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ON INLINE PROCESS CONTROL FOR SELECTIVE LASER SINTERING

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Abstract: *In Selective Laser Sintering, powdery materials are locally melted layer by layer by the energy input of a laser. The temperatures within the powder bed and the energy input of the laser have a decisive influence on the properties of the workpiece to be manufactured. Poor temperature conditions can lead to distortion due to premature crystallization, uncontrolled growth or other defects within the part. In order to avoid the production of time-consuming and cost-intensive scrap but also to meet the requirements for mass personalized products, it is of considerable economic importance to identify and apply optimal fabrication parameters. For this purpose, an approach for an industrially scaled inline process control for Selective Laser Sintering is introduced. In combination with monitoring systems, e.g. thermographic cameras, the presented architecture can be used to adjust fabrication parameters to the transient conditions in order to guarantee high-quality results and the reliability of the process.*

Key Words: Selective Laser Sintering, Monitoring, Thermo-mechanic Modeling, Inline Process Control

1. INTRODUCTION

Additive Manufacturing technologies are becoming increasingly important on the international market. Especially for the personalization of products with regard to mass production, called *Mass Personalization*, Additive Manufacturing processes play a decisive role [1,2]. In this context, personalization means the customer's creative participation in the product development process. The personalization can be achieved by e.g. the pro-active use of design tools by the customer itself, or through semi-automated design adaptations based on gathered personal data. In contrast to individualization, it is not only possible to select and combine single components from a limited pool of predefined options; rather, unique shapes and geometries can be generated during the process of personalization. In any case, the efficient manufacturability and resulting part quality are central challenges and illustrate the need for flexible production technologies like Additive Manufacturing [3]. With these technologies parts of small batch sizes can be produced economically, since the time-intensive and cost-intensive tool and mold production is completely eliminated [4,5]. Additionally, it is possible to create complex geometries like internal and freeform structures, which cannot - or only with great effort - be realized by conventional manufacturing processes [6]. However, the use of additive processes currently still entails a number of challenges, which have to be redressed in order to make the technology competitive on industrial scale. This includes, in particular, the level of automation, the number of applicable materials and the productivity as well as the reliable quality of parts, i.e. dimensional and geometrical accuracy and mechanical properties.

In Additive Manufacturing, the part quality depends to a large extent on non-linear multi-physical phenomena [7,8]. These phenomena are often influenced by unknown factors, such as inhomogeneous material properties and the position and orientation of the part geometry during manufacturing [9]. To ensure successful production, the effects often have to be determined iteratively with trial-and-error approaches by skilled operators within test builds or on basis of experience gathered from similar build jobs [10,11]. Under this condition, design engineers cannot efficiently utilize the potential in freedom of design, which is one of the key aspects of Additive Manufacturing. Since the high-quality production of new geometries is uncertain and can lead, in the worst case, to a damaged machine, process control is indispensable. The challenge of a batch size one production shifts the focus from the design into the manufacturability of the product. Consequently, the flexibility and agility required for *Mass Personalization* cannot be guaranteed without a deeper understanding of the process [12]. Unfortunately, this is currently only conditionally controllable, due to the limited opportunities for high-resolution and comprehensive simulation of the processes [13,14]. To counteract this fact and to meet the high requirements for *Mass Personalization*, a continuous monitoring of key state variables, like the temperature, is necessary, beginning at an early stage of the process using inline monitoring systems [15]. Based on the evaluation of these variables, quality statements can be derived. However, these assertions only are not sufficient to achieve a zero-defect manufacturing of small batch sizes without test builds. Rather, it is necessary to make use of this information and dynamically adjust selected fabrication parameters to the transient conditions in order to lay the foundation which contributes to a successful and standardized production [16]. The aim is not only the increase of process reliability, but also to reduce the duration of manufacturing, the occurrence of defects, and thus the required post-processing for improvement of the accuracy and surface finish. In addition, the need for an in-depth understanding of the process is shifted from the end users to the machine manufacturers, thus enabling a broad and less restricted use of the technology [17].

In this paper, fundamentals of Selective Laser Sintering are presented and the necessity for an inline closed-loop process control is illustrated in the context of *Mass Personalization*. In addition, a literature research was conducted and an overview is given about state-of-the-art closed-loop process control systems for powder bed fusion processes with reference to process monitoring (Section 2). Thereby, a number of challenges and current deficits have been identified, which limit the efficient use of the technology on an industrial scale. Therefore, new approaches for inline closed-loop process controls for Selective Laser Sintering of thermoplastics based on field programmable gate arrays (FPGA) were developed. Section 3 presents the developed concepts for a holistic architecture of an industrial closed-loop control system for Selective Laser Sintering and exemplarily shows possibilities for the adjustment of fabrication parameters. Section 4 summarizes and critically examines the preliminary results and describes the future work.

1.1. Fundamentals

Suitable Additive Manufacturing technologies for industrialized applications are next to Fused Filament Fabrication (FFF) mainly powder bed fusion processes as Selective Laser Melting of metals (SLM), and Selective Laser Sintering (SLS), usually of thermoplastics, ceramics, sands or various composites [18–20]. In Selective Laser Sintering of thermoplastics, polymer powder is applied in layers to a retractable platform inside a building chamber. The powder is preheated by infrared radiation between the crystallization point (glass transition temperature) and melting point. Usually, the chamber is filled with inert gas for reducing the oxidation capability of the powder and to suppress smoke emission, which can pollute the laser window or the powder bed. The protective atmosphere also influences variables like the melt pool size [21]. Subsequently, cross sections of the part to be manufactured are scanned and thus locally fused by the energy input of a laser. For this, a laser source provides a laser beam, which is focused by optical components and deflected by a scanner system. The scanner system mostly uses mirrors for positioning the laser spot across the building surface, which are driven by galvanometers. In the next step, the bed is lowered by the height of one layer and a recoater blade or roll applies new powder on top of the previous layer. Excess material is disposed in an overflow tank and can mostly be reused in the next building job. This sequence is repeated until the three-dimensional object is finished. Fig. 1 shows the schematic diagram of SLS.

A number of upstream and downstream steps are required to carry out the Additive Manufacturing process i.e. the production of a physical part based on a virtual three-dimensional model. The general process chain for Additive Manufacturing is shown in Fig. 2. However, the necessity and characteristics of the flanking steps largely depend on the used technology, machine properties and the later application of the part [22]. The geometry to be manufactured can be created using computer-aided design (CAD) software or derived from scan data of an existing physical part. The three-dimensional object is often converted into a STL file format (abbreviation of Stereolithography), also known as Standard Tessellation Language. The STL file format describes the surface of an object by triangular facets. Each triangle is defined by its three edge points and a surface normal vector. The STL file format is the de facto standard and mostly supported by software applications used for preparing the virtual three-dimensional model for the build process. In the next step, the position and orientation of the created model in reference to the coordinate system of the machine has to be determined. Depending on the orientation, the characteristics of the used technology and the geometry of the part, support structures have to be generated to ensure the manufacturability of overhangs or, in SLM, to dissipate heat introduced into the material. In SLS, the unfused powder serves as support for the solid areas within the powder bed, and thus, dedicated support structures are dispensable. This reduces the time for manufacturing and post-processing and improves the surface quality of the part, compared to other technologies, as no support structures need to be sintered and removed. In addition, large quantities of the unfused powder can be reused after reprocessing measures.

As most Additive Manufacturing technologies are layer-based processes, two-dimensional cross sections are required for describing the geometry of the part to be manufactured. Therefore, a mathematical separation of the three-dimensional volumetric model into the layers is necessary, which is mostly executed by a software application called slicer. The fabrication settings, such as the layer thickness and, in the case of SLS, mainly the diameter of the laser spot as well as the scan spacing, the path and velocity of the tool (here of the laser spot), are generated in relation to the cross-section.

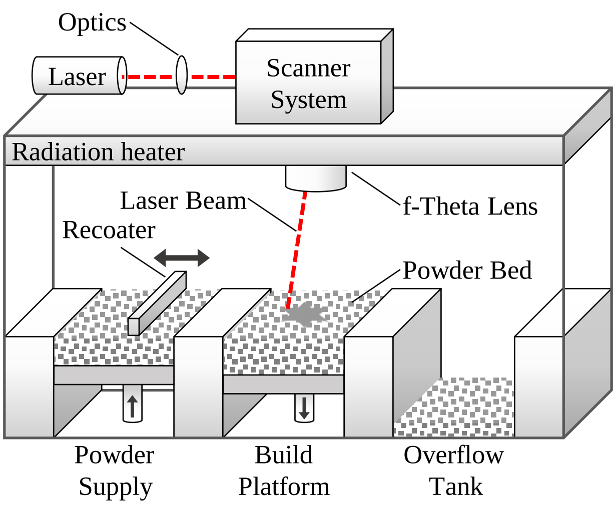

Fig. 1. *Schematic diagram of Selective Laser Sintering*

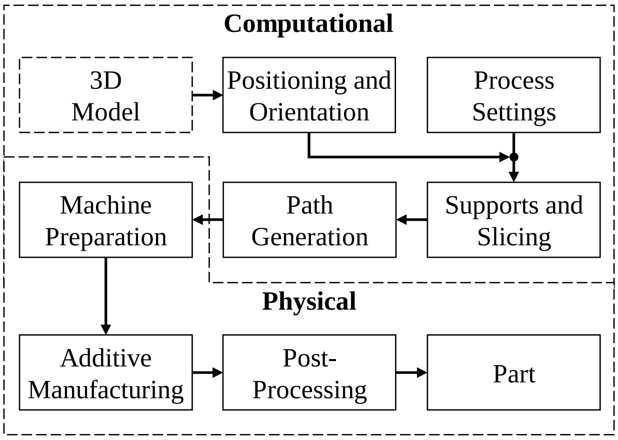

Fig. 2. *Process chain for Additive Manufacturing*

Various algorithms and strategies, aiming at different goals like the homogenous distribution of the energy input on the build surface, can be applied to generate these tool paths [23]. The used scan strategy, in addition to the position and build orientation of the part, has a significant influence on the manufacturing process and the resulting part properties, e.g. the part strength [24–27].

The paths are usually linear interconnected data points on the contour as well as specific points inside the geometry for describing the infill pattern. The slicer generates a machine-readable G-Code from the available geometric information, containing all instructions for the motors and other machine components, e.g. nominal values for heaters. The G-Code is then loaded and stored in the numerical control (NC) of the machine and subsequently processed and executed sentence by sentence, thus moving the laser spot and creating the part geometry. Next to the computation-based steps within the process chain, some physical preparations for Additive Manufacturing processes have to be performed. The machine has to be supplied with raw material for the manufacturing of the part. In SLS, mostly a mixture of new and reconditioned powder from previous builds is used. In addition, the atmosphere, as well as the powder is preheated. Then the actual process can be carried out. After the building process is completed, the entire powder bed containing the finished part has to be slowly cooled down, in order to prevent the occurrence of residual stress within the part due to thermal phenomena [28].

In the following, the part can be removed and cleaned of powder residues. Depending on the application of the manufactured part and the requirements to be met, additional post-processing steps are required. In order to achieve a good surface quality and high dimensional accuracy, mechanical or chemical post-processing is often indispensable, e.g. to reduce the staircase effect, which is caused by the discretization during the slicing process. In addition, deformations or uncontrolled growth of the part during the process itself often adversely affect quality factors and have to be reworked. These influences are in particularly results of poor process conditions, i.e. inhomogeneous temperature states. Due to the resulting fluctuating part properties, often a final quality assurance is needed. Especially in times of boost from rapid prototyping to rapid manufacturing, it is crucial to ensure consistent and high product quality.

1.2. Motivation

One of the main limitations in the practical use of SLS is the occurrence of defects, reducing the productivity of this technology and thus the possibilities for a broad industrial application. Most defects can be traced back to the thermal history and correlating variables like resulting microstructures and the geometric design of the part. These phenomena are often based on transient process conditions and difficult to predict, as they are related to machine-specific characteristics, environment or material properties, leading to unknown results in terms of part quality and process reliability. In general, the aim is to maintain the temperature fields of the entire powder bed in the metastable thermodynamic range between the crystallization point and the melting point of the used material – the so-called processing or sintering window [29]. If the temperature in sintered regions falls below the crystallization point, curling may occur due to contraction caused by premature crystallization and the resulted residual stresses. This effect can lead to the termination of the entire process due to recoater interferences and thus the loss of precious time and material [30]. Furthermore, residual stress can cause micro cracks and reduce the mechanical properties of the workpiece [31]. In addition, mechanical properties like tensile and fatigue strength are depending on the cohesion of the single paths and layers, but also influenced by pores and slags generated by e.g. present oxygen or hydrogen during the solidification of the melt pool.

In case of too low preheating temperature, it is possible that the energy input of the laser beam is not sufficient to achieve the penetration depth required to fuse the particles. This can cause deficient interlayer bonding and thus low tensile strength. In this context, also a slow and particularly homogeneous cooling of the semi-finished geometry after the actual building process is indispensable to prevent the occurrence of differential shrinkage, which can lead to warpage. In case of too high temperature, i.e. the temperature is slightly below or even above the melting point, uncontrolled growth of the part geometry and balling effects may occur. In addition, surrounding powder particles can adhere to the surface of the sintered geometry, which reduces the accuracy and surface quality of the part. Moreover, high temperature fields can lead to cracks on the powder surface. In fact, the temperature ranges in the entire powder bed are difficult to control due to unknown influences such as heterogeneous warming by the heating elements, thermal conduction and the time- and location-dependent energy input of the laser. These effects can lead to so-called hot or cold spots and high temperature gradients, adversely affecting process reliability and part quality by causing the mentioned defects [32].

In addition to the temperature fields, a large number of other variables are influencing the later part properties [33]. These variables can be laser-related (e.g. laser power, spot size, wavelength, etc.), scan-related (e.g. hatch spacing, scan speed and scan strategy) or depending on powder properties like the grain size and layer thickness. In order to overcome the negative effects of these phenomena and to apply optimum fabrication parameters, an inline closed-loop process control is necessary [34]. This control structure can compensate unpredictable events of process variation. The goal is to ensure process conditions related to the actual circumstances and thus enabling the manufacturing of high-quality parts. For this purpose, selected fabrication parameters are to be adjusted inline, based on strategies and algorithms related to monitoring data. In addition, the gathered measurement data can be used to determine quality statements of the manufactured part. Thus, the productivity can be increased, due to the reduction of safety factors, as the current scan speed and laser energy can be adjusted to the actual process properties and temperatures. The impact of deficient fabrication parameters due to lack of experience are to be mitigated. The goal is to support the industrial manufacturing of personalized high-quality parts without the need of extended test builds.

2. STATE OF THE ART

Beside extensive research in the field of modeling and simulation of thermo-mechanical phenomena in Selective Laser Sintering and Selective Laser Melting by e.g. Kruth et al. [18] and [35–37], only a small number of approaches can be found in literature aiming to implement closed-loop process controls for powder bed fusion processes. However, approaches for closed-loop controls are made for comparable processes like Laser Cladding [38–45]. These concepts can be mostly adapted and used for the control of powder bed fusion processes, particularly with regard to the monitoring and the underlying control architecture. A variation of the powder flow rate as control output for Laser Cladding, is not possible in powder bed fusion processes, due to the nature of the technology. In general, in-situ monitoring data, as feedback of the process state is required to realize a closed-loop process control. Due to the fact that the product quality e.g. geometrical, mechanical and physical properties of the part cannot be directly measured inline, process signatures have to be used to determine the later results. Based on the measured values and the correlating quality aspects, controllable process parameters can be adjusted. To monitor the process, various sensor systems can be integrated co-axially to the laser beam [46] or stationary [47], e.g. for monitoring the powder surface.

For this purpose, different non-destructive sensors like thermographic cameras [48,49], pyrometers [50,51], x-ray imaging [52] and acoustic emission sensors [53] can be deployed. An overview of monitoring approaches is given in [54] and with regard to closed-loop controls in [55]. In most cases of laser material processing, back-reflected radiation is monitored [56] and the prevailing temperature or the geometry of the melt pool, generated by the laser beam is derived. In the following, an overview of the research efforts for control schemes in Selective Laser Sintering of thermoplastics is given. Table 1 presents the feedback signal, the used setup and the control outputs for each mentioned approach. The table is sorted by publication date, starting with the latest articles.

Renken et al. [57] introduce extensive adjustments in the process itself, controlling the laser power and scan sequence by measuring the temperature distribution on the powder surface as well as the melt pool geometry. In addition, the powder surface is recoated if defects are identified. Fox et al. [58] measured the melt pool size with an infrared camera and recommend next to the adjustment of the laser power, the control of the scan speed by fast data processing. Craeghs et al. [59] measured the melt pool geometry using an estimation based on a modulated photo diode signal and stabilized the melt pool size with the adjustment of the laser power. The controls implemented by Chivel et al. [60] are based on the measurement of the temperature within the melt pool and the temperature on the layer surface to adjust the laser trajectory for a more uniform temperature distribution. Kruth et al. [61] compared two sensors for controlling the melt pool geometry by adjusting the laser power. Benda [62] developed a two beam approach, in which a larger beam is heating powder, surrounding the focused beam, which is used for the actual sintering. Both laser beams are temperature-controlled, whereby a more uniform sintering is reported.

The mostly used feedback signals in the presented research efforts are the melt pool geometry and the measured temperatures. All presented control schemes are primarily adjusting the laser power to maintain constant melt pool properties. The referenced authors have proven that inline controls are feasible and improving the quality criteria of the part to be manufactured.

Table 1. *Overview of the research efforts for control schemes in powder bed fusion processes*

Authors	**Feedback signal**	**Setup**	**Control Outputs**
Renken et al. [57]	Melt Pool Depth, Temperature Distribution, Topography	RGB Sensor, Infrared Camera Low Coherence Interferometer,	Laser Power, Scan Sequence, Recoating
Fox et al. [58]	Melt Pool Geometry	Infrared Camera	(Laser Power, Scan Speed)
Craeghs et al. [59]	Melt Pool Geometry	Photodiode	Laser Power, (Scan Speed)
Chivel et al. [60]	Melt Pool Temperature, Temperature Distribution	ICCD–Camera, Two-wavelength Pyrometer	Laser Power, Trajectory
Kruth et al. [61]	Melt Pool Geometry	Photodiode, CMOS Camera	Laser Power
Benda [62]	Melt Pool Temperature	Thermal Emission Detector	Laser Power

In order to achieve a near real-time control, the main challenges are a high-speed measuring and analysis as well as the exact measurement itself. For the control of the SLS process, a direct measurement of local process temperature and the temperature distribution is necessary. Additionally, the measurement of the melt pool geometry is useful for avoiding pores and an inhomogeneous melting process. To ensure the needed high frequency control systems, a field programmable gate array (FPGA) is recommended by [40,58,63]. Besides the hardware factors, deep knowledge of the process is necessary for implementing control strategies and models, for a positive influence on the process and the resulting part quality.

3. INLINE PROCESS CONTROL FOR POWDER BED FUSION PROCESSES

Closed-loop process control systems aim to adjust controllable fabrication parameters based on feedback derived from process variables in order to achieve uniform temporal and spatial process conditions and thus reliable and high-quality results. An overview, comparable with work presented in [64] and [65], of controllable fabrication parameters, related process variables and important part quality metrics is given in Table 2. In general, it is possible to adjust the listed fabrication parameters inline, if the system input values are estimated in high frequency, which is necessary for laser processes.

The effect of the adjustment influences process variables, which can be measured with in-situ monitoring systems. The gathered feedback is used to adjust the set points with regard to the actual process and thus compensating unknown disturbances. These process variables represent the process conditions, which are responsible for the product parameters. The controllable fabrication parameters are the basis for the development of a suitable control architecture. The aim is to identify strategies and laws for adjusting these parameters in a way that the process conditions are uniform and within defined limits, so that a high product quality is achieved.

Table 2. *Overview of parameters and variables for SLS*

Inline Controllable Fabrication Parameters	**Measurable Process Variables**	**Important Part Quality Metrics**
Laser power	Melt pool temperature	Dimensional deviations
Laser spot geometry	Powder bed temperature	Strength and elongation
Laser scan speed	Chamber temperature	Hardness
Fill scan spacing	Melt pool geometry	Density and porosity
Scan strategy/path	Powder surface quality	Fatigue resistance
Order of scans	Powder characteristics	Residual stress
Layer thickness	Oxygen content	Surface roughness
Recoater velocity	Inert gas speed	Surface quality
Heater Outputs	Plume characteristics	Color and appearance
Inert gas level and flow	Process times	Defects

Therefore, different control architectures can be applied. Fig. 3 shows the schematic structure of a closed-loop control architecture with feedforward and feedback controller. The feedforward control compensates predictable disturbances of the process and improves the reaction to changes of the set points without reduction of the stability. The feedback controller can include different approaches.

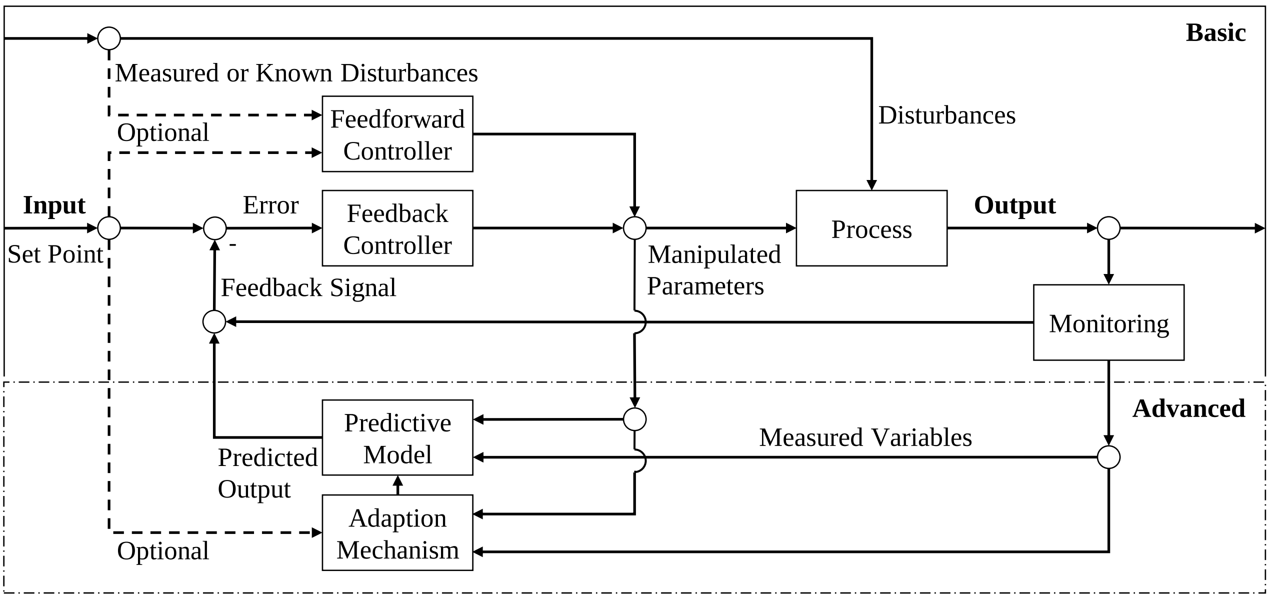

Fig. 3. *Simplified control architecture with feedback, feedforward and adaptive model predictive control*

A common method is the proportional–integral–derivative (PID) controller, calculating the difference between the desired set point and the measured feedback signal and thus setting corrected parameters. Advanced solutions use e.g. adaptive process models. These models are especially useful for complex processes with initially uncertain parameters, because the model can be adapted to the time-varying process parameters. Adaptive control approaches can be realized in various architectures with different goals. Next to these solutions, predictive control systems can be used to estimate the future state of the process and thus optimize the input.

3.1. Industrial-Scale Control Platform

For conventional industrial applications, real-time industrial personal computers (IPC) are used which provide superordinate holistic control systems. However, the IPC cycle frequency of typically 1 kHz is not suitable for high-frequency clocked laser control applications (typically 100 kHz). To enable a dynamic and flexible high-frequency real-time process control, an open and modular automation platform is required. Here, the control architecture is divided into two frequency cycles: high-frequency calculations on the FPGA-platform, which provides control variables by interpolating the given set points from the lower-frequency IPC-control platform (see Fig. 4) [66]. This enables direct machine control e.g. for scanner movements (path of the laser spot), which is usually hardly accessible due to its separation from the central control system in commercial systems. Here, a FPGA-application is developed which controls both, the laser scanner system and the laser beam source synchronously in the required cycle frequency of 100 kHz. The real-time communication between the high-level control (IPC) and the FPGA is realized by a fieldbus (here EtherCAT). Through a fieldbus port, the high-frequency controller receives set point arrays, which are to be run within the current IPC-cycle. These set points are processed by logical operations and can be manipulated by a software that runs on an internal processor. The interpolated set points are provided to the laser system via specified input/output (I/O) ports. For utilization of industrial laser and laser scanner products, certain protocol standards are used (e.g. XY2-100-E). In addition, monitoring data can be analyzed effectively, using the FPGA resources, by ensuring the time-critical provision of feedback signals. The FPGA board contains besides the programmable hardware module, software algorithms for real-time computation that can easily be edited and adapted to certain application needs. Next to the FPGA, an industrial scaled control platform containing a programmable logic controller (PLC) and a numerical control (NC) module is used to achieve a high flexibility. The PLC and NC communicate in real time on an internal communication protocol. The fieldbus connects process I/Os as well as other external components, such as drive amplifiers, to the PLC module. Within this control architecture, the IPC provides all system-oriented automation and NC-cycled program calculation and exposes process strategies. For example, trajectory planning can directly be calculated in sequences of NC cycles or also be processed in NC subprograms that are pre-configured in the process planning.

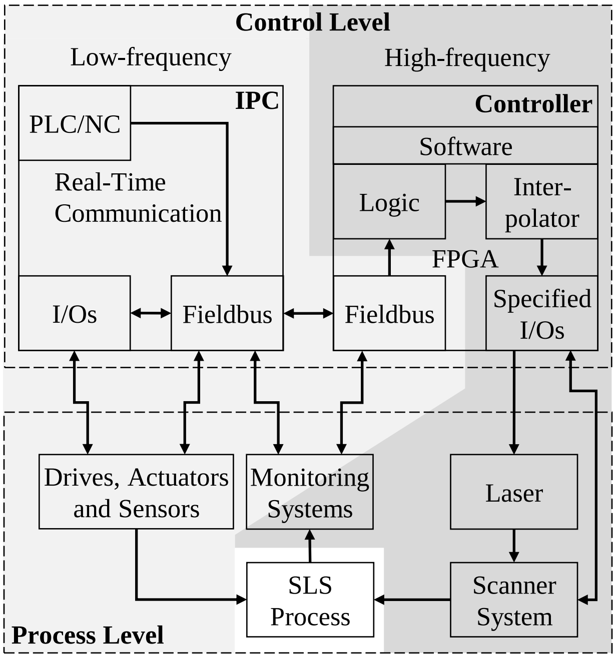

Fig. 4. *Schematic diagram of control platforms for laser-based processes using FPGA*

Process events or measured process states can directly be detected on the IPC. Thus, algorithmic evaluation can trigger system reconfigurations, which initiate automated closed-loop disturbance compensation. This control architecture is modularly and flexibly designed and yet high-frequently cycled so that inline process control can effectively be applied by direct control access.

3.2. Closed-Loop Control Concepts for SLS

With the gained freedoms and the possibilities offered by an open automation platform, various closed-loop control architectures and strategies for improving the process quality can be realized. However, the real-time requirements of the control platforms and the associated reduction of numerical processing capabilities as well as the process-related implementation limit the scope for technical realization. Therefore, efficient strategies for closed-loop control must be developed, regarding the process properties, with respect to control and process boundary conditions. Different concepts and combinations of these strategies can be pursued, with the aim to achieve uniform process conditions and thus high-quality product standardization. Fig. 5 shows the ascertained decision basis for the control strategy. The control strategy can be based on various architectures, e.g. adaptive model predictive control approaches, adjusting controllable process parameters. The main parameters are the laser power and laser scan speed, which have a significant effect on the process variables and thus the resulting part properties [67]. Here, the laser power and laser scan speed have a non-linear correlation, requiring a complex control. The laser power and laser scan speed is to be controlled on the FPGA. The laser spot geometry and the order of scans require less strict frequency control. Therefore, the control is implemented on the high-level IPC, with the aim of uniform process conditions. The adjustment of the laser spot geometry depends on the area of the powder surface to be exposed and is realized by modulating the laser beam.

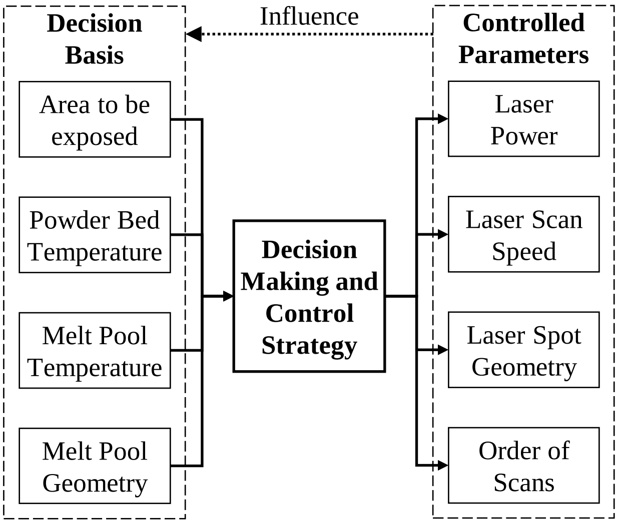

Fig. 5. *Basis for the control strategy and controlled parameters*

The aim is to regulate a constant process temperature over the entire working area by using a larger laser spot to heat cold spots on the powder surface without sintering the material. The cold spots are identified by a thermographic camera. A small spot size is to be applied, when outer contours have to be sintered, in order to ensure a high resolution and the associated accuracy. The infill of the geometry can then be sintered with a medium laser spot size, to increase the exposed area along a path motion. In this context, especially multi-laser solutions are feasible to reduce the time of scanning for each layer and thus the manufacturing time. For this purpose, the process evaluation in the PLC-system gets its information directly from the camera and can not only influence the laser beam configuration but also reshape the trajectory to be planed (e.g. corner-grind or sky-writing for higher path velocity).

Based on the possibility of influencing the current laser trajectory, the position and velocity of the point of energy input can be optimized. With the knowledge of the negative effects of hot spots on the parts quality, it is important to avoid them effectively. However, overall path planning algorithms cannot run in the high-frequent controller cycle due to the high numerical effort. Therefore, an intelligent slicing strategy is required. The proposed concept uses a hybrid decision structure for path control. Here, workpiece geometry-oriented small-area sub-regions of every layer are predefined in the process planning system (see Fig. 6).

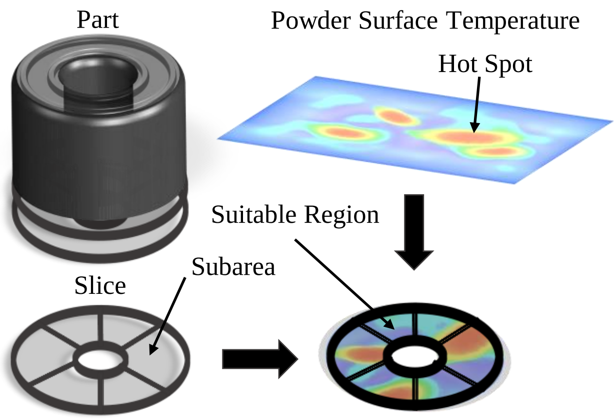

Fig. 6. *Generation of geometry-dependent subareas*

This structures all paths into contour blocks and the discrete subareas of each layer into NC-subprograms. These are decoded in the IPC and prepared for scanning. In the event of an impending hot spot, the IPC commands a subarea change, while the scanner is recommunicating its current working position and area and continue here at a later point in time after cooling down.

4. CONCLUSION AND FUTURE WORK

The paper discusses the state of the art regarding closed-loop process controls for Selective Laser Sintering. Therefore, a literature research has been conducted to examine current approaches in the field of Selective Laser Sintering of thermoplastics. It was shown that the most approaches mentioned, aim to adjust the laser power to achieve a uniform melt pool geometry. Furthermore, the need for a high frequency FPGA was addressed by several authors, to guarantee a high performance control of the fabrication parameters. Based on the identified potential, the architecture of an industrial scaled control platform using a FPGA was introduced. The presented control platform enables the realization of different control architectures and a high-frequent analysis of monitoring data and thus the adjustment of fabrication parameters in real-time. In addition, new concepts for closed-loop control strategies were developed and introduced.

The first concept aims to select the scan area with regard to the actual temperatures within the powder bed. Therefore, an intelligent slicing strategy is used to create single subareas to be sintered. The second approach modulates the laser spot in dependence of the geometry to be scanned. Furthermore, the modulation can be used to heat cold spots on the powder surface without sintering the material. Next to these concepts, the laser power and scan speed is to be adjusted. The introduced concepts are based on an industrial programmable logic controller and a numerical control, enabling a flexible adjustment of the Selective Laser Sintering process as well as other laser-based processes like laser cladding. Due to the possibility of implementing various control strategies and the flexible addition and adaption of components, e.g. monitoring systems, the presented control platform enables a modular use in industrial scaled applications.

In the overall context, all described measures aim to enhance the part quality, the process sustainability and the time of manufacturing by adjustment of the fabrication parameters on basis of monitoring data. In addition, new materials and part geometries can be manufactured more easily by automatically identifying ideal process parameters. Therefore, the realization of *Mass Personalization* is supported, due to the gained freedoms in manufacturing of not tested geometries or materials. The necessary process knowledge by the end users is reduced, due to the fact that the implemented control system enables an independent use of the technology.

In future work, the presented concept of the control platform, based on a FPGA, is validated in the context of a Selective Laser Sintering process. In addition, various control schemes and strategies are to be developed, implemented and compared, using the introduced control platform. Therefore, different monitoring systems as well as correlation analysis of the fabrication, process and product variables are necessary to achieve a zero-defect manufacturing as well as high-quality parts. In this context, also the development of detailed process models is needed. Through modeling and simulation, the control strategies to be developed can be effectively tested and optimized. Furthermore, additional process knowledge can be acquired.

5. ACKNOWLEDGEMENT

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