Sensing for AM

PROF. MICHELE LANZETTA

LUPI FRANCESCO

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Online control of Additive Manufacturing (AM) in the era of Industry 4.0 (I4.0)

Goal: Offer a systematic and comprehensive review on the four main drivers (i.e., online controllable input parameters, online observable output signatures, online sensing techniques, online feedback strategies) adopted from a general control loop for process optimization.

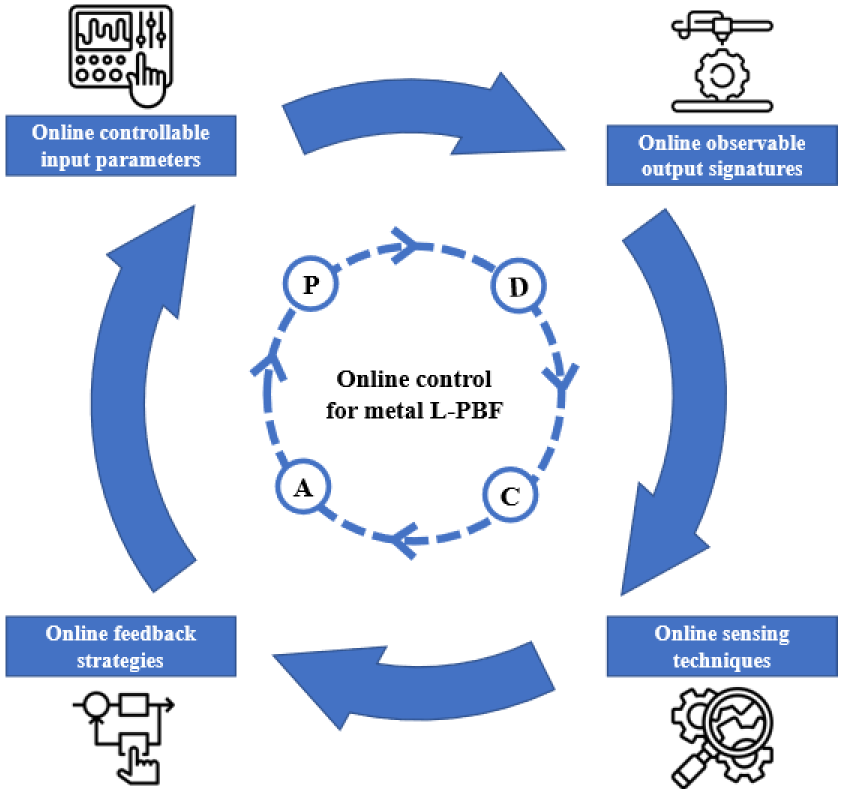
Scope: metal Laser Powder Bed Fusion (L-PBF), mainly focusing on two subcategories, Selective Laser Sintering (SLS) and Selective Laser Melting (SLM).

Gap: Although many efforts have been dedicated by industry and research in the last decades, a significant room for improvements is still present.

Future directions: Application of Big Data, Digital Twin (DT) and Cyber Physical System (CPS) approach for AM Predictive Model Control.

General control loop

The four drivers are highlighted in the blue boxes. Each box has been labeled via the initials of Deming's control loop step (P-Plan, D-Do, C-Check, A-Act)

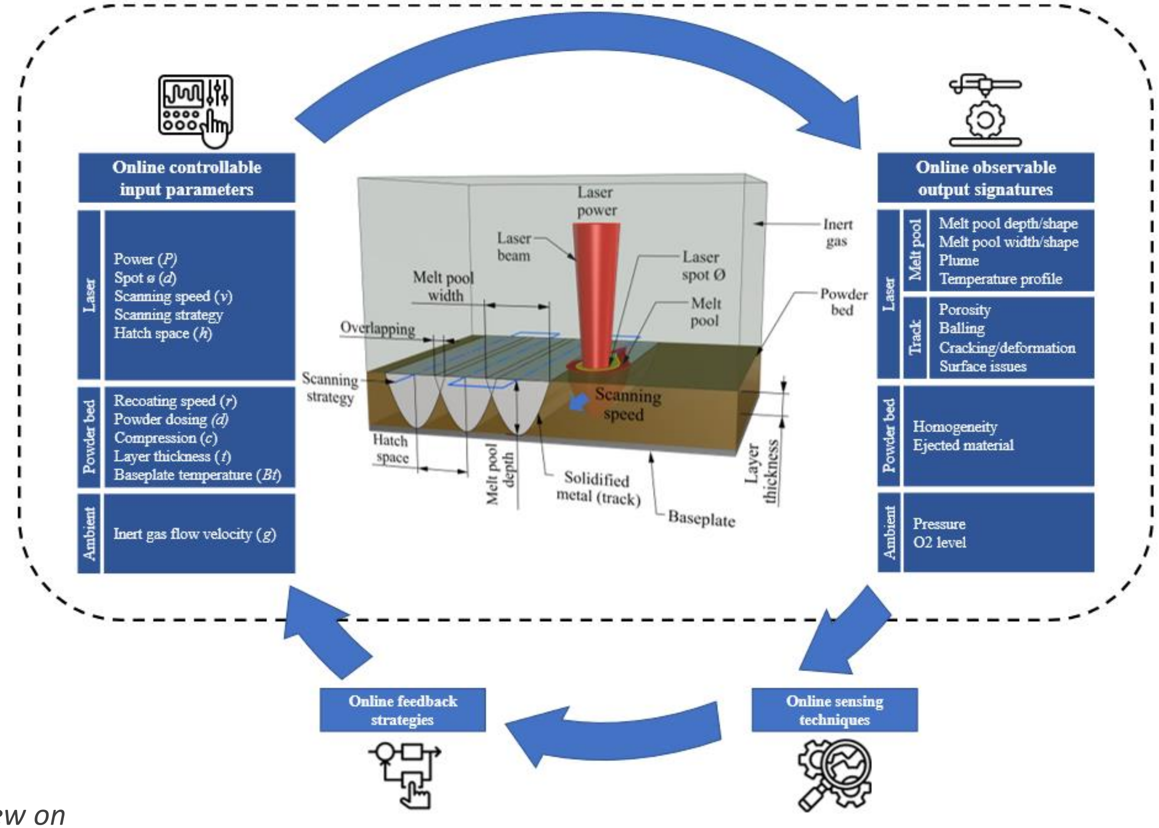


[Lupi, F., Lanzetta, M., (2022, June). Laser Powder Bed Additive Manufacturing: A Review on the Four Drivers for an Online Control. Under review for Journal of Manufacturing Processes

A quick overview on input parameters and output signatures

- Classification of the online controllable input parameters in the L-PBF process (left).
- Classification of the online observable output signatures in the L-PBF process (right).

Schematic representation of L-PBF along with some controllable input parameters and observable output signatures labels (center). Light blue arrow in the schematic representation highlights the laser beam direction, and light blue dotted path represents the scanning strategy



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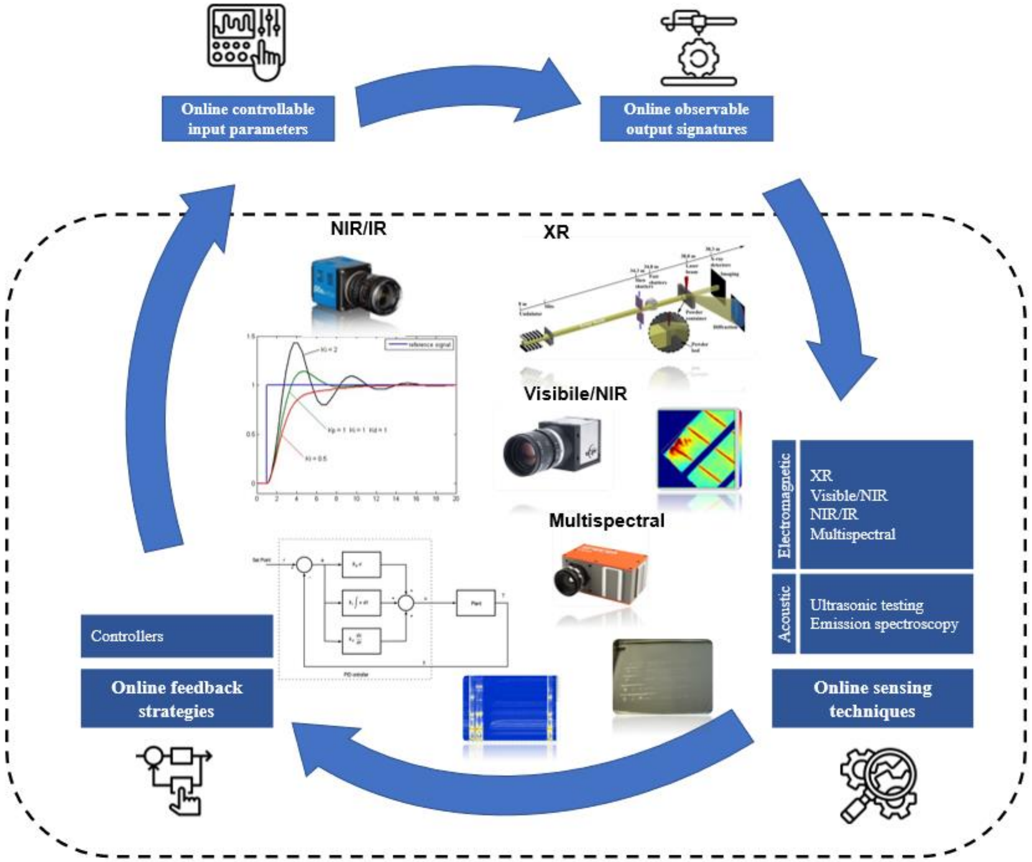
A quick overview on online sensing techniques and feedback strategies

Classification of common in situ sensors suitable for online observable output signatures monitoring and online feedback strategies applied in literature



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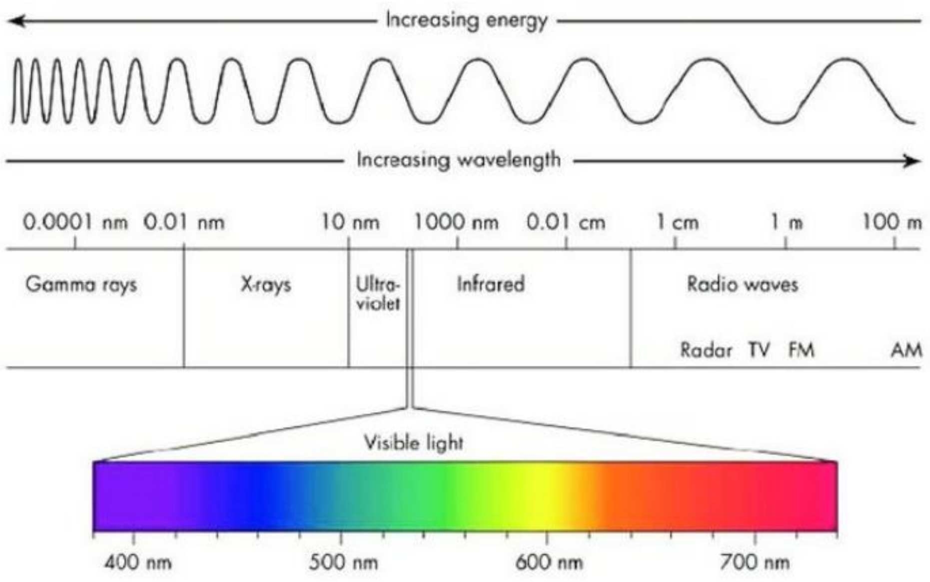
Sensors for AM

Classification of common in situ sensors suitable for online observable output signatures monitoring and online feedback strategies applied in literature

	Sensor type	Sampling rate [kHz]	Costs and time consuming	Signatures detectable
Electromagnetic	XR	50	High	Melt pool: depth/shape Track: porosity, balling, surface issue Powder bed: ejected material
	Visible-NIR	>1-900	Low	Melt pool: width/shape Track: porosity, balling, crack/deform, surface issue Powder bed: ejected material, homogeneity
	NIR-IR	0.05-10	Low	Melt pool: width/shape, plume, temperature profile Track: porosity
	Multispectral	0.01-170	Medium-high	Melt pool: width/shape, plume, temperature Track: porosity, surface issue
Acoustic	Sonic or ultrasonic	3 - >20	Low	Melt pool: depth and width Track: porosity, surface issue Powder bed: ejected material,

Electromagnetic wavelength spectrum



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3Vs = Big Data in AM

Velocity: regardless of the type of sensor used, online control requires that the sensors have a very fast response time and a high degree of spatial resolution. Laser scanning speed in SLS/M are typically on the order of 100 to 1000 mm/s, while the laser focus area is on the order of 10–100 μm. Any electromagnetic monitoring system must be equally capable of reacting to these high scanning velocities and rapid melt pool dynamics in addition to being able to resolve slight spatial variations.

Volume: Because of the high frame rate required (e.g., hundreds of kHz), existing commercial in situ monitoring systems end to the generation of the enormous volume of the data (e.g., 100 GB for 10 mm height cylindrical sample), which is very difficult to store and analyze. For this reason, several authors propose data reduction techniques as a possible solution for heavy dataset management.

Variety: Using multiple sensor-based systems (i.e., sensor fusion) to collect data of the manufacturing process is essential for better part quality monitoring.

-[J. Z. Sasiadek, "Sensor fusion," Annual Reviews in Control, vol. 26, no. 2, pp. 203–228, Jan. 2002, doi: 10.1016/S1367-5788(02)00045-7.]
-[S. L. Sing, C. N. Kuo, C. T. Shih, C. C. Ho, and C. K. Chua, "Perspectives of using machine learning in laser powder bed fusion for metal additive manufacturing," Virtual and Physical Prototyping, vol. 16, no. 3, pp. 372–386, 2021, doi: 10.1080/17452759.2021.1944229.] M. Grasso and B. M.
-[Colosimo, "Process defects and in situ monitoring methods in metal powder bed fusion: a review," Measurement Science and Technology, vol. 28, no. 4, p. 044005, Feb. 2017, doi: 10.1088/1361-6501/AA5C4F]

CPS and Digital twin for AM model predictive control

Cyber-Physical Systems (CPSs) are complex engineered systems, where cyber and physical components are strongly interconnected (i.e., **Digital-twin**). In particular, CPSs obey both a continuous-time physical plant dynamics, and a hybrid control dynamics having both a discrete-time (event-driven) and a continuous-time component.

The digital-twin is useful for ***system analysis***, ***monitoring in operation***, ***prediction of future states*** of the assets and prediction of their impact on damage or malfunction.

Due to the Sensors application to AM and the huge amount of data Model Predictive Control (i.e., co-simulation multi-physics approach will gain more and more interest for online control)

[Bernardeschi, C., Dini, P., Domenici, A., Mouhagir, A., Palmieri, M., Saponara, S., ... & Zaourar, L. (2021, December). Co-simulation of a Model Predictive Control System for Automotive Application. In CoSim-CPS 2021: 5th Workshop on Formal Co-Simulation of Cyber-Physical Systems (pp. paper-3). Springer LNCS.]