Spatio-temporal detection of defects is SLM by using in-situ high-speed vision

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AddMe.Lab

AddMe.Lab – Additive Manufacturing lab @ Department of Mechanical Engineering (Politecnico di Milano)

Who we are

Three Full Professors

Prof. Q. Semeraro

Quality Control & Process optimization

Prof. B.M.Colosimo

Process monitoring & quality Control

Prof. B. Previtali

Laser processes

Two Assistant Professors

Ali G. Demir

Laser processes

Marco Grasso

Process monitoring & quality control

Seven PhD students and research assistants







Giulia Repossini
Stefania Cacace
Giorgia Galimberti
Marco Montani
Claire Bruna Rosso
Chiara De Giorgi
Vittorio Laguzza

AddMe.Lab – Additive Manufacturing lab @ Department of Mechanical Engineering (Politecnico di Milano)
Processes and technologies

Powder Bed Fusion (PBF)

- Renishaw AM 250
- 250x250x300 mm^3
- AISI 316L, Maraging, CoCr, Al, Ti…

Selective Laser Melting

- Prototype α version (β under development)
- 50x50x15 mm^3
- Materiali: Zn, Fe, AlSi12, AISI 316L, blends…

SLM Prototype

- Arcam (A2)
- 200x200x180 mm^3
- Ti6Al4V

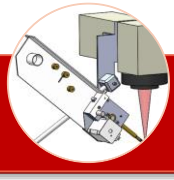
Electron Beam Melting

Direct Energy Deposition (DED)

- 6 dof ABB Robot arms- Fiber laser source (IPG, 1kW – 3kW)
- Coaxial deposition head
- AISI 316L, Inconel 625 & 718, Stellite 6 & 21

Laser DED - powder

- PowerWeld workstation
- Source: Trumpf Nd:YAG
- Microlaser deposition
- AISI 301, Al Si12



Laser DED - wire

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Post-process and metrology equipment

- Kern EVO 5 axis CNC machining center
- GF Mikron5 axis machining

Post-processing machining

- X25 North Star Imaging
- X-ray computed micro-tomography

X-ray CT

- Alicona Infinite Focus
- Mahr Perthometer PGK

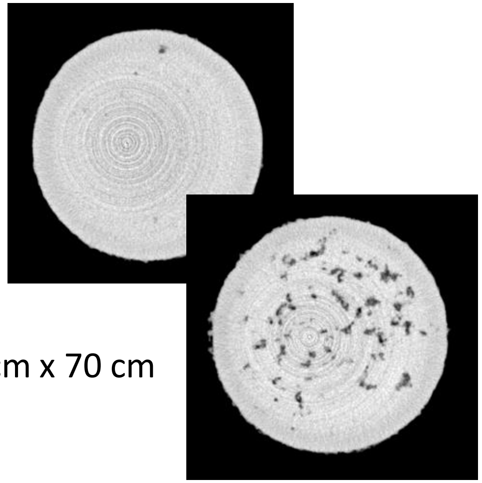
Surface topography and roughness

- Zeiss Prismo 5 Coordinate
- Mahr Surf CWM 100

3D dimensional measurements

NSI x25 system

- Maximum Power: 160 kV/0W
- Nominal resolution < 1mm
- Max sample volume: 15 cm x 20 cm x 70 cm
- Max weight: 11 Kg
- Detector: 149 mm x 119 mm



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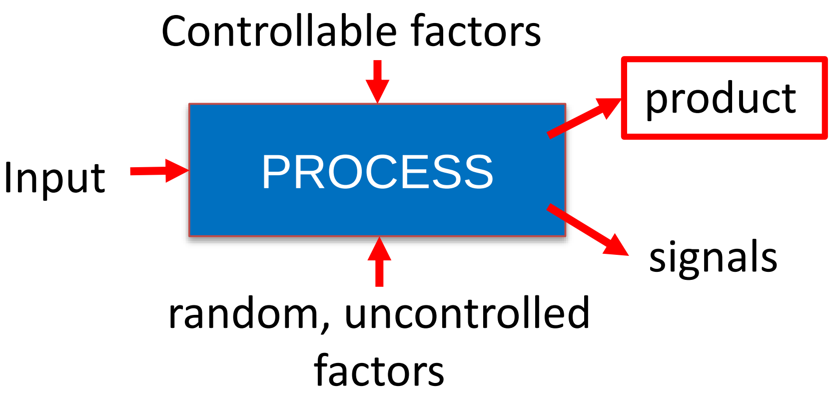
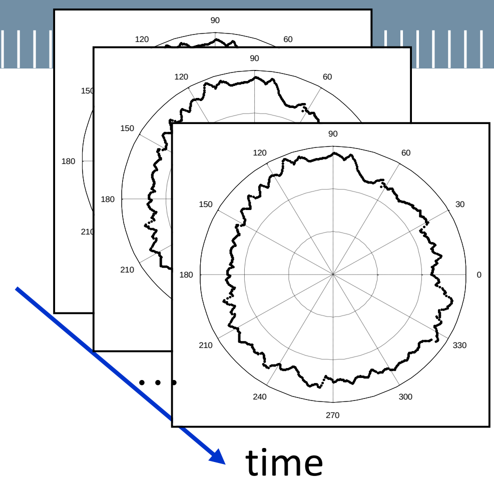
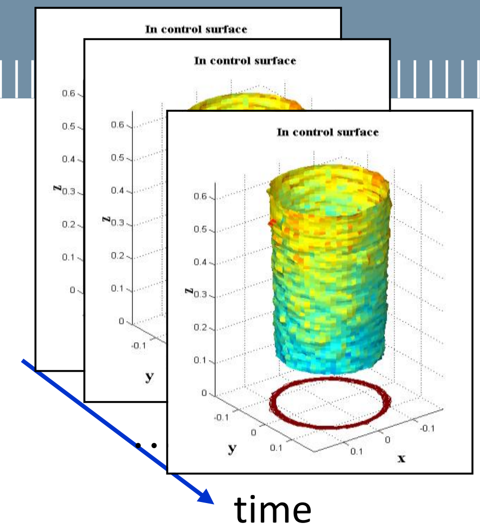
Statistical monitoring of PRODUCT and PROCESS data

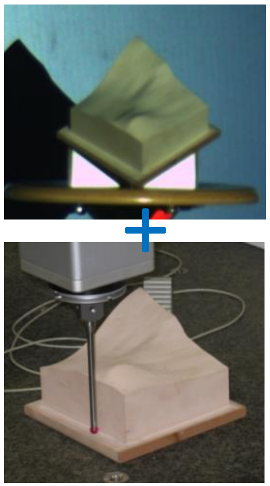




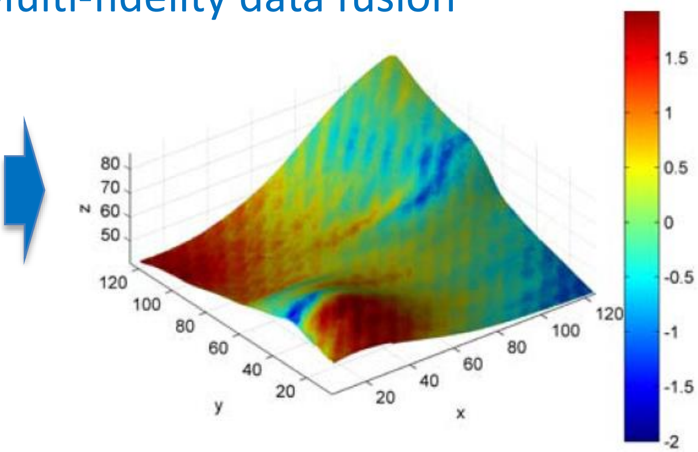
Profile monitoring



Surface monitoring



Multi-fidelity data fusion



- BM Colosimo, Q Semeraro, M Pacella (2008) **Statistical process control for geometric specifications: on the monitoring of roundness profiles**, JQT 40 (1)
- BM Colosimo, P Cicorella, M Pacella, M Blaco (2014) **From profile to surface monitoring: SPC for cylindrical surfaces via Gaussian Processes** JQT 46 (2), 95
- BM Colosimo, M Pacella, N Senin (2015) **Multisensor data fusion via Gaussian process models for dimensional and geometric verification** Precision Engineering 40, 199-213

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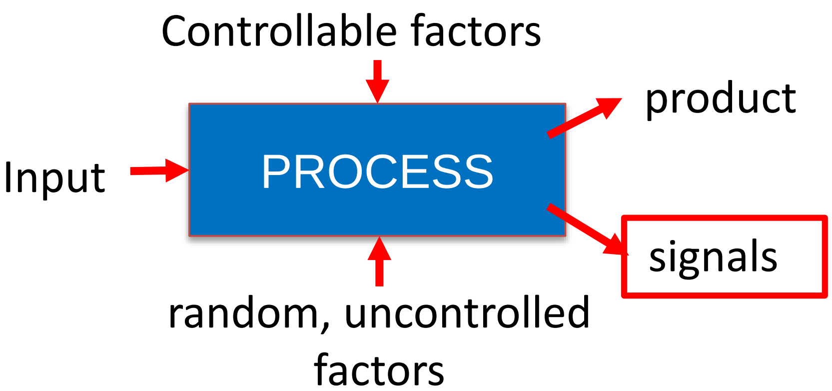
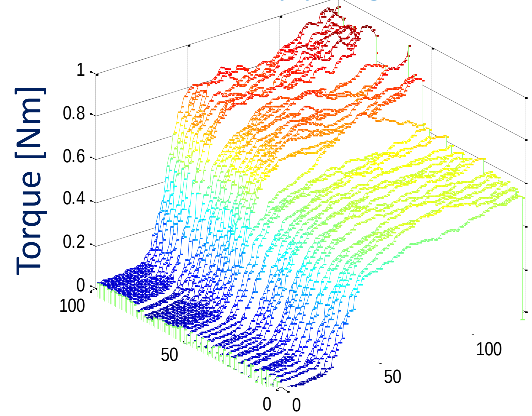
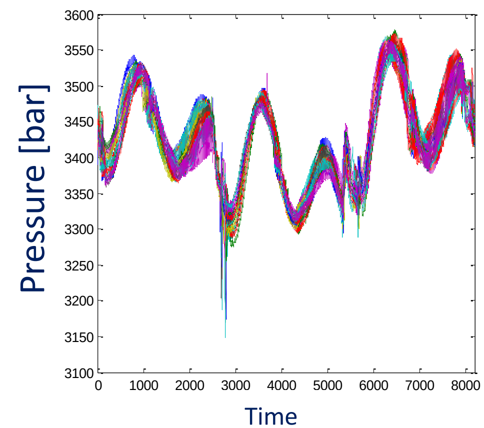


Tapping

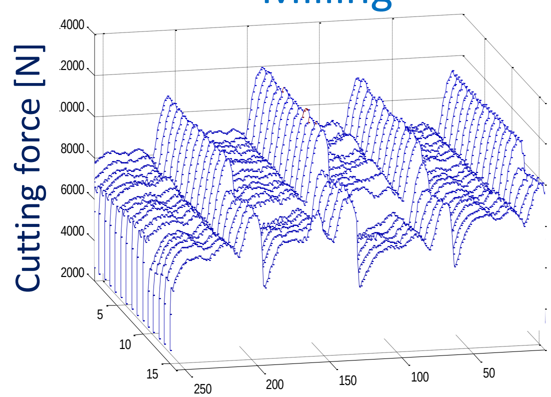


Waterjet cutting

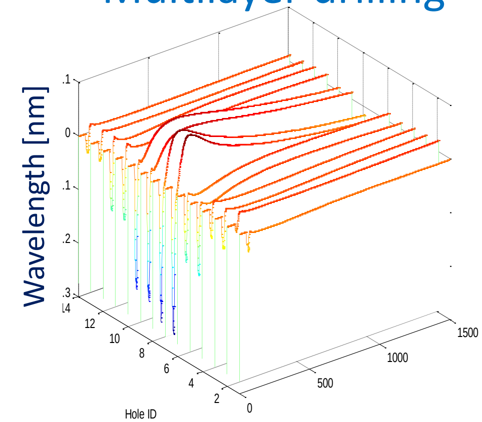


- Grasso M., Menafoglio A., Colosimo B. M., Secchi P. (2016), **Using Curve Registration Information to Enhance Profile Monitoring of Signal Data**, JQT, 48(2)
- Grasso M., Colosimo B.M., Pacella M. (2014), **Profile Monitoring via Sensor Fusion: the use of PCA Methods for Multi-Channel Data**, IJPR, 52 (20)
- Grasso M., Chatterton S., Pennacchi P., Colosimo B.M., (2016), **A Data-Driven Method to Enhance Vibration Signal Decomposition for Rolling Bearing Fault Analysis**, MSSP, 81, 126-147

Milling



Multilayer drilling



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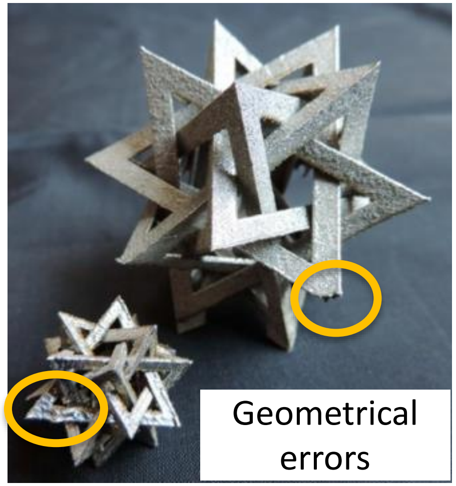
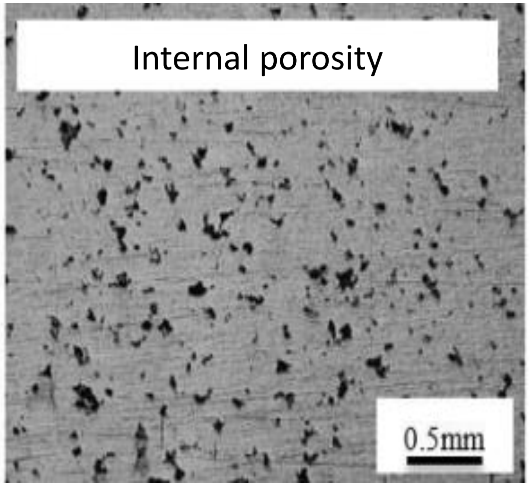
Towards zero-defect in metal AM

Statistical process monitoring and data mining techniques applied to metal AM

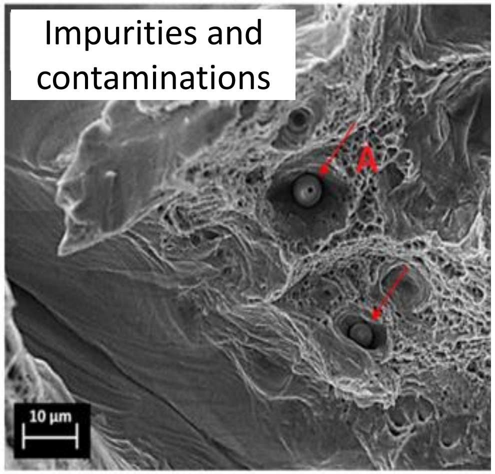


Cracking & delamination

Zaeh and Lutzmann, 2010



Gong, 2013



Casati et al., 2016

Goal:

- Quickly detect the onset of defects during the process via in-situ sensing

Challenges:

- Automated alarm rules when there is no time to learn
- Identification of *WHEN* and *WHERE* the defect has originated within the part
- Processing and analysis of large amounts of high frequency data streams

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Process signatures and sensing methods in PBF

from: Grasso, Colosimo, *Process Defects and In-situ Monitoring Methods in Metal Powder Bed Fusion: a Review,* Measurement Science and Technology, 2017

Monitored signature		In-situ sensing (main categories)			
		Pyrometry	Imaging (visible to NIR)	Thermal imaging (NIR to LWIR)	Interferometric imaging
Melt pool	**Size**	*Clijsters et al., 2014; Craeghs et al., 2010 - 2011;*	*Craeghs et al., 2010 - 2012; Clijsters et al., 2014; Berumen et al., 2010; Kruth et al., 2007; Van Gestel, 2015*		
	Shape		*Craeghs et al., 2011; Berumen et al., 2010; Van Gestel, 2015; Kruth et al., 2007*	Doubenskaia et al., 2015	
	Temperature intensity	*Craeghs et al., 2011; Berumen et al., 2010; Chivel, 2013; Clijsters et al., 2014; Doubenskaia et al., 2012; Pavlov et al., 2010; Thombansen et al., 2015;*	*Berumen et al., 2010; Van Gestel, 2015; Yadroitsev et al., 2014; Chivel, 2013;*		
	Temperature profile		*Doubenskaia et al., 2012;*	Gong et al., 2013b; Price et al., 2012	
Track (scan path)	**Track geometry**			Doubenskaia et al., 2015	*Kanko et al., 2016*
	Temperature/ intensity profile	Bayle and Doubenskaia, 2008; *Thombansen et al., 2015*	Grasso et al., 2016	Krauss et al., 2012 - 2014; Lane et al., 2015; Bayle and Doubenskaia, 2008; Gong et al., 2013b; Price et al., 2012; Schilp et al., 2014;	
	Ejected material	Bayle and Doubenskaia, 2008		Bayle and Doubenskaia, 2008; Lane et al., 2015	
Slice	**Surface pattern**		Foster et al., 2015; zur Jacobsmühlen et al., 2013; Kleszczynski et al., 2012; Zhang et al., 2016	Ridwan et al., 2014; Schwerdtfeger et al., 2012; Mireles et al., 2015; Dinwiddie et al., 2013	*Neef et al., 2014*
	Geometry		Foster et al., 2015	Ridwan et al., 2014	
	Thickness profile		zur Jacobsmühlen et al., 2013 - 2015; Kleszczynski et al., 2012; Land et al., 2015; Zhang et al., 2016		
	Temperature/ intensity profile		Grasso et al., 2016	Krauss et al. 2014; Rodriguez et al., 2012 - 2015; Schilp et al., 2014; Wegner and Witt, 2011; Dinwiddie et al., 2013	
Powder bed	**Homogeneity**		Foster et al. 2015;		*Neef et al., 2014*
	Temperature intensity	Islam et al., 2013			
	Temperature profile			Wegner and Witt, 2011	

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	Shape		*Craeghs et al., 2011; Berumen et al., 2010; Van Gestel, 2015; Kruth et al., 2007*	Doubenskaia et al., 2015	
	Temperature intensity	*Craeghs et al., 2011; Berumen et al., 2010; Chivel, 2013; Clijsters et al., 2014; Doubenskaia et al., 2012; Pavlov et al., 2010; Thombansen et al., 2015;*	*Berumen et al., 2010; Van Gestel, 2015; Yadroitsev et al., 2014; Chivel, 2013;*		
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	Thickn		zur Jacobsmühlen et al., 2013 - 2015; t al., 2015;		
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Powder bed	Homog				*Neef et al., 2014*
	Temperature intensity	Islam et al., 2013			
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Monitoring tools more consolidated in industry (images acquired before and after scanning)

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Monitoring tools more cor
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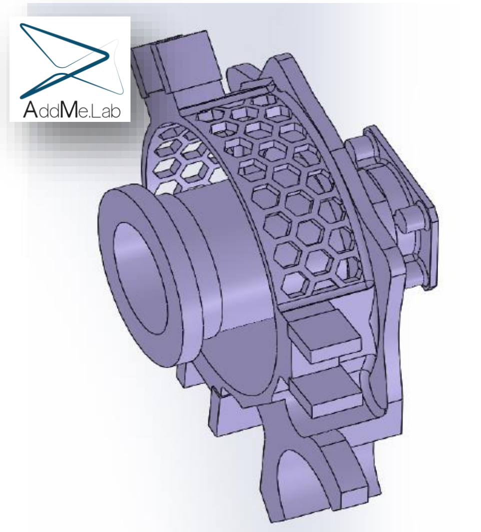
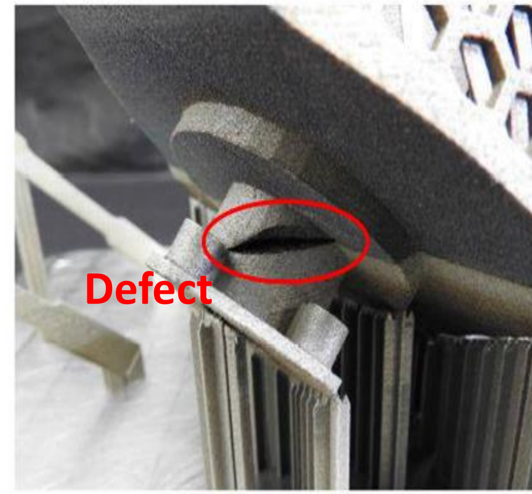
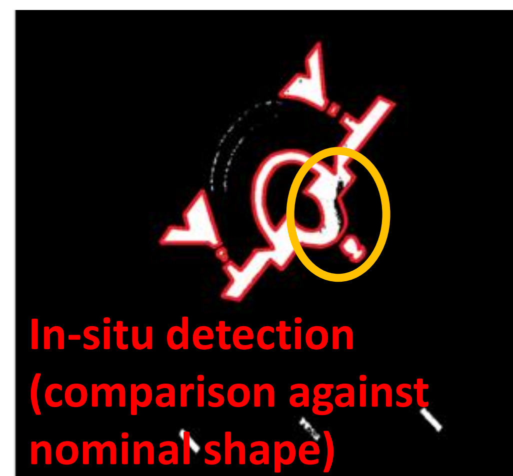
Example of application to complex aeropace part





Original image



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Typology and sources of defects in PBF

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Sources of defects		Categories of defects: Porosity	Balling	Geometric defects	Surface defects	Residual stresses, cracks & delamination	Microstructural inhomog. & impurity
Equipment	Beam scanning/ deflection	Foster et al., 2015		Moylan et al., 2014b; Foster et al., 2015			
Equipment	Build chamber environment	Ferrar et al., 2012; Spears and Gold, 2016	Li et al., 2012			Edwards et al., 2013; Chlebus et al., 2011; Buchbinder et al., 2014; Kempen et al., 2013	Spears and Gold, 2016
Equipment	Powder handling & deposition	Foster et al., 2015		Foster et al., 2015; Kleszczynski et al., 2012	Foster et al., 2015; Kleszczynski et al., 2012		Foster et al., 2015
Equipment	Baseplate			Prabhakar et al., 2015		Prabhakar et al., 2015	
Process	Parameters and scan strategy	Matthews et al., 2016; Yasa et al., 2009; Attar, 2011; Gong, 2013; Read et al., 2015; Kruth et al., 2004; Weingarten et al., 2015; Thijs et al., 2010; Scharowsky et al., 2015; Puebla et al., 2012; Tammas-Williams et al., 2015; Biamino et al., 2011; Zeng, 2015	Li et al., 2012; Kruth et al., 2004; Tolochko et al., 2004; Zhou et al., 2015; Attar, 2011; Gong, 2013	Yasa et al., 2009; Mousa, 2016; Kleszczynski et al., 2012; Thomas, 2009	Li et al., 2012; Kruth et al., 2004; Matthews et al., 2016; Attar, 2011; Gong, 2013; Zaeh and Kanhert, 2009; Delgado et al., 2012;	Mercelis and Kruth, 2006; Parry et al., 2016; Cheng et al., 2016; Van Belle et al., 2013; Casavola et al., 2008; Zah and Lutzmann, 2010; Zaeh and Branner, 2010; Kempen et al., 2013; Kruth et al., 2004; Carter et al., 2012 - 2014	Carter et al., 2012 - 2014; Arisoy et al., 2016; Niu and Chang, 1999; Huang et al., 2016; Thijs et al., 2010; Scharowsky et al., 2015; Puebla et al., 2012; Biamino et al., 2011
Process	Byproducts and material ejections	Liu et al., 2015; Khairallah et al., 2016;					Liu et al., 2015; Khairallah et al., 2016;
Design choices	Supports			Foster et al., 2015; Kleszczynski et al., 2012; Zeng, 2015	Foster et al., 2015; Kleszczynski et al., 2012; Zeng, 2015	Foster et al., 2015; Kleszczynski et al., 2012; Zeng, 2015	
Design choices	Orientation		Li et al., 2012; Strano et al., 2013;	Delgado et al., 2012	Delgado et al., 2012; Fox et al., 2016; Strano et al., 2013		Meier and Haberland, 2008
Feedstock material (powder)		Liu et al., 2015; Van Elsen, 2007; Das, 2003		Das, 2003	Seyda et al., 2012		Das, 2003; Niu and Chang, 1999; Huang et al., 2016

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Process	Parameters and scan strategy	Matthews et al., 2016; Yasa et al., 2009; Attar, 2011; Gong, 2013; Read et al., 20 … Puebla e … Williams … 2011; Ze …			Li et al., 2012; Kruth et al., … thews et al., … r, 2011; Gong, … n and Kanhert, … gado et al.,	Mercelis and Kruth, 2006; Parry et al., 2016; Cheng et al., 2016; Van Belle et al., 2013; Casavola et al., 2008; Zah and Lutzmann, 2010; Zaeh and Branner, 2010; Kempen et al., 2013; Kruth et al., 2004; Carter et al., 2012 - 2014	Carter et al., 2012 - 2014; Arisoy et al., 2016; Niu and Chang, 1999; Huang et al., 2016; Thijs et al., 2010; Scharowsky et al., 2015; Puebla et al., 2012; Biamino et al., 2011
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	Orientation		Li et al., 2012; Strano et al., 2013;	Delgado et al., 2012	Delgado et al., 2012; Fox et al., 2016; Strano et al., 2013		Meier and Haberland, 2008
Feedstock material (powder)		Liu et al., 2015; Van Elsen, 2007; Das, 2003		Das, 2003	Seyda et al., 2012		Das, 2003; Niu and Chang, 1999; Huang et al., 2016

Local geometrical defects may be caused by non-optimal process parameters in critical features and/or non optimal supporting strategies

Hot-spot (local over-heating) detection and localization methods

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Equipment	Powder handling & deposition	Foster et al., 2015		Foster et al., 2015; Kleszczynski et al., 2012	Foster et al., 2015; Kleszczynski et al., 2012		Foster et al., 2015
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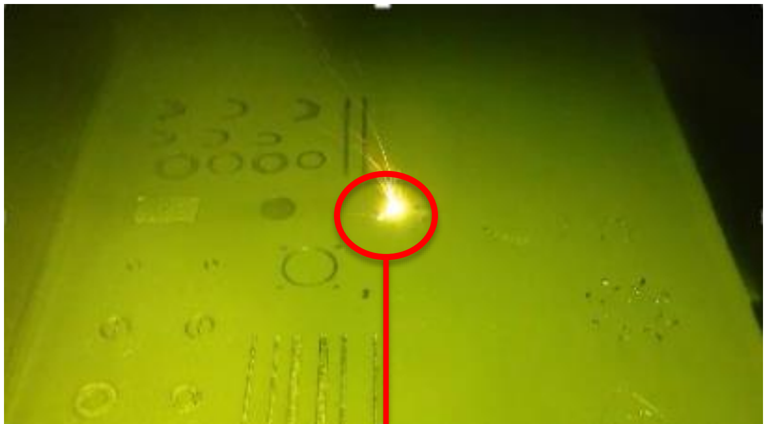
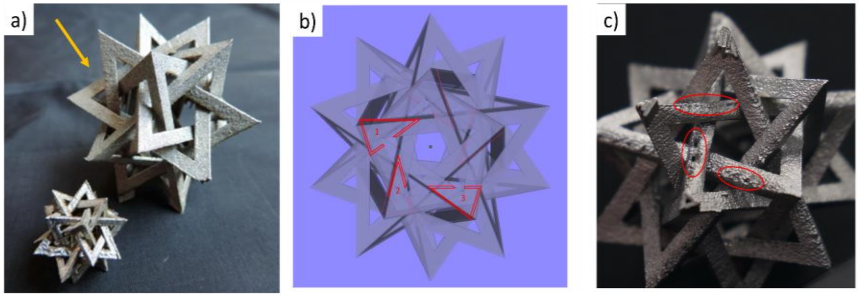
Process	Parameters and scan strategy	Matthews et al., 2016; Yasa et al., 2009; Attar, 2011; Gong, 2013; Read et al., 2015; Kruth et al., 2004; Weingarten et al., 2015; Thijs et al., 2010; Scharowsky et al., 2015; Puebla [illegible] William[illegible] 2011; Ze[illegible]	Li et al., 2012; Kruth et al., 2004; Tolochko et al., 2004; Zhou et al., 2015; Attar, 2011; [illegible]	Yasa et al., 2009; Mousa, 2016; Kleszczynski et al., 2012; Thomas, 2009 [illegible]	Li et al., 2012; Kruth et al., 2004; Matthews et al., 2016; Attar, 2011; Gong, 2013; Zaeh and Kanhert, [illegible] [illegible]gado et al., [illegible]	Mercelis and Kruth, 2006; Parry et al., 2016; Cheng et al., 2016; Van Belle et al., 2013; Casavola et al., 2008; Zah and Lutzmann, 2010; Zaeh and Branner, 2010; Kempen et al., 2013; Kruth et al., 2004; Carter et al., 2012 - 2014	Carter et al., 2012 - 2014; Arisoy et al., 2016; Niu and Chang, 1999; Huang et al., 2016; Thijs et al., 2010; Scharowsky et al., 2015; Puebla et al., 2012; Biamino et al., 2011
Process	Byproducts and material ejections	2[illegible]	[illegible]	[illegible]	[illegible]		Liu et al., 2015; Khairallah et al., 2016;
Design choices	Supports	[illegible]	[illegible]	[illegible] Zeng, 2015	[illegible]al., 2015; [illegible]ski et al., 2012; Zeng, 2015	Foster et al., 2015; Kleszczynski et al., 2012; Zeng, 2015	
Design choices	Orientation		Li et al., 2012; Strano et al., 2013;	Delgado et al., 2012	Delgado et al., 2012; Fox et al., 2016; Strano et al., 2013		Meier and Haberland, 2008
Feedstock material (powder)		Liu et al., 2015; Van Elsen, 2007; Das, 2003		Das, 2003	Seyda et al., 2012		Das, 2003; Niu and Chang, 1999; Huang et al., 2016

Study of spatter behaviour produced by the laser/material interaction, which are related to process stability and local defects

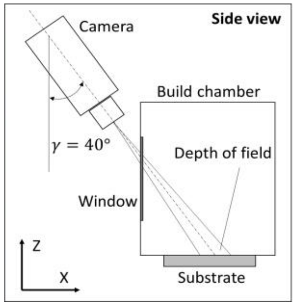
Hot-spot detection and localization in SLM
Case study

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





High-speed image acquisition (off-axis)
Olympus i-speed 3



Grasso et al. (2016) In-process Monitoring of Selective Laser Melting: Spatial Detection of Defects via Image Data Analysis. Journal of Manufacturing Science and Engineering, 139(5), 051001-1-16.

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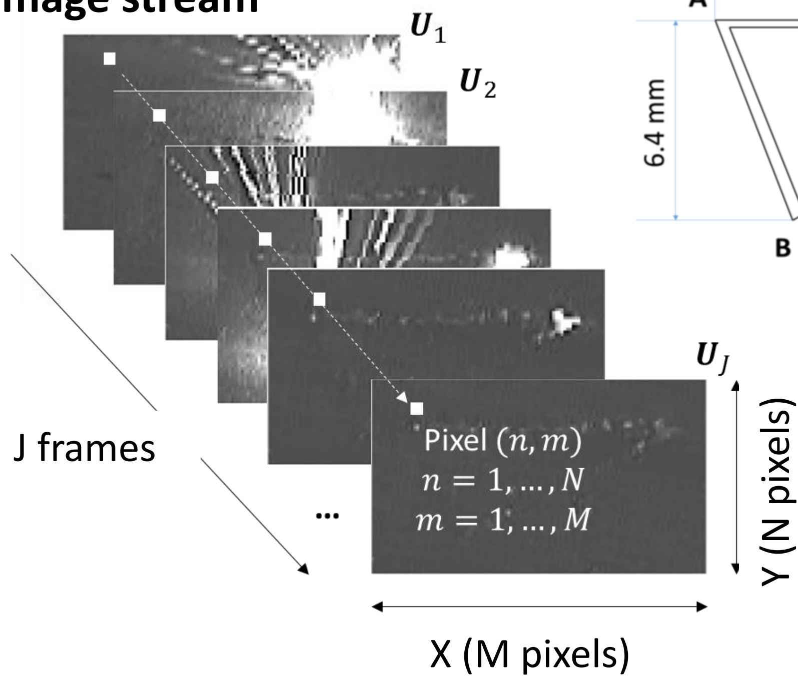
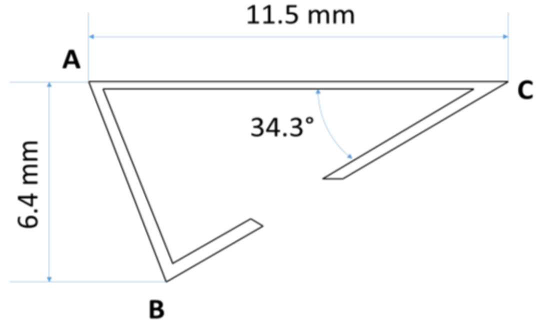
Hot-spot detection and localization in SLM
Proposed approach

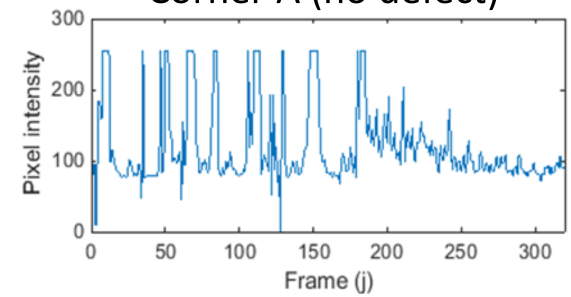
Image stream



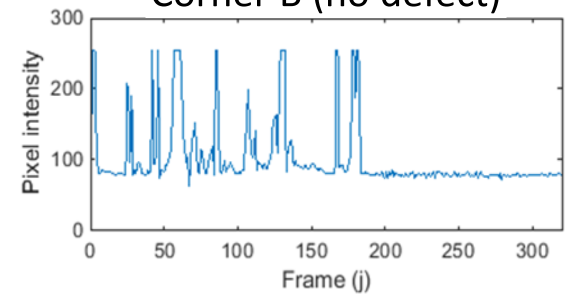


350 frames of size 121 × 71
Intensity profiles over time
(8bpp – scale: 0-255)

Corner A (no defect)

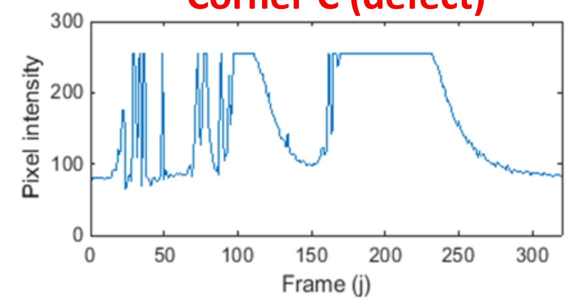


Corner B (no defect)



Corner C (defect)

HOT-SPOT



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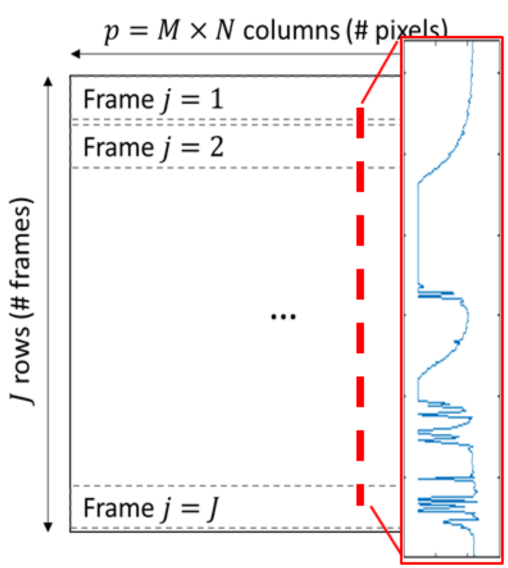
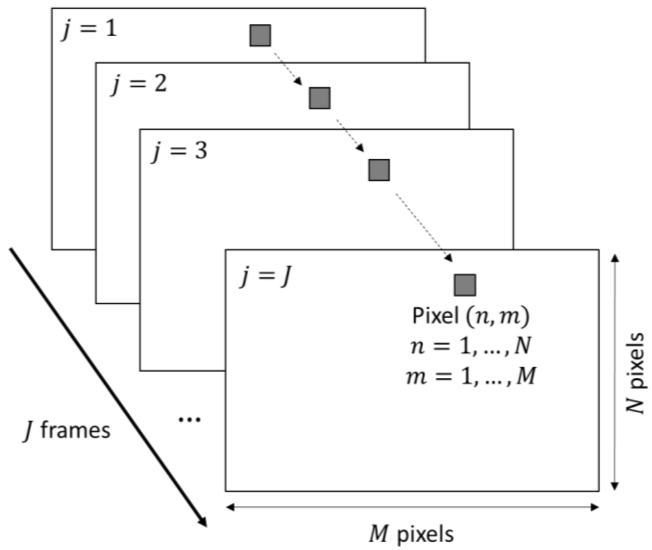
Hot-spot detection and localization in SLM
Proposed approach

Image stream processing

Temporal PCA
(S-mode)

$$\mathbf{X} \in \mathbb{R}^{J\times(M*N)}$$





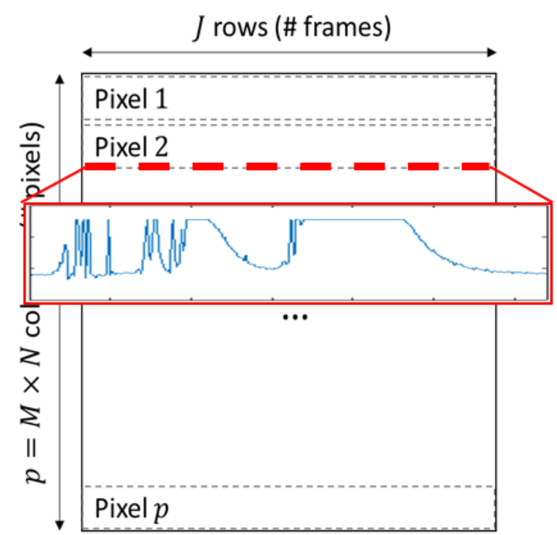
- Principal Component Analysis (PCA) applied to image data
- No segmentation or edge detection operation needed

$$\boldsymbol{\mathcal{U}} \in \mathbb{R}^{J\times M\times N}$$

$$\boldsymbol{\mathcal{U}} = \{\boldsymbol{U}_1, \boldsymbol{U}_2, \dots, \boldsymbol{U}_J\}$$

Spatial PCA
(T-mode)

$$\mathbf{X} \in \mathbb{R}^{(M*N)\times J}$$



Geospatial statistics & atmospheric science

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Data matrix

$\mathbf{X} \in \mathbb{R}^{(M*N)\times J}$

Var-covar matrix

$$\mathbf{S}_T = \frac{1}{J-1}\mathbf{X}^T\mathbf{X}$$

T-mode PCA

Iterative update as new video frames are acquired

Statistical descriptors

$T^2(X,Y)$ Hotelling's distance

$SPE(X,Y)$ Squared PCA residuals

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Hot-spot detection and localization in SLM
Proposed approach

Data matrix

$\mathbf{X} \in \mathbb{R}^{(M*N)\times J}$

Var-covar matrix

$\mathbf{S}_T = \frac{1}{J-1}\mathbf{X}^T\mathbf{W}\mathbf{X}$

Spatio-Temporal PCA

ST-PCA

Iterative update as new video frames are acquired

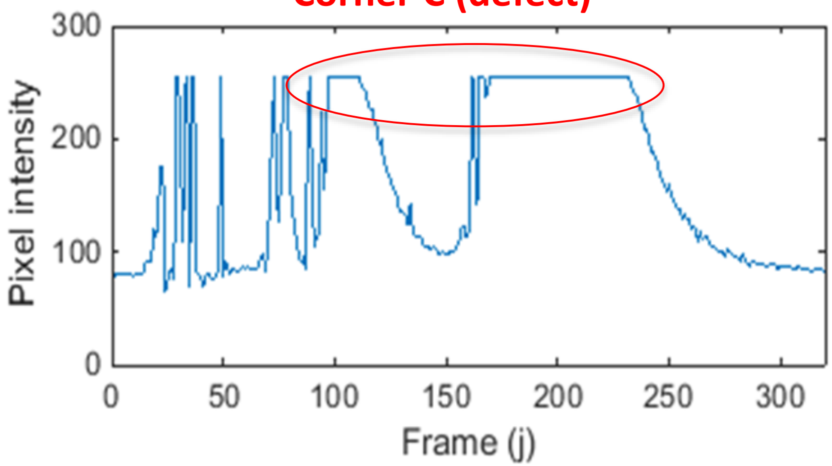
Statistical descriptors

$T^2(X,Y)$ Hotelling's distance

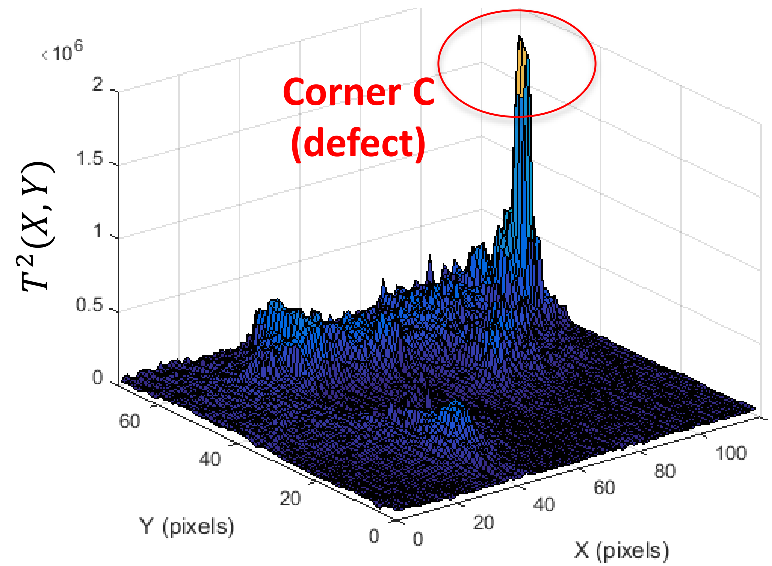
$SPE(X,Y)$ Squared PCA residuals

Temporal correlation (pixel intensity profile)

Corner C (defect)



Spatial mapping (statistical descriptor)



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Hot-spot detection and localization in SLM
Proposed approach

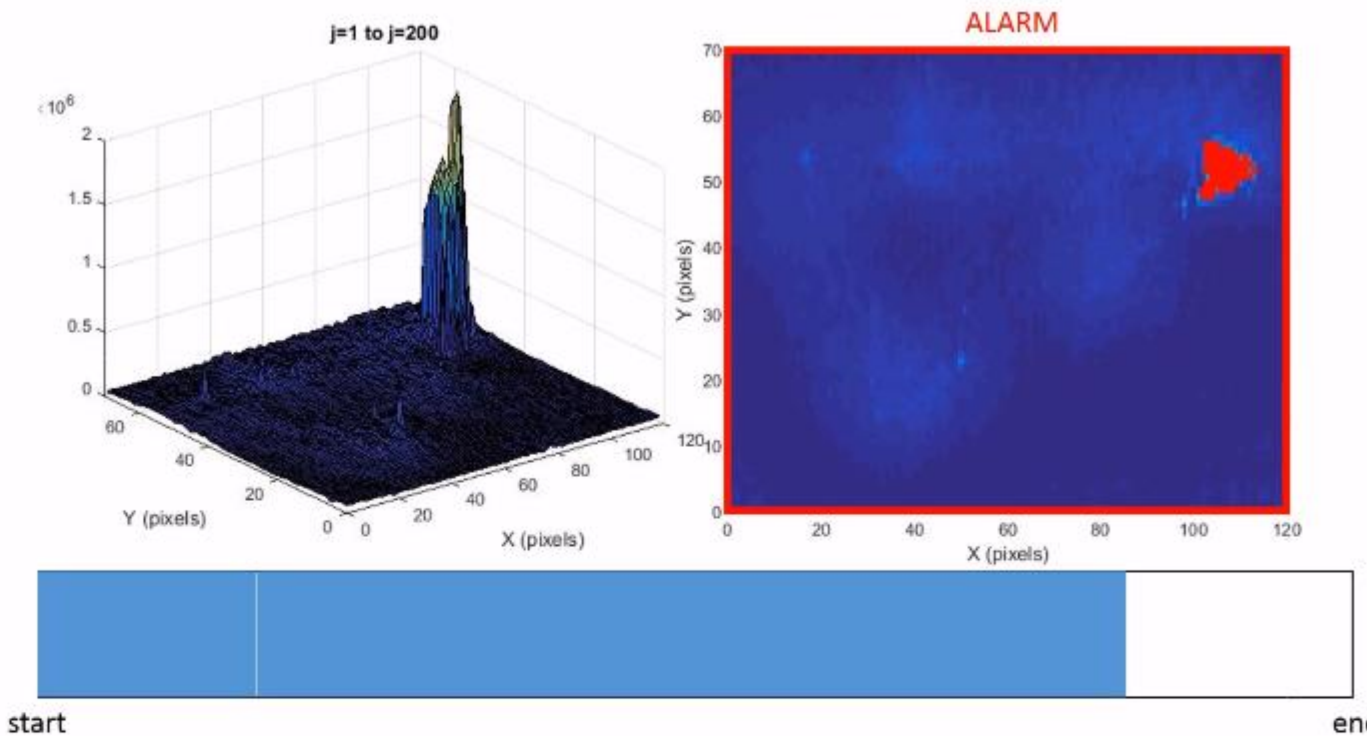
Spatial clustering-based alarm rule (*Hastie et al., 2009; Tisbshirani et al., 2001*)

- **1 cluster: no hot-spot, process in-control**
- **2 clusters (or >2): hot-spot detected, process out-of-control (alarm)**

Example of results

Iterive update every 20 frames (0.067s)

Red area indicates the signalled cluster (alarm)



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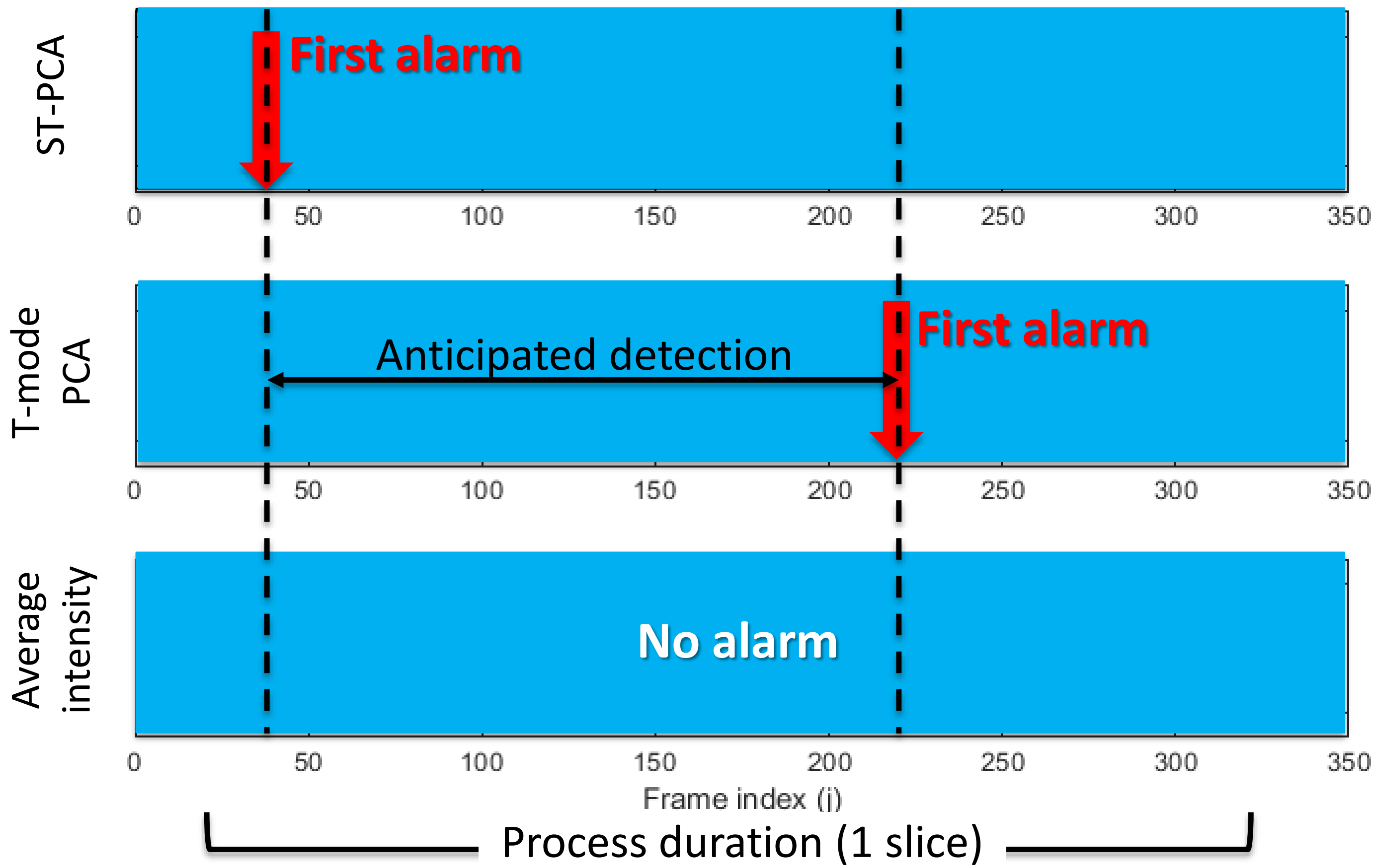
Hot-spot detection and localization in SLM
Proposed approach

Benefits against competitor methods



Proposed approach (*Grasso and Colosimo, 2017, JQT – under review*)

Competitors from previous study (*Grasso et al., 2016, ASME Transactions*)

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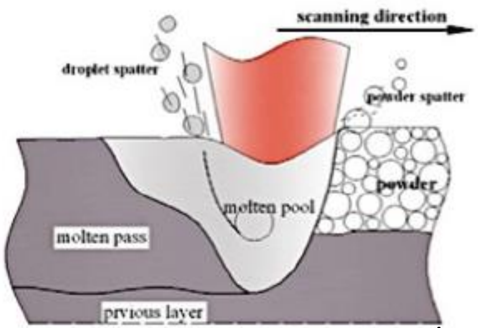
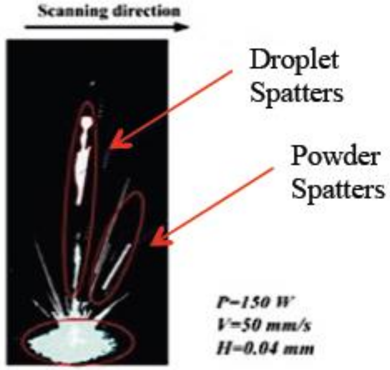
Spatter behaviour analysis for process monitoring in SLM

Repossini *et al.* 2017, *Spatter behaviour in Selective Laser Melting as process signature for in-situ monitoring*, Additive Manufacturing (under review)

Spatters generated by the laser/material interaction could be suitable *process signatures* for SLM process monitoring?

- “droplet spatters” and “powder spatters” *(Liu et al., 2011; Khairallah et al., 2016)*
- OOC spatter behaviour may produce inclusions & powder bed inhomogeneity *(Gong, 2013)*
- *Lack of studies on correlation between spatter behaviour and SLM process quality*





Liu et al., 2011

Image processing approach

High-speed image acquisition (1000 Hz)

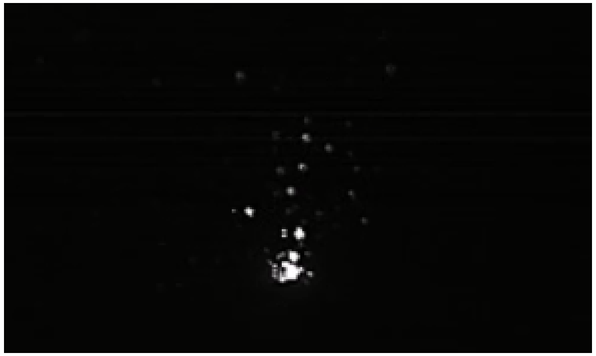
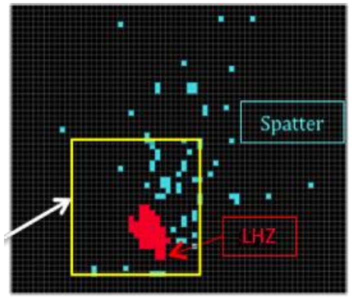


Image segmentation and classification between laser heated zone (LHZ) and spatters



Estimation of statistical descriptors of spatter behaviour
(average area, spatial spread, number,…)

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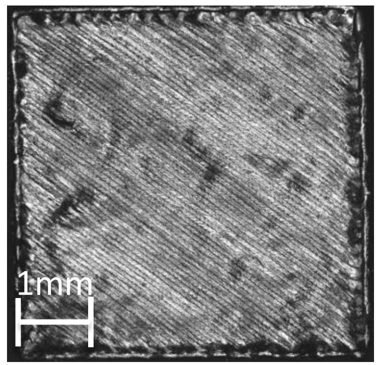
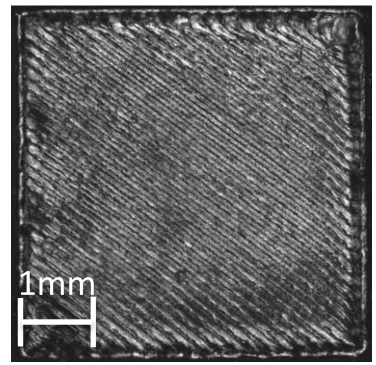
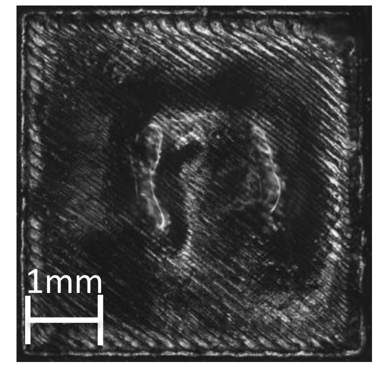
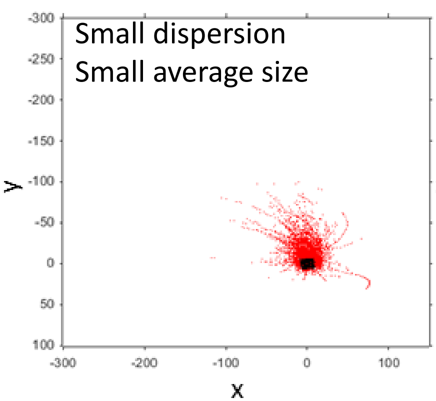
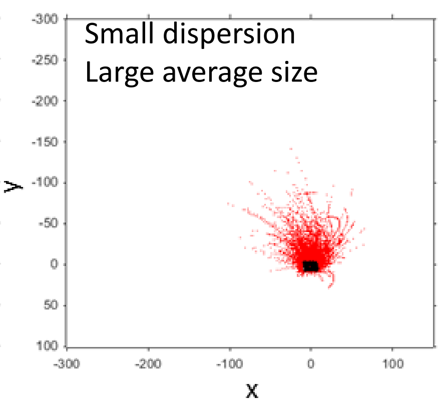
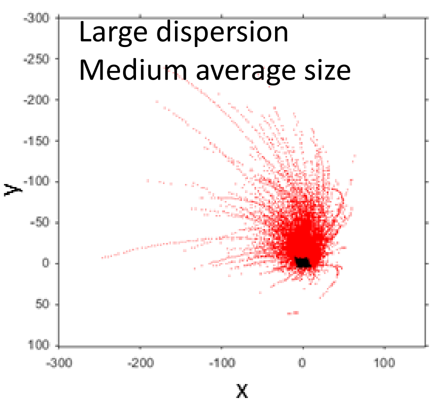
Repossini *et al.* 2017, *Spatter behaviour in Selective Laser Melting as process signature for in-situ monitoring*, Additive Manufacturing (under review)

Study of spatter behaviour under different *energy density* conditions (maraging steel)

	Low energy density (40 kJ/cm^3)	**Normal energy density (80 kJ/cm^3)**	**High energy density (120 kJ/cm^3)**
Top surface of produced specimens (5 x 5 x 10 mm)			
Centroids of spatters (red) and laser heated zone (black)			

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Spatter behaviour analysis for process monitoring in SLM

Repossini *et al.* 2017, *Spatter behaviour in Selective Laser Melting as process signature for in-situ monitoring*, Additive Manufacturing (under review)

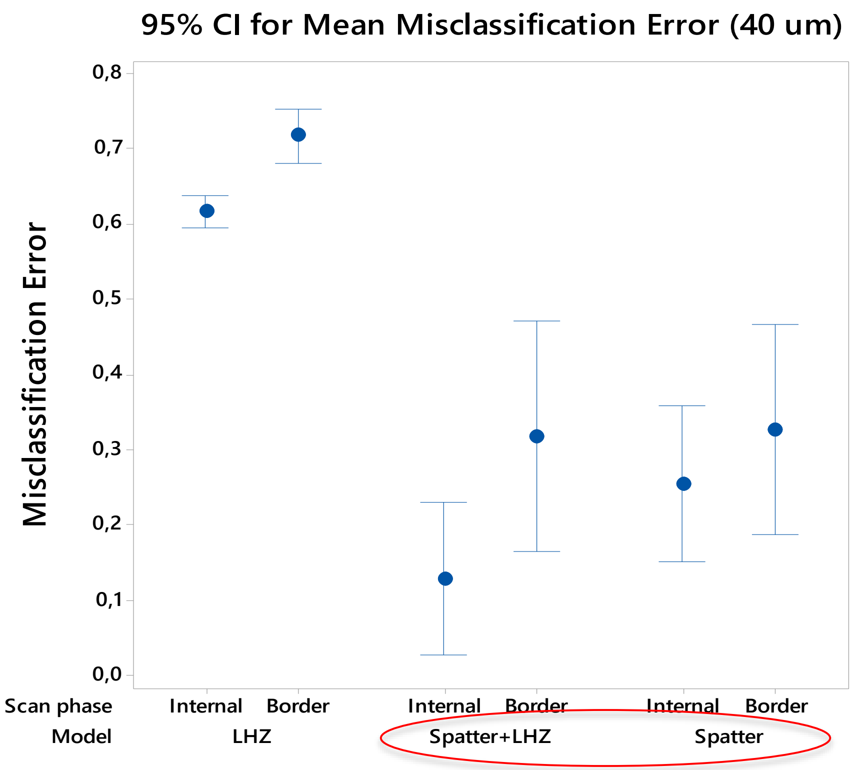
Classification of energy density conditions via logistic regression

Three classification models were compared:

1. Only LHZ area (benchmark)
2. LHZ + spatters
3. Only spatters

Results:

- Inclusion of spatter-related descriptors **enhances the classification** performances with respect to including only laser heated zone area
- Spatter behaviour can be used as a **proxy of process stability** (to be further investigated in future studies)



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Challenges and next steps

Challenges and barriers to face

- ***Computational feasibility***:

  Breadboard implementation on real-time platform needed to improve the computational efficiency (possibillity of monitoring larger areas);

- ***Integration & synchronization*** of image acquisition system with machine controller

- ***Big data stream management*** for continuous process monitoring

Next steps

Study of **multi-sensor data fusion** methods to enhance process monitoring performances

- co-axial + off-axis sensing (process monitoring at multiple levels)
- Evaluation of novel in-situ sensing solutions

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Thanks for your attention

Casati et al. 2016. Microstructure and Fracture Behavior of 316L Austenitic Stainless Steel Produced by Selective Laser Melting. *Journal of Materials Science & Technology*, *32*(8), 738-744.

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