A UNIFIED SYSTEM CONTROLLER FOR OPEN-SOURCE POWDER BED FUSION SYSTEMS

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Abstract

This paper presents an open-architecture systems controller for laser powder-bed fusion (LPBF). The controller gives the operator direct low-level hardware control, and thereby bridges the gap, between system and researcher, often invoked by the proprietary nature of commercial LPBF systems. As part of the open-source framework, the bespoke controller provides an open and customizable way of controlling the governing subsystems, e.g., scanner (XY2-100), laser, gas flow, and motorized actuation. Furthermore, the unified system controller was designed to retrieve feedback from the scanner and designated process sensors. Utilizing the process feedback the unified system controller demonstrates its capabilities to support both open and closed-loop control routines. The embedded firmware and custom circuitry allow the unified systems controller to serve as a versatile controller for PBF systems, and a powerful tool when investigating and coupling process effects to system behavior.

Introduction

AM is a digitally native cyber-physical process and requires a heavily automated process flow to generate the required numerical control (NC) programming driving the production platform. As the NC programming is generated differently not only based on material, process parameters and geometry but also according to the targeted production platform, machine vendors have been able to keep laser powder-bed fusion (LPBF) systems mostly proprietary. Most LPBF systems are offered through solutions providers accompanied with bespoke materials to solve a specific manufacturing problem (e.g. implants, engine components). While this model allows companies to efficiently grandfather certification for specialized production, the broader adoption of LPBF is limited by the lack of direct and open access to the controllers of said production equipment.

To democratize access to customizable systems solutions and increase the generic systems understanding the LPBF systems and process control will need to be addressed and standardized, from the preliminary part-specific generation of NC programming to the automated machine response to such NC command protocol. Granting the researcher full and open access to the system, process flow, process parameters, sensor data, and material selection allows a deterministic and holistic process understanding. Some system providers have over recent years presented more open systems (e.g. Aconity GmbH), however, openness can be perceived as a gradient, and the current commercially available systems do not provide access to the embedded core programming of their systems controllers.

Presented in this paper is an embedded open-architecture systems controller providing the direct low-level hardware control relevant for in-depth LBPF systems research.

Openness and Access in AM

Defining *openness* is not straightforward, however, it is more intuitive to describe what it is not. Examining the contradistinction reveals a proprietary, black-boxed system, where only a predefined subset of process parameters can be changed by the user. The intermediate process flow is concealed, and the inner workings of the machine are executed by proprietary control algorithms. Openness is the opposite namely, access and transparency. To further define openness in terms of a production system, it can be subdivided into key constituents; material selection, process parameter selection, process sensors data, process control and system access, see Figure 1. Openness is however not a strict division, it is better described as a gradient, and each of these constituents can be more or less open. In the extreme, no component or subsystem of the entire system would be allowed to carry out any task not fully revealed and controlled by the researcher. This is not feasible, as specialized equipment such as lasers, scanner systems and process sensors are all introduced to the system as off-the-shelf components, the important aspect of utilizing such subsystems is ensuring that the communication protocols are open and accessible, ideally, but not necessarily, following a standardized control protocol.

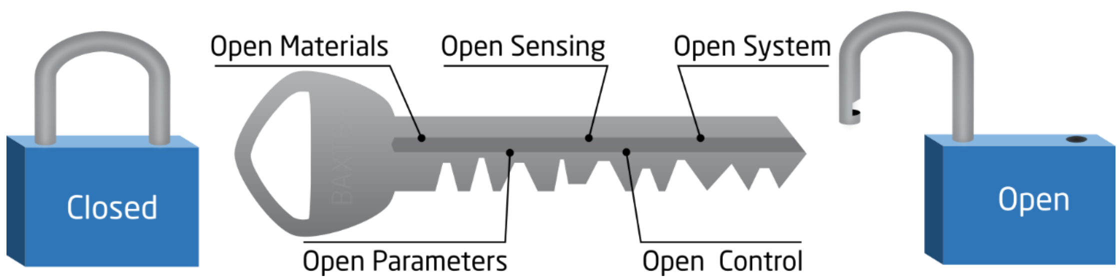

Figure 1: Key constituents of PBF openness.

Truly open architecture systems are open not just in terms of the hardware but also allow the user access to the underlying control routines. To conduct system research and study elaborate cause-effect relations relevant to LPBF the system will have to be open and accessible, and thereby require the developer and the user to distinctly access, assess, and influence the underlying process assumptions. Assuming control over such a system and pursuing real-time closed-loop process control is not a trivial task[1]. Coupling the controllable process parameters' process signatures and their influence requires the researcher to have access to the sensor data reflecting the process signature as described by Vlasea et. al. [2] . Furthermore, to determine cause and effect and the resulting signature, the researcher will be required to alter the controllable process parameters.

In their review of in-situ process monitoring and metrology of metal AM (MAM), Everton et al. recognized that a lack of reliability and maturity is one of the main barriers to the adoption of MAM processes more widely in the industry[3]. The integration of process monitoring systems in LPBF would enable an understanding of the interaction between laser and the powder bed. Further, it will help generate process-structure-property-performance relationships which are highly influenced by the temperature distribution and homogeneity of the powder bed. As an example, the temperature distribution can especially be related to the final product quality, as it affects residual stresses, microstructure, mechanical performance, surface finish, and dimensional accuracy. Keeping the temperature of the powder bed under control is therefore essential to ensure consistent and high-quality products[4]. Process monitoring can also help overcome existing challenges in non-destructive post-process inspection[5].

LPBF monitoring collects process data using sensors installed inside the machine (in-situ). Many different technologies can be used, and descriptions have been presented in various review papers[4–6]. The main types of sensors used in LPBF are optical/ electromagnetic sensors that capture light from the process and correlate it to the part quality. Acoustic sensors are also feasible, but they present challenges in data analysis and correlation to part quality. Electromagnetic sensors are divided into spatially resolved and spatially integrated sensors. Spatially integrated sensors like a photodiode convert one single point of information at each spatial location into a heat map. Spatially resolved sensors like a CMOS camera are slower to capture data but can contain information regarding the entire spatial field of interest, and sometimes at a high spatial resolution. Kruth et al. developed a feedback control system that keeps temperature below a threshold in real-time, using a high-speed CMOS camera and photodiodes in an own-built machine. The laser power was adjusted in accordance with the changes recorded in the controlled parameters. Parts were then printed using the photodiode control loop or the CMOS control loop. The photodiode control loop showed a clear improvement on the overall surface [7–9]. An intelligent type of sensor analysis can also be guided by the results of process simulation, which identify the most critical areas in advance and signal where an accurate monitoring is required or plan for a change of process parameters. This reduces the amount of data to be collected and analyzed for quality control, by limiting this to the crucial area identified by the simulation.

The most important limiting factor in LPBF systems today is the lack of a robust feedback control from existing monitoring systems. The control architectures necessary to process large amounts of data in real-time, perform computations and generate recipes for changing process parameters are complicated and not possible today in commercially available systems [10]. The current work presents an open-architecture control framework that can capture data from many types of in-process sensors and in real-time make process parameter changes. Such a control architecture opens the door for real-time feedback control in the LPBF process.

Controllable Process Parameters in LBPF

To determine the required capabilities of the unified system controller, the controllable process parameters will have to be defined. LPBF describes a process using a scanner to move a high-power laser across a powder bed in order to melt and consolidate the feedstock into solid matter. In between each scan, the powder bed is lowered vertically equal to one layer, the unconsolidated feedstock is spread on top of the consolidated layer, and the laser consolidation is repeated until the full extent of the desired geometry has been consolidated. Historically, energy density has been applied as a useful but simplified process designator and comparator. Line Energy Density (LED), Areal Energy Density (AED) and Volumetric Energy Density (VED) all appear in literature, and jointly provide account for governing and directly controllable process parameters; laser power (P), scanning speed (v), layer thickness (t), spot size (d), and hatch distance (h):

$$LED = \frac{P}{v}\left[\frac{J}{mm}\right] \qquad AED = \frac{P}{vd}\left[\frac{J}{mm^2}\right] \qquad VED = \frac{P}{vht}\left[\frac{J}{mm^3}\right]$$

Energy density serves as a starting point in describing the required parameter control, however, to ensure a stable process it is essential to remove unwanted spatter and plume from the consolidation process. This is carried out by providing an inert laminar gas flow across the powder bed, furthermore, to avoid balling and oxidation the melting process will have to be conducted in an inert atmosphere (<1000 ppm O2).

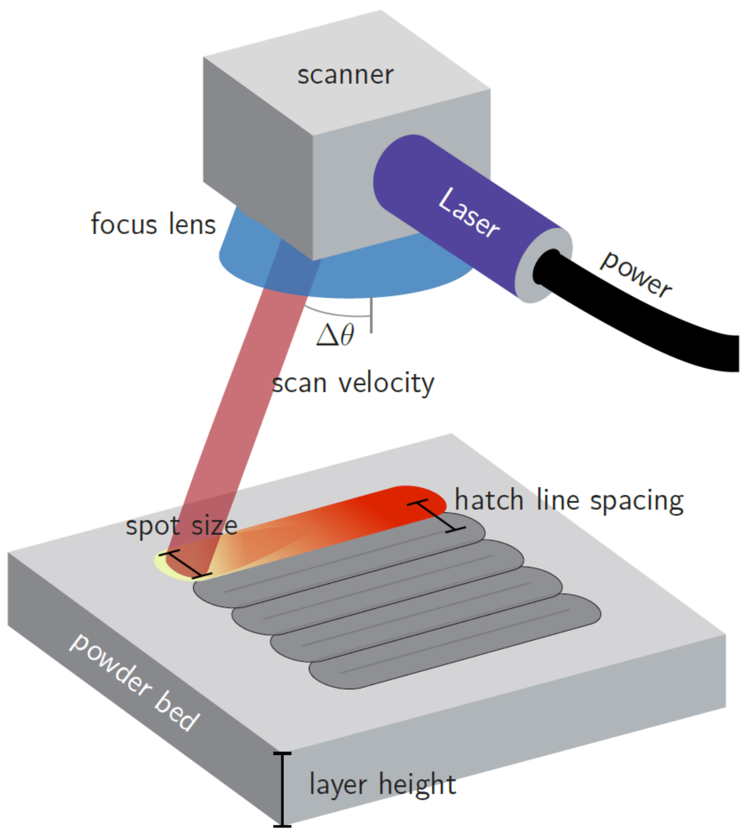

Figure 2: Sketch of process parameter.

Open Architecture Constituents

The unified systems controller is currently demonstrated on 3 open architectures experimental PBF systems, two LPBF systems and one SLS system. The initial open architecture LPBF system[11] features a digital scanner system, a single mode fiber laser, beam expander, gas flow, multi-material powder deposition, process sensors and powder handling mechanics. An overview of the different subsystems is displayed in Figure 3, and Table 1 provides a list of the specific control protocol utilized to drive the different subsystems. Shared among all the subsystems are open and accessible control protocols. The systems at DTU have been developed to meet state of the art, while maintaining an open architecture, and will eventually deploy under the Open Additive Manufacturing Initiative as part of an open-source framework.

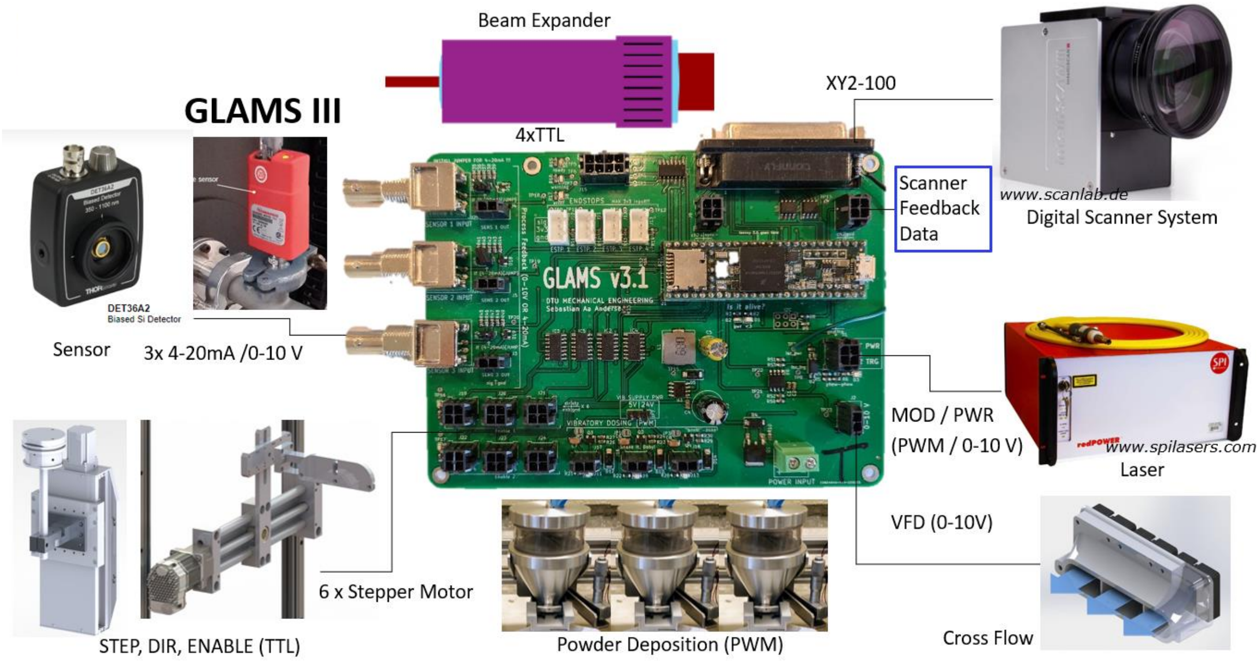

Figure 3: Overview of the unified systems controller and the auxiliary subsystems that it currently serves as constituents of the open architecture L-PBF research platform at DTU.

Table 1: List of the auxiliary capabilities featured by the unified systems controller.

	Count	Control Protocol
Scanner	1	XY2-100
Stepper Motor	6	TTL (STEP,DIR,ENB)
Endstops	3	
Laser	1	TTL/0-10V
Crossflow	1	0-10V
Sensor	3	4-20mA or 0-10V
Beam Expander	1	TTL
Powder Dosing	3	PWM TTL

Process Operations

Initially, the NC program is prepared from a 3D geometry loaded into a job generator, coupled with scan strategy and process parameters. This software subdivides the geometry into required layers and converts the geometry into a list of commands that defines the way the unified systems controller operates the PBF machine the commands resemble traditional NC programming and adheres to some fundamental functionality. The adapted NC commands have been specialized to the relevant open architecture PBF system.

The processing operations are subdivided into different categories; synchronized-, unsynchronized- as well as continuous operations. The laser and scanner directly control the laser power and the scanning strategy. Typical scanning trajectories can reach several meters per second, and therefore, laser and scanner operations are required to be run in a carefully synchronized control-loop. The other main operations of the LPBF machine does not require as carefully timed. Powder handling mechanisms, such as dosing, repositioning the build plate and recoating a powder layer, are driven by motorized movements and occur subsequently step by step in between the consolidation process.

The gas flow removes undesired spatter and plume from the consolidation process and needs to run continuously throughout the build, therefore it is run by closed-loop PID control, where the gas flow is measured by a thin film anemometer and the data is transmitted into the unified systems controller correcting the gas flow to reach the setpoint by regulating a variable frequency drive (VFD) coupled to a vortex flow pump.

Synchronized Process Control

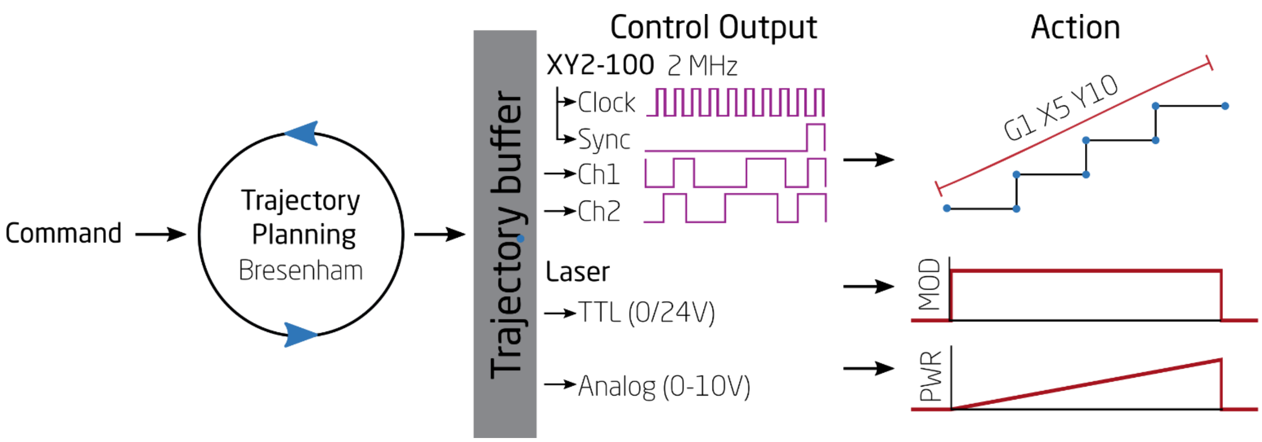

Figure 4: Laser and Scanner Command flow. Initially, the command is received and stored in a circular buffer. As the XY2-100 protocol starts transmitting the position to the scanner system, the unified systems controller enables the laser to provide a synchronised laser and scanner output.

The synchronized laser and scanner operation is displayed in Figure 4. Each single NC command is initially received over the communication port from the workstation computer. The received command is then processed and stored in a circular buffer. The commands are carried out in the same order as they are received. The trajectory buffer only holds instructions about the current command, and then as the XY2-100 protocol transmits the positional control word to the scanner system, the laser is synchronously enabled and modulated to match the instructions. The scanning trajectory is then realized incrementally until the required position is reached, and the following command commences.

Laser Control

The state of the laser is operated with a simple two-line control protocol. One line is responsible for setting the output power level of the laser, this is controlled by a 0 - 10 V control signal. On the controller this is operated by a 10-bit DAC, providing 1024 discrete power output levels. With the current 250 W SPI laser installed in the open architecture system, this equals a resolution of 0.24 watts per increment. The other control line sets the enable signal of the laser and can be set to run both in continuous mode and in pulsed mode. The pulsed laser output is determined by setting the duty cycle and frequency of each period and is driven by a 24V PWM signal, currently, the laser can be modulated with 100 kHz.

Scanner Control

The scanner system responsible for generating the trajectory and traversing the laser around the powder bed consists of two mirrors mounted on galvanometer motors. Scanners like this are either analog or digital, referring to the control interface. Typically, an analog scanner is controlled by distinct analog setpoint voltage-signals, whereas a digital scanner adheres to a control protocol. The theoretical application of analog control signals provides infinite resolution, in reality, however, the set point voltage is generated digitally. Therefore, the control signal is only quasi-analog, as it is fitted into a discrete control regime, controlled by the resolution of the digital to analog converter (DAC).

Different digital scanner protocols exist, some are open and freely accessible as the XY2-100 protocol, see Figure 5, whereas others are proprietary as the SL2-100 protocol. When controlling an analog scanner system one must be careful as the control signal is susceptible to electrostatic noise. The digital protocol is more robust as the signals transmitted are binary and transmitted as differential pairs, another strong point of the digital protocol is the additional information that can be fitted between the controller and scanner.

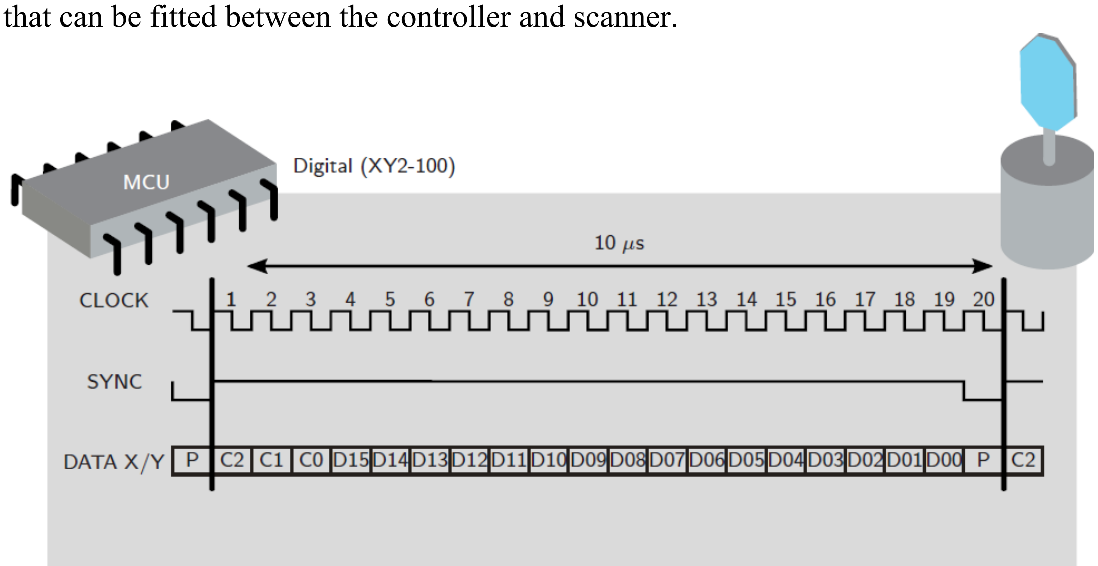

Figure 5: XY2-100 digital scanner protocol [11]

The XY2-100 protocol is a 20-bit 2 MHz asynchronous control protocol that consists of 4 differential pairs that transmit a clock, sync and two data channels holding the mirror position to each mirror, see Figure 5. The first 3 bit of the data stream describes the control mode of the scanner (C0,C1,C2) the next 16 bit determines the position of the scanner (D00-D16) , and the last bit is a parity bit used to set the check the validity of the 20-bit control word, and disregard it if it were corrupted during transmission. The resolution of the two galvanometers mounted within the scanner systems defines a 2D discrete space with 16-bit x 16-bit resolution, as the laser trajectory moves Bresenhams line approximation algorithm is applied to utilize the correct incremental positional change of each galvanometer to provide an approximation of the straight-line segments contained with the job file.

Direct Memory Access

To achieve this 20MHz control protocol with the ARM Cortex-M4 mounted on the teensy 3.6 that is applied in the current uniform systems controller, the embedded programming takes advantage of the direct memory access (DMA) capabilities of the microcontroller. DMA allows the pin state to directly reflect the state of an internal set register without occupying additional CPU time. The processors 180 MHz ARM Cortex-M4 is single-threaded, and therefore to be able to receive additional commands, precompute the intermediate positions and control other subsystems the XY2-100 designated operational loop setting the register reflected on the output pins is coupled to a timer interrupt service routine (ISR). To ensure that the scanner and laser operations is never halted while waiting for new commands sent by the workstation, the commands are continuously received processed and stored in a circular buffer. The communication with the workstation transmitting the NC job file one command at a time is only halted briefly every 10us in order to set the next incremental update of the scanner.

In-situ Process Monitoring

The open architecture system developed was intended to provide state of the art capabilities not only in terms of accessibility and control but also to meet the research requirement of providing open and accessible sensor data. As the unified system controller provides 3 different sensor inputs, all individually capable of receiving either 0-10 V or the more industrially adopted 4-20 mA sensor signal. The sensors currently integrated into the embedded programming cover a variety of different industrial sensors measuring oxygen content, gas flow, pressure and light intensity.

Several publications[12–14] have deployed coaxial monitoring systems to measure the back reflection from the consolidation process and worked on correlating the generated data to useful metrics providing the basis for a closed-loop process optimization. The open architecture system is therefore also equipped with an optical breadboard to allow easy instalment of sensor modules or optical beam preparation, see Figure 6. A schematic of the initial coaxial sensor module is displayed in Figure 7, the dichroic mirror reflects the laser wavelength (1050 nm - 1150 nm) into the scanner. The process emission returned coaxially along the laser meets the same dichroic mirror, where, the wavelength outside of the reflected range is transmitted and sent through a cut-off filter (>1180 nm), and the back emission finally reaching the photodetector is then in the near-infrared range 800 nm – 1800 nm.

Figure 6: Image of current the current open architecture system at DTU (left), alongside (right) render of the top side enclosure holding the coaxial process sensor, scanner system and laser collimator.

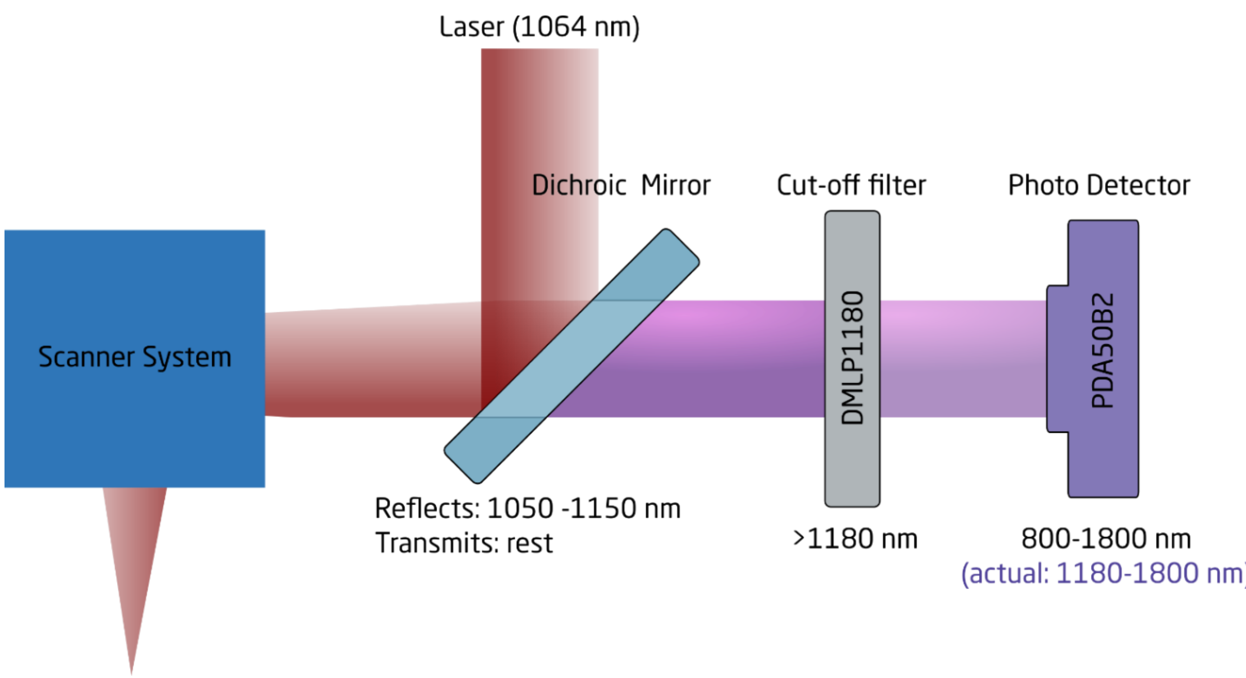

Figure 7: In-situ coaxial photo diode sensor configuration.

The initial test of the in-situ coaxial sensor module was done to producing a baseline. This was done by engraving 18 straight lines with constant velocity and power while recording the back-reflection at 100kHz by a NI-9215 module. By coupling light intensity to the spatial position of the laser it was possible to provide the baseline intensity map displayed in Figure 8. The intensity map displayed a uniform response in the center of the build plate. The unstable ring-shaped region is believed to be an artefact of spherical aberration. This will be remedied in future versions by including achromatic doublets and focusing optical elements.

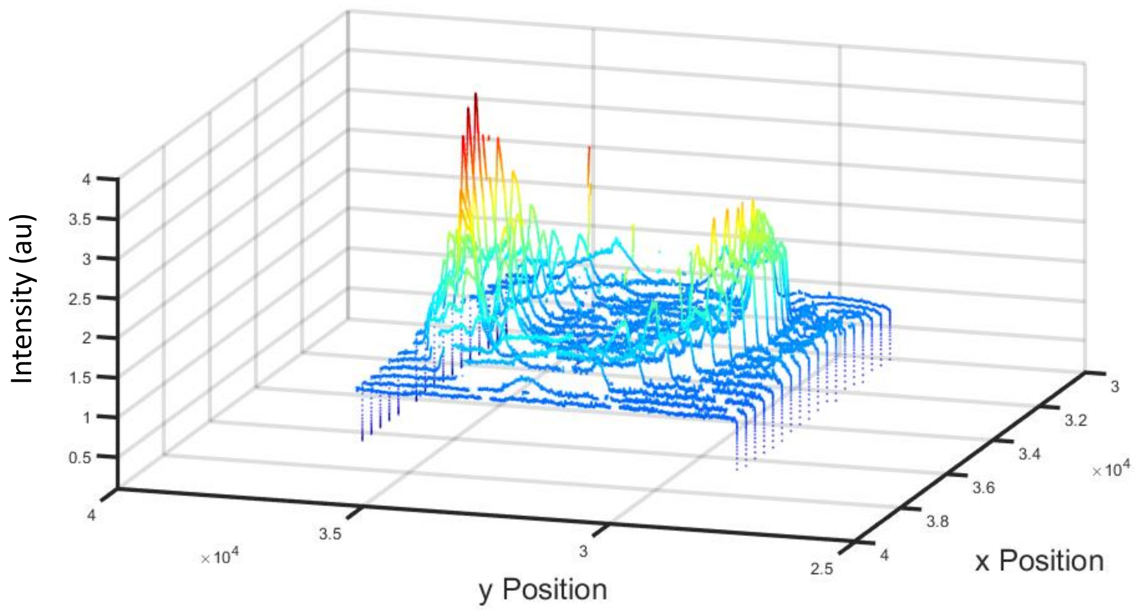

Figure 8: Coupling the scanner positional data with the photo diode intensity.

Utilizing the uniform center region revealed by the base-line map, a DOE was carried out to create weld tracks in 316L, with different laser powers (50 W, 100 W, 150 W, 200 W and 250 W) and scanning velocities (100 mm/s, 200 mm/s, 300 mm/s, 400 mm/s, 500 mm/s and 600 mm/s) . Figure 9 displays the results, the image shows the different scan tracks carried out, the numbers highlighted on the image correlates to the order in which the average track intensities are displayed in the average line intensity plot. The intensity of the back reflected data were averaged for each line and displayed, supporting the intuitive understanding that a higher energy density results in higher process emission intensity.

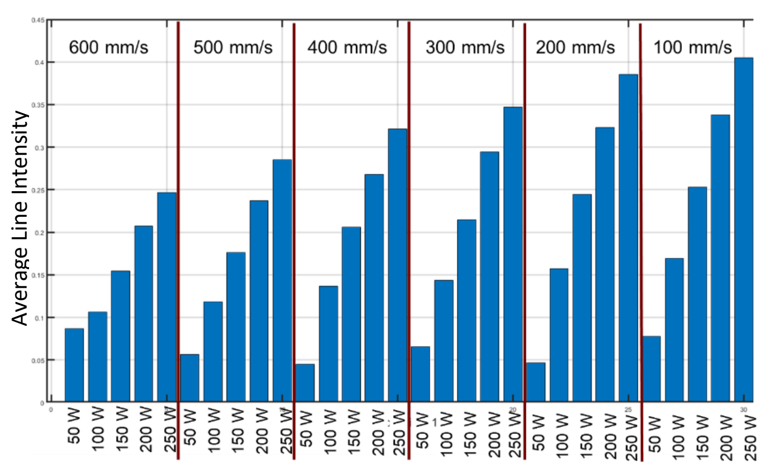

Figure 9: DOE, image of weld tracks conducted in 316 L (left), average line intensity plot (right).

Power Ramping

A unique feature implemented in the unified systems controller and supported by the adapted NC programming for laser and scanner control is ramping of the laser power. Meaning that the power and duty cycle of the laser can be gradually adjusted across a single command. Currently, it has only been demonstrated in a preplanned way, however, decoupling the need to maintain constant laser power and modulation during single commands paves the way for adjusting the laser on the fly, ideally providing a closed-loop control algorithm. In figure 10 the normalized intensity plots show a code sequence equal to the 4 commands (with constant scanning velocity 300 mm/s):

1. Move to position -5.5
2. Move to position -1.5 while ramping the laser from 0 W to 250 W
3. Move to position 1.5 while keeping laser steady (no ramping)
4. Move to position 5.5 while ramping the laser from 250 W down to 0 W

The left plot in figure 10 displays this ramping maneuver while keeping the laser continuously on, while the right plots display the normalized intensity of the back-emission when the laser is pulsed at 1 kHz and with a duty cycle of 80%. Hence, having demonstrated the coaxial monitoring module as presented in the previous section, it now serves as a tool to measure and verify the embedded control algorithms.

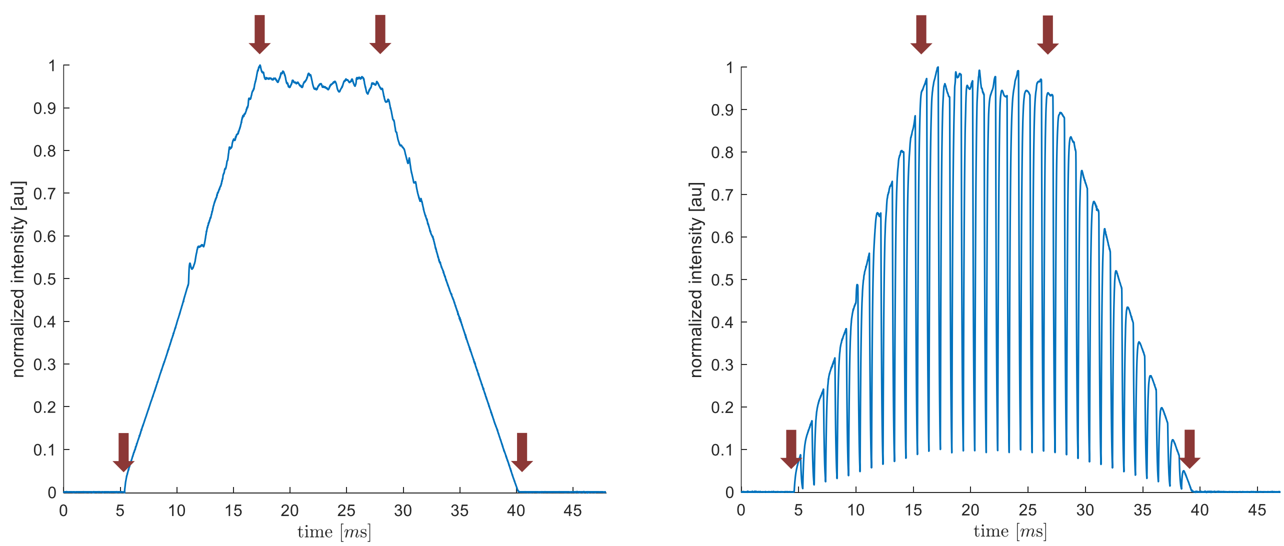

Figure 10: Back-reflection emission intensity while ramping the laser power, both in continuous mode (left) and pulsed 80 % duty cycle 1kHz (right).

Conclusion

The unified systems controller presented within this paper is currently running 3 different open architecture PBF systems at DTU. Demonstrating versatile and specialized functionality relevant for PBF systems. The embedded firmware allows the user to readily implement new and unique features, coupling sensor data directly to the laser control, or by creating multi-material in-situ powder blends. The controller supports a wider variety of auxiliary subsystems; digital scanner systems, lases, motor control (recoating and layer adjustment), endstops, multi-material powder deposition, gas flow control, beam shaping and process sensors.

Coupling the controller with ever changing open architecture experimental platforms will require the embedded programming and unified systems controller to evolve. But, as the fundamental design and programming has already been provided and demonstrated, the next iterations will not require massive restructuring, and readily be able to support future research within PBF.

The unified systems controller fills a void in the PBF market, and with its open-source release it will be able to aid system research, by providing an open and customizable way of directly controlling open-architecture PBF systems without being retained by proprietary systems and system controls.

References

1. Mani, M. *et al. Measurement Science Needs for Real-time Control of Additive Manufacturing Powder Bed Fusion Processes*. (2015) doi:10.1201/9781315119106.
2. Vlasea, M. L., Lane, B., Lopez, F., Mekhontsev, S. & Donmez, A. Development of powder bed fusion additive manufacturing test bed for enhanced real-time process control. in *Proceedings - 26th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2015* 527–539 (2020).
3. Everton, S. K., Hirsch, M., Stavroulakis, P. I., Leach, R. K. & Clare, A. T. Review of in-situ process monitoring and in-situ metrology for metal additive manufacturing. *Materials and Design* vol. 95 431–445 Preprint at https://doi.org/10.1016/j.matdes.2016.01.099 (2016).
4. Spears, T. G. & Gold, S. A. In-process sensing in selective laser melting (SLM) additive manufacturing. (2011) doi:10.1186/s40192-016-0045-4.
5. Tapia, G. & Elwany, A. A Review on Process Monitoring and Control in Metal-Based Additive Manufacturing. *J Manuf Sci Eng* **136**, (2014).
6. McCann, R. *et al.* In-situ sensing, process monitoring and machine control in Laser Powder Bed Fusion: A review. *Addit Manuf* **45**, 102058 (2021).
7. Kruth, J. P., Mercelis, P., van Vaerenbergh, J. & Craeghs, T. Feedback control of selective laser melting. *Proceedings of the 15th International Symposium on Electromachining, ISEM 2007* 421–426 (2007).
8. Clijsters, S., Craeghs, T., Buls, S., Kempen, K. & Kruth, J. P. In situ quality control of the selective laser melting process using a high-speed, real-time melt pool monitoring system. *International Journal of Advanced Manufacturing Technology* **75**, 1089–1101 (2014).
9. Kruth, J.-P. *et al.* On-line monitoring and process control in selective laser melting and laser cutting. in *Proceedings of the 5th Lane Conference, Laser Assisted Net Shape Engineering* vol. 1 23–37 (2007).

10. Dunbar, A. J., Nassar, A. R., Reutzel, E. W. & Blecher, J. J. A Real-Time Communication Architecture for Metal Powder Bed Fusion Additive Manufacturing. *Solid Freeform Fabrication 2016: Proceedings of the 27th Annual International* 67–80 (2016).
11. Andersen, S. A. Open Architecture Laser Power Bed Additive Manufacturing. (Technical University of Denmark, 2020).
12. Fox, J., Lane, B. & Yeung, H. Measurement of process dynamics through coaxially aligned high speed near-infrared imaging in laser powder bed fusion additive manufacturing. in *SPIE Vol. 10214* (eds. Bison, P. & Douglas, B.) (SPIE, 2017). doi:10.1117/12.2263863.
13. Fisher, B. A., Lane, B., Yeung, H. & Beuth, J. Toward determining melt pool quality metrics via coaxial monitoring in laser powder bed fusion. *Manuf Lett* **15**, 119–121 (2018).
14. Demir, A. G., Giorgi, C. de & Previtali, B. Design and Implementation of a Multisensor Coaxial Monitoring System with Correction Strategies for Selective Laser Melting of a Maraging Steel. *Journal of Manufacturing Science and Engineering, Transactions of the ASME* **140**, 1–14 (2018).