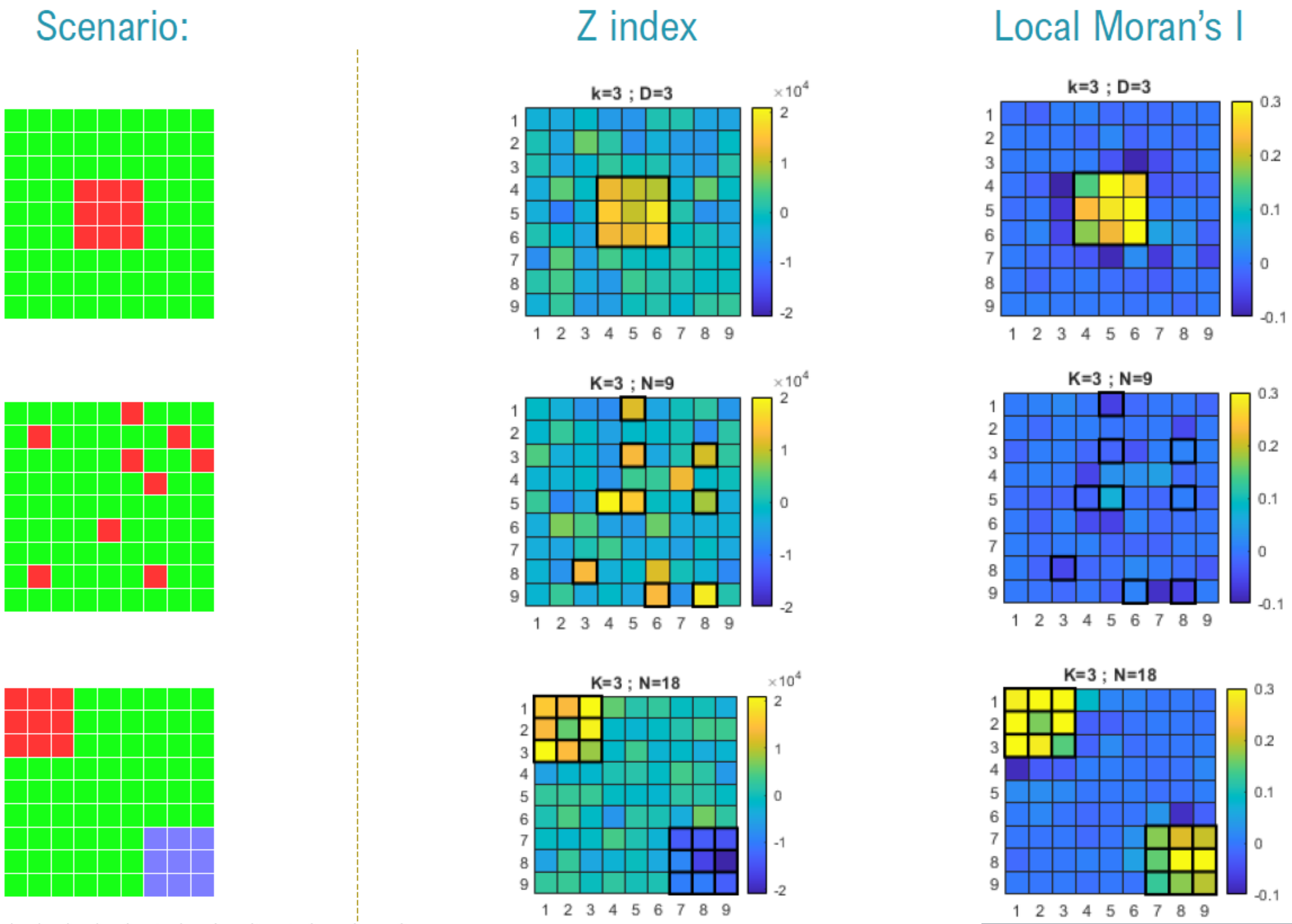
Moran's I > 0

Inputs:

- ➢ Spatial coordinates of each cell
- ➢ Indicator of deviation from mean (Z INDEX)

Monitoring Spatio-temporal profiles

Colosimo, Caltanissetta, Carraro, 2022



Both the metrics highlight defective profiles when they are clustered

Only the Z-index can detect randomly sparse anomalies of the cooling profiles

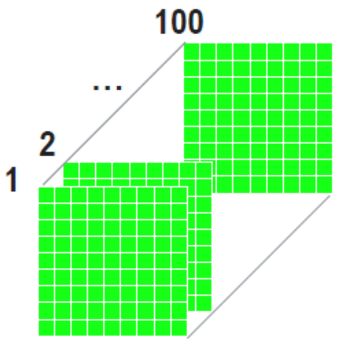
Moran index can clearly highlight clustered events on cooling profiles

Control charting

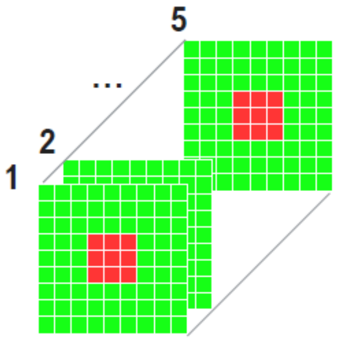
Approach

Global Metrics:

- Global Moran's I
  (mean of all Local Moran's I)
- Mean Z index
  (mean of all Z indexes)

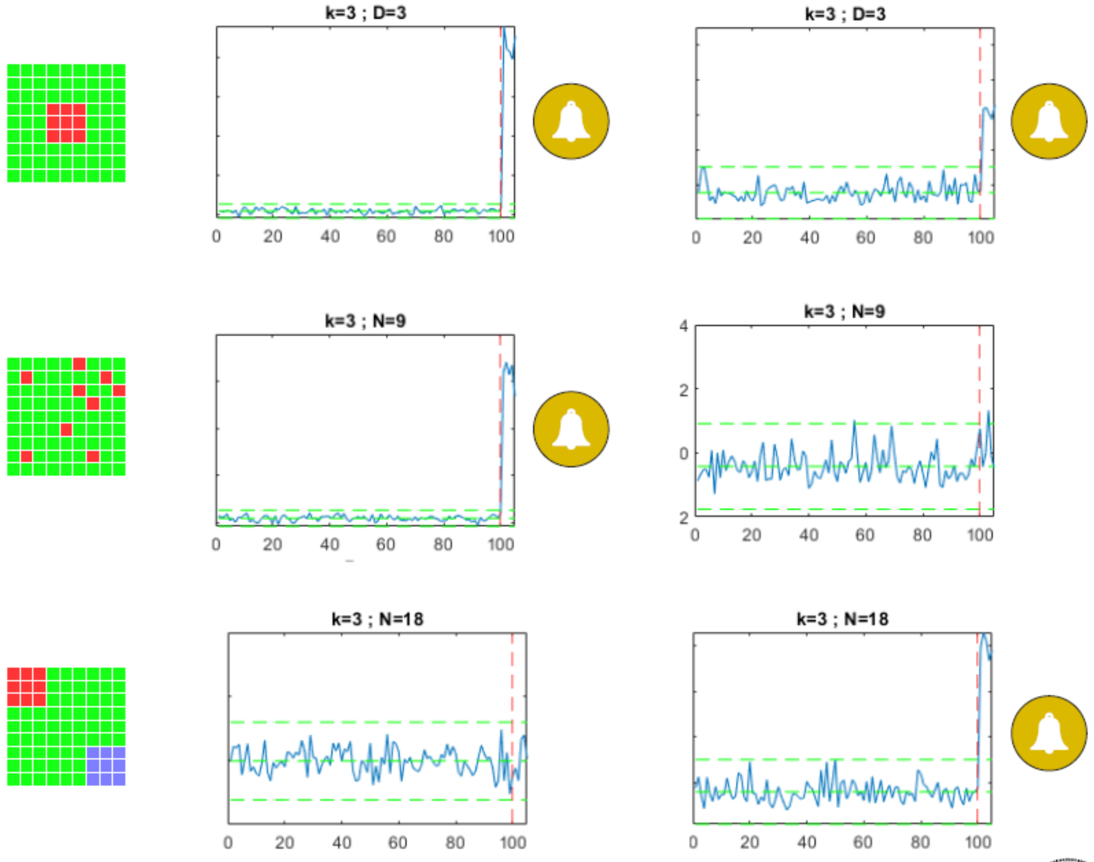


Build CC for global metrics on 100 IC matrices



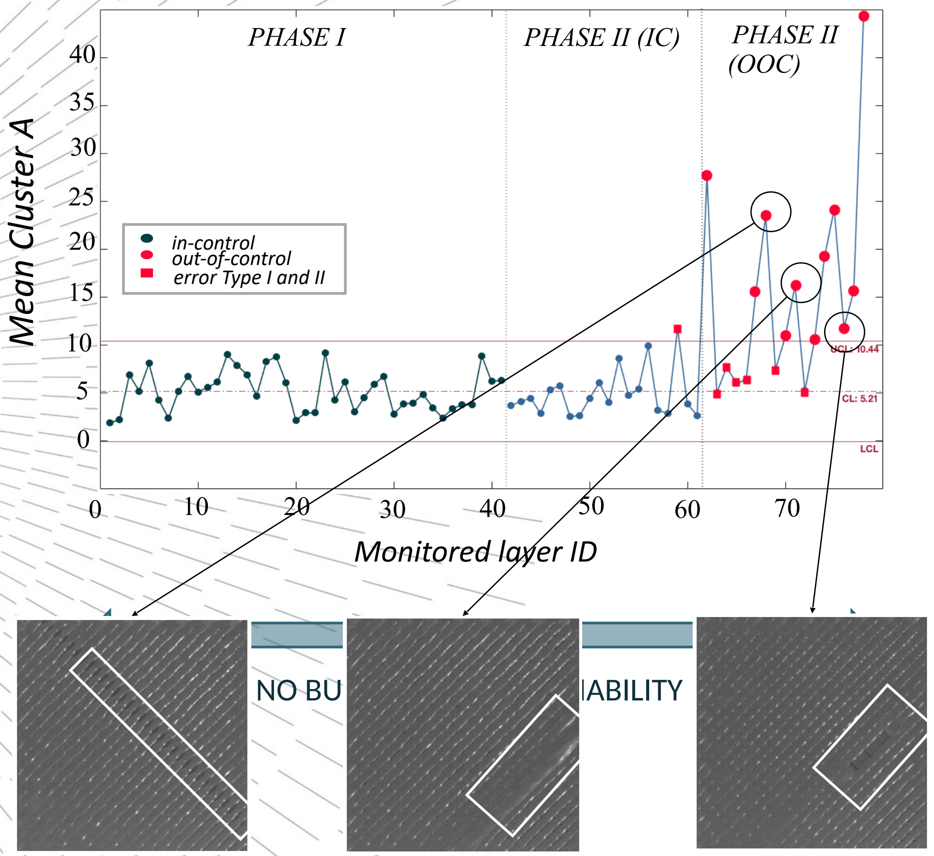
Test CC performance on 5 defective runs

Results



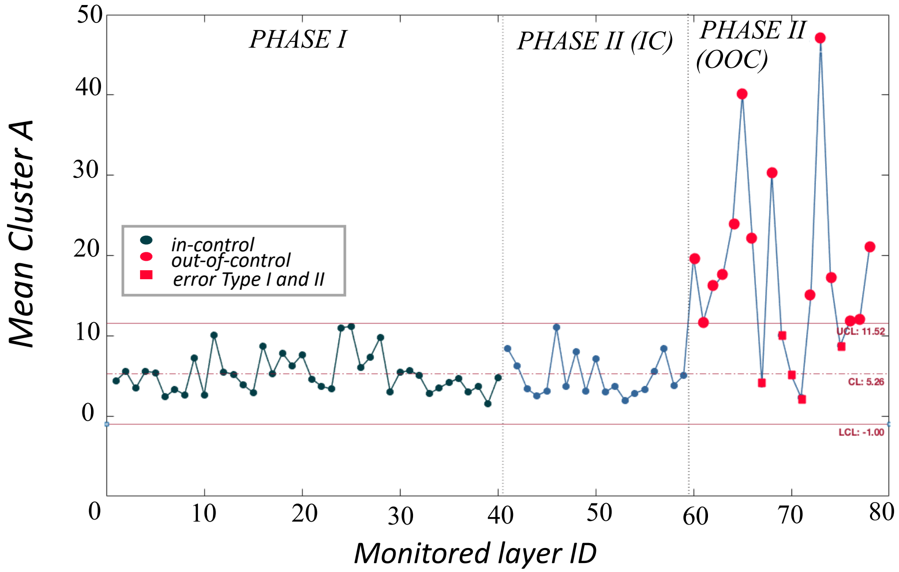
Comparison between methodologies
Monitoring stage: Proposed Approach

45°



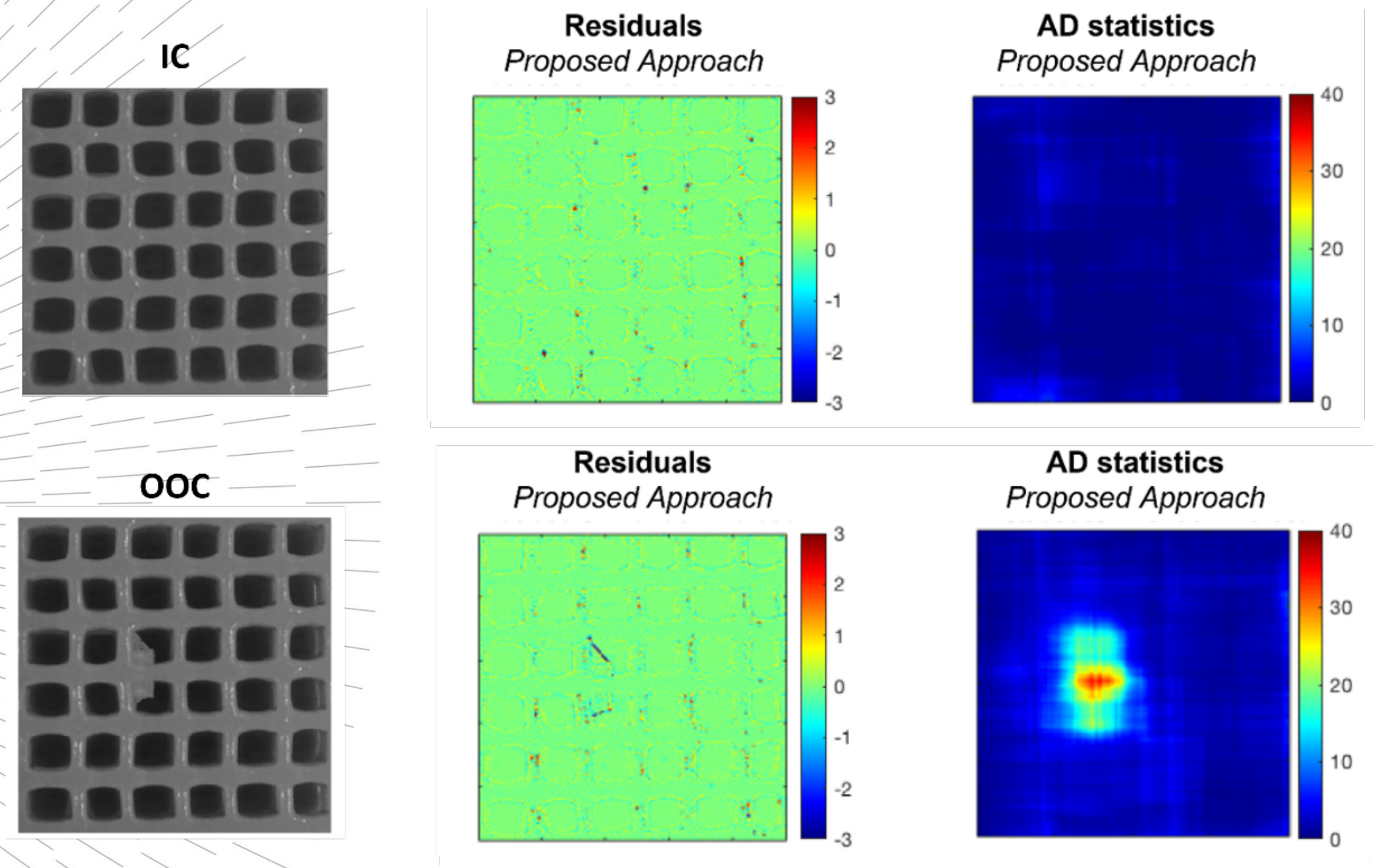
NO BU IABILITY

135°



NO BUILD-TO-BUILD VARIABILITY

Application of the procedure to lattice-like structures (bioprinting)



Examples of IC and OOc images for a lattice-like structure. Each rows reports the original image, the residual model and the AD matrix

Spatially weighted PCA