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Digitalization of directed energy deposition process through a multidirectional height monitoring sensor system

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ABSTRACT

Industrialization of directed energy deposition (DED) process relies on the development and implementation of a quality assurance system that makes the process reliable and repetitive. One of the geometrical characteristics that needs constant monitoring and control during any DED process is the height of the deposited layer. In this paper, a multidirectional layer height monitoring system relying on the laser triangulation principle that has been developed for real-time direct measurement, in contrast to the majority of the sensor systems that derive layer height based on melt pool temperature, is presented. Existing commercial laser triangulation systems are unidirectional, which hinder the flexibility of the material handling system, like industrial robot, in most of the cases. An additional challenge lies on the integration with the deposition head due to its form, size, and extreme working conditions. Therefore, a novel configuration of laser triangulation sensors that enable multidirectionality and limit shadowing effect has been developed at Fraunhofer IAPT. In this paper, the development of such a sensor with a focus on the mechanical design has been presented. The sensor is designed for operation at high temperature and harsh environmental conditions close to the build zone. The developed sensor has been successfully tested for the powder-based laser metal deposition system. In-process layer height measurement and control are possible with this sensor, thereby enabling digitalization and quality assurance during the build process. 3D point cloud generated using this sensor can be used for the dimensional deviation measurement and also for downstream processes like machining. Such an in-process quality measurement and assurance system negates a postmeasurement step, thereby saving cost and time and ensuring quality.

Key words: additive manufacturing, directed energy deposition, sensor systems, process digitalization, high temperature

INTRODUCTION

Directed energy deposition (DED) process is a layer-based additive manufacturing process that utilizes an energy source to melt atomized metal powder or a metal wire to deposit the material on a substrate to form the desired structure. Although originally developed for cladding purposes, continuous research in the process development and the control system has enabled the technology to build 3D structures,[1,2] and the DED process is gaining more and more importance in the aviation industry because of its high deposition rate and large part building capabilities.[3] In combination with the resource-friendliness, high material utilization, and the multidirectional building flexibility of the process, sustainable parts with shorter lead time can be produced.[4]

The common material handling systems used in this layer-by-layer building process are three-axis gantry system and six-axis industrial robot manipulator, along with an additional turn-tilt table. The accuracy and control of the material handling system have a direct implication on the accuracy of the build geometry. In addition, environmental- and process-related instabilities cause variation in the deposited layer geometry and melt pool dynamics. Though the variation could be negligible in one particular layer, accumulation of this error along the build direction can lead to build job termination.[5–7] To overcome such issues, closed-loop control systems that encompass sensors are used for process control.[8]

In the wake of Industry 4.0, manufacturing processes need to be digitalized and integrated into the digital process chain. Varying process dynamics and process environment in the DED process raise the need for digitalization to develop quality assurance systems and to achieve traceability of the built component.

QUALITY ASSURANCE IN DED

As a result of the occurring instabilities, a sensor-based quality assurance system in the production environment is mandatory to ensure the required build quality and to avoid wastage. Therefore, the process is commonly utilized with melt pool monitoring cameras or the OCT sensor.[9,10] Due to its robustness during the measurement and less calibration effort, structured light sensor devices are usually equipped for the monitoring task.[5,8,9,11] By utilizing such sensors, layer-by-layer digitalization and closed-loop control of the process are possible. Stand-off-distance control between the processing head and the deposition surface through such sensors has gained a lot of popularity due to its processes stabilizing behavior,[5,8,11] as shown evidently in Fig. 1. Figure 2 shows the increase in stand-off distance between the processing head and the deposition layer over layers in an uncontrolled build process that leads to build job failure and consequently process termination.

Conventional structured light sensor systems are based on the laser triangulation principle and consist of one CMOS camera and one laser diode. To equip these systems into the DED process, the sensor is mounted on one side of the processing head (Fig. 3). This approach and the unidirectional measuring capability of the sensor system limit the movement flexibility of the handling system and the multidirectional DED process. Furthermore, due to their low operating temperatures, the systems are mounted at a safe distance from the melt pool zone and often measured after the deposition of one complete layer

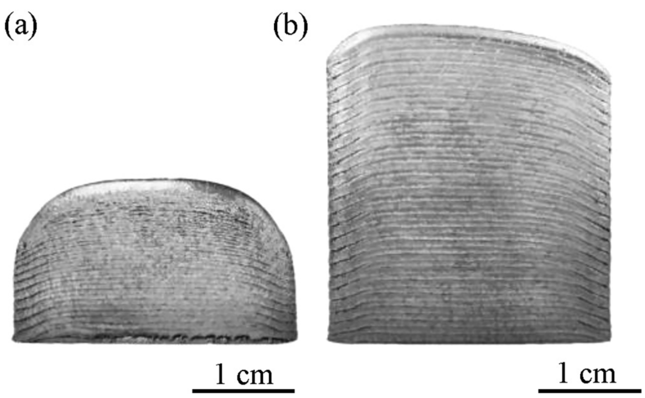

FIG. 1. Wall geometry built using the laser metal deposition process (a) without control and (b) with closed-loop control; process parameters: ti64, 1500 W, 0.01 m/s, 11.6 g/min, and z-offset—0.9 mm. Reproduced with permission from Buhr *et al.*, Procedia CIRP **74**, 149–153, 2018. Copyright 2018, Elsevier.

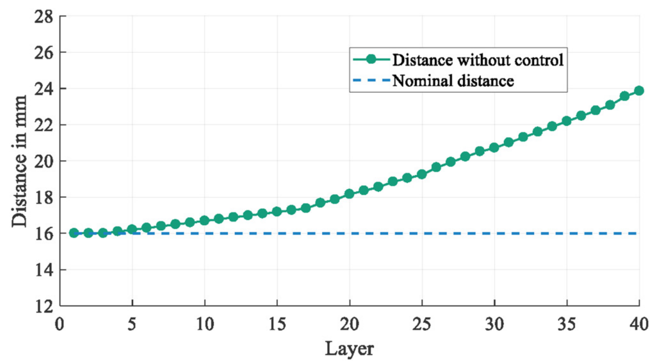

FIG. 2. Increasing stand-off distance between the processing head and the deposition layer during an uncontrolled DED process. Reproduced with permission from Buhr *et al.*, Procedia CIRP **74**, 149–153, 2018. Copyright 2018, Elsevier.

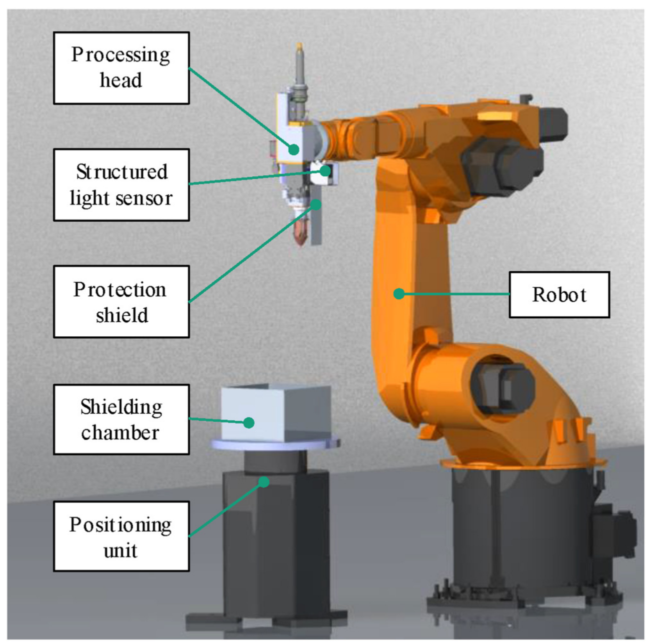

FIG. 3. Laser metal deposition processing head mounted with a commercially available unidirectional laser triangulation sensor. Reproduced with permission from Buhr *et al.*, Procedia CIRP **74**, 149–153, 2018. Copyright 2018, Elsevier.

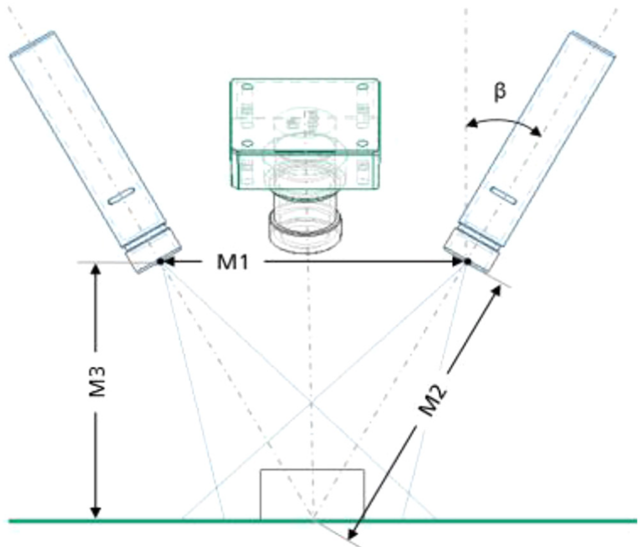

FIG. 4. Novel configuration of the laser triangulation sensor to avoid shadowing.

through a scanning strategy. This evokes process down time, thereby increasing cost and longer lead time. Finally, the shape, form, and size of the sensor limit the in-process scanning capability due to for-run of the projected laser line and the interfering processing head with the sensor system.

As a consequence of current system limitations, a novel configuration of the laser triangulation sensor system has been developed that enables real-time in-process stand-off distance control and capability to be used in harsh process conditions. Additionally, the sensor is capable of measuring in all directions, thereby eliminating deposition head reorientation.

SENSOR CONFIGURATION

The necessary multidirectional sensing is achieved by a projected laser curtain around the processing head. As a consequence of the forerunning laser lines, the necessity of scanning the actual solidified layer surface is gained.

To overcome shadowing effects due to perpendicular laser projections of conventional laser triangulation systems, a novel configuration based on two lasers and one CMOS camera was developed. Both lasers form one line on the surface as depicted in Fig. 4. This orthogonal design enables the reduction of the shadowing effect. The combination of four separate structured light sets, designed in the form of a square, constitutes the multidirectional sensor system. Additionally, the novel configuration enables smaller housing footprint.

The laser triangulation parameters M1, M2, and M3 are designed depending upon the chosen system configuration, stand-off distance, desired resolution, and measurement grid size.

PROCESS ENVIRONMENT FACTORS FOR DESIGN CONSIDERATION

In order to investigate the process-related influencing factors, which will have effects on the stability of the measurement and physical housing, preliminary tests were performed. As the sensor system will be placed around the process nozzle, the temperature distribution was investigated. Figure 5 shows that the occurring ambient temperature differs along the axis of the process nozzle. The tests were performed with 400 s process time. Along with convection from ambient temperature, heat radiation due to laser reflection and glowing weld lines of the deposited layer will also heat up the sensor system. Therefore, an active cooling for the sensor system is mandatory. Furthermore, the sensor should be resistant to unused metallic powder particles that fly around inside the process chamber and the weld spatter generated during the process.

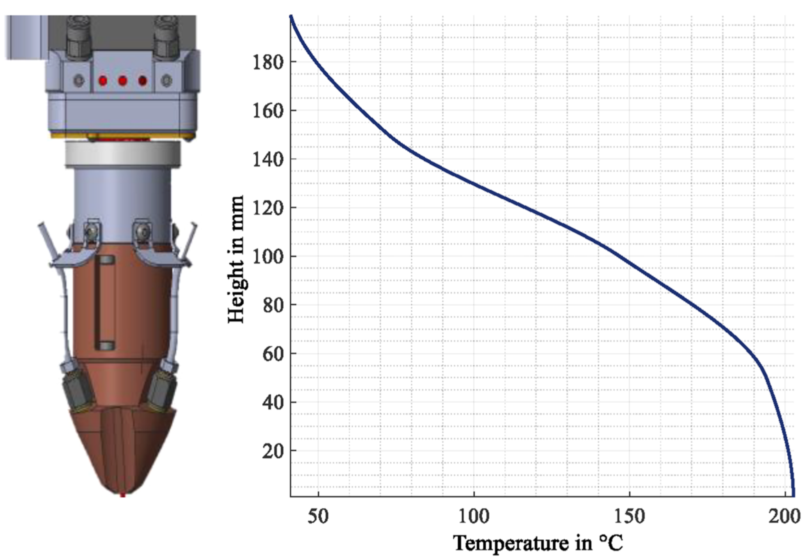

FIG. 5. Temperature distribution of the region around the processing head during the LMD process with 1500 W laser power. Reproduced with permission from Buhr *et al.*, Procedia CIRP **74**, 149–153, 2018. Copyright 2018, Elsevier.

SENSOR DESIGN

Owing to the configuration of the optical elements and the mechanical restrictions of the processing head, the sensor takes up a cylindrical form with an outer diameter of 180 mm and a height of 90 mm. The sensor is mounted coaxially around the processing head (Fig. 6). The working distance (field of view) of the sensor is around 60 ± 10 mm. With a rectangular measuring grid of $50 \times 50\,\text{mm}^2$, distance measurement is feasible in all directions. This compact grid makes it feasible to measure the built geometry closer to the melt pool at a frequency of 300 fps within the specified range. With a resolution of 6 MP, measurements with a precision of 0.1 mm are achievable.

The sensor is composed of the following four main modules: mechanical module, optical module, optomechanical module, and embedded processing uit.

MECHANICAL MODULE

The mechanical module comprises an inner optical bench and an outer housing. The optical bench holds the optical elements like laser diodes, cameras, and filters. It is additively manufactured with the laser beam melting process with integrated air channels, which dissipates any environmental heat and the heat generated by the optical elements. The module has a detachable adapter that is designed specifically to suit the processing head used. With the three adjustment screws, the sensor can be aligned to be in concentric with the processing/deposition head (Fig. 7).

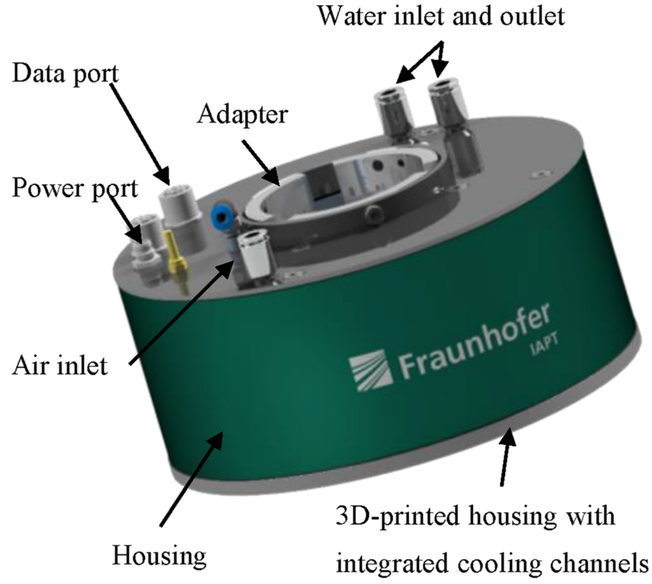

FIG. 7. Mechanical module of the sensor system with pneumatic and electrical connections.

The challenge posed by the harsh environmental and high process temperature condition is overcome with the help of a 3D-printed housing with integrated cooling channels and replaceable shield module (Fig. 8). The housing is integrated with water

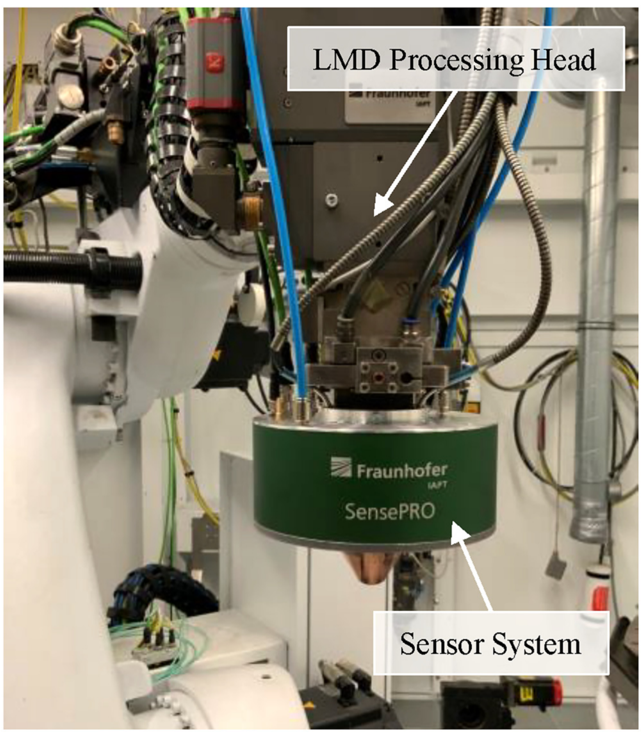

FIG. 6. Fraunhofer IAPT multidirectional laser triangulation sensor system mounted on a DED processing head.

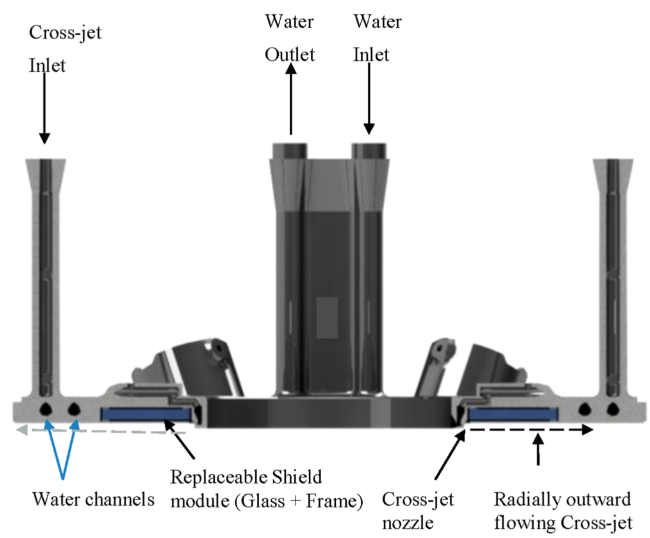

FIG. 8. 3D-printed housing component with integrated cooling channels, cross-jet, and replaceable shield module.

channels running in spiral manner dissipating heat from the sensor and the shield module. The shield module is a replaceable IR-cut annular glass ring with a metal frame that protects the sensor and the optical elements from harsh operating conditions, especially, the laser reflections. A radial crossjet integrated in 3D-printed housing creates a radial stream of pressurized air that prevents powder particles and weld spatter damaging the shield module.

OPTICAL MODULE

The elements of the laser triangulation system like laser diodes, the camera module, and the optical filter form the optical module of the sensor. Figure 4 shows the configuration of the optical elements that prevents the shadowing effect using two laser diodes. Industry-grade line laser diodes of wavelength in the range of 405–520 nm are used, in contrast to the standard 640 nm wavelength diode, for the measurement of surfaces at higher temperature close to the melt pool. CMOS camera with a filter on the optical path transmits only the necessary wavelength needed for accurate distance measurement.

OPTOMECHANICAL MODULE

The novel configuration of this sensor requires two laser diodes to be positioned in a way that these laser lines overlap on the target surface. This requires positioning of the laser diodes in three degrees of freedom. Adjustment mechanisms are an industry ready solution widely used in optical benches for the purpose of orientation of optical elements. However, to make the system compact and integrate the laser clamping element, these fine adjustment mechanisms were redesigned and manufactured additively. The additive design of the adjustment mechanism is shown in Fig. 9. The degrees of adjustment required are follows: Translation along Y and rotation along X and Z axes. These fine adjustment mechanisms are integrated into the optical bench of the mechanical module.

EMBEDDED PROCESSING UNIT

The processing unit for processing of the camera data was embedded into the sensor system. It consists of a combination of FPGA and CPU integrated circuits. The integration ensures less space consumption in the robotic cell as well as real-time processing and protection against dust. The processing unit performs data capturing, image processing, calculation of the sensor model, and in-process digitalization along with close-loop control algorithms with direct handling system communication.

EFFECTIVENESS OF THE MECHANICAL MODULE

The developed multidirectional sensor system was tested with the powder-based laser metal deposition (LMD) system available at Fraunhofer IAPT. Figure 10 shows the LMD system setup with a six-axis industrial robot. The robot manipulator is mounted with the processing head and the sensor system.

To validate the effectiveness of the mechanical module and to ensure safe usage of the sensor system during the process, initial

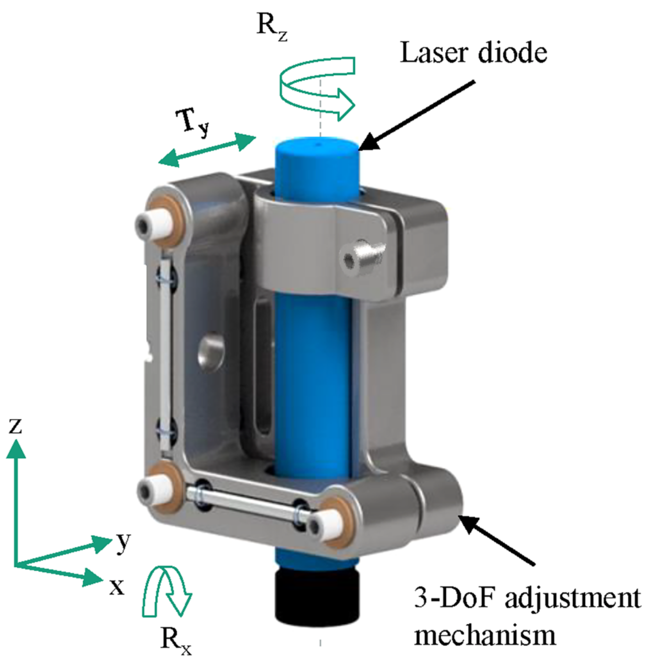

FIG. 9. 3D-printed fine adjustment mechanism for the orientation of line laser diodes.

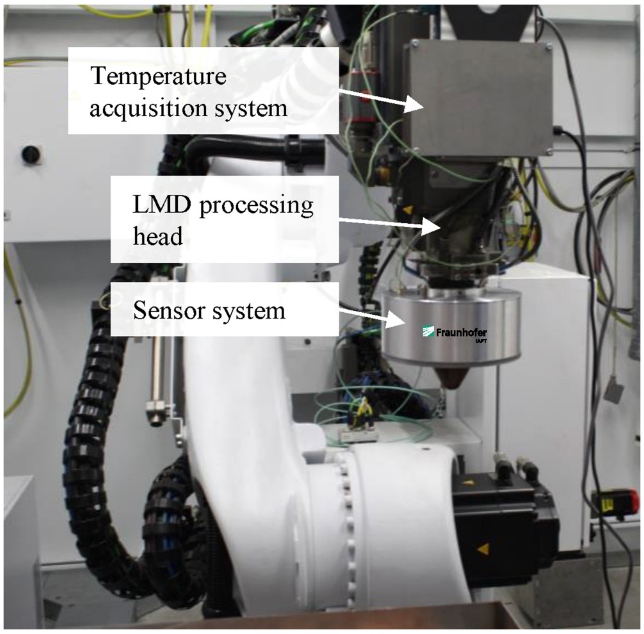

FIG. 10. Laser metal deposition processing head mounted with the developed sensor system and the temperature measurement system.

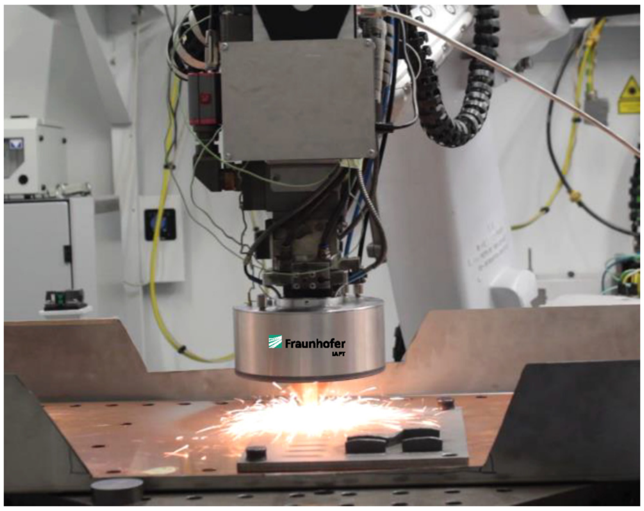

FIG. 11. Multidirectional sensor system being tested in process environment for checking the effectiveness of the mechanical module.

experiments were carried out to monitor the temperature inside the sensor and to check the intactness of the sensor from process environment like powder particles and weld spatter. Type K thermocouples were placed inside the sensor, and the temperature was monitored at different locations on the 3D-printed housing using an eight-channel data acquisition system. Figure 11 shows a photograph of the experiment with a sensor system during the deposition process.

Deposition of Ti6Al4 V wall geometries was carried out with a laser power of 1500 W, weld velocity of 0.01 m/s, and 13 g/min of powder flowrate.

Figure 12 shows the measured temperature data in degree Celsius during a 45 min LMD process. Mean temperature of about 38 °C was maintained during the entire process proving the effectiveness of the integrated water cooling channels. After the process, the sensor was disassembled to observe any powder particles and intactness of the shield system. The inside of the sensor system was still intact.

IN-PROCESS DIGITALIZATION

As shown in section "Effectiveness of the mechanical module," the sensor system is capable of resisting the rough process environment. This enables a laser triangulation-based scanning of the deposited layers during additive manufacturing. Due to the geometrical connections and kinematics of the robotic system, all measurement data need be transformed into a global coordinate system.

Figure 13 depicts the transformation relations between the local coordinate systems.

Based on the transformed data and the movement of the handling systems, three-dimensional layer-wise point clouds are continuously generated during the manufacturing process. Figure 14 shows the 3D point cloud data gathered during the deposition process mentioned in section "Effectiveness of the mechanical module." These point clouds are finally used for target/performance comparison and could as well be used for close-loop control strategies.

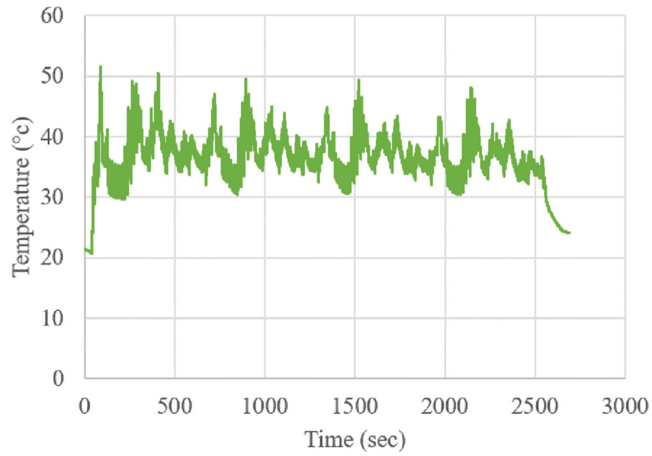

FIG. 12. Measured temperature data of one thermocouple inside the sensor system during the in-process test.

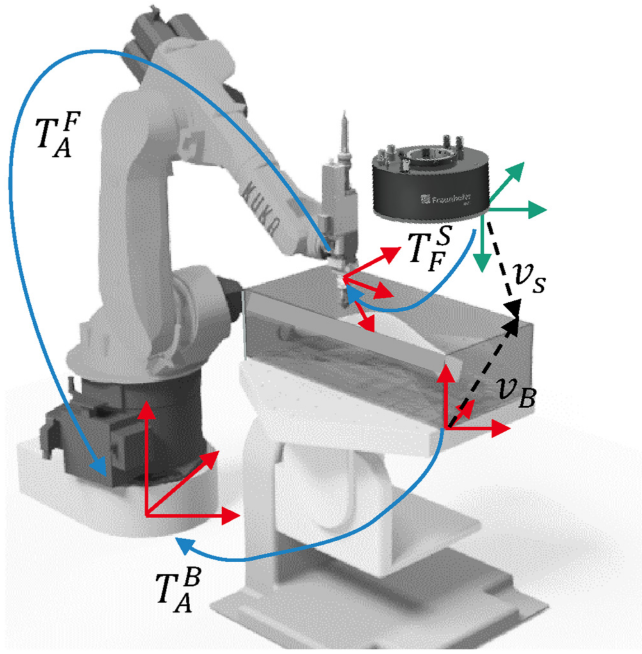

FIG. 13. Data transformation cycle based on geometrical connections and kinematics.

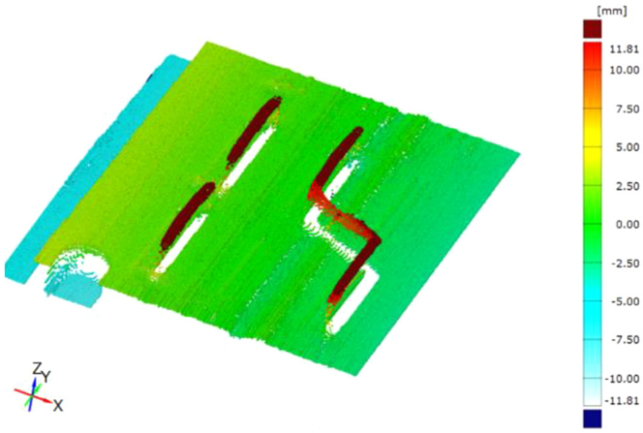

FIG. 14. 3D point cloud data generated with the sensor during the laser metal deposition process.

CONCLUSION

- A novel configuration of a structured light-based sensor system has been conceived for stand-off distance measurement to enable the multidirectional measurement and to eliminate the shadowing effect.
- Based on the novel configuration, a new multidirectional laser triangulation sensor system has been designed and developed.
- This sensor system is very compact in comparison to other commercial systems and can be mounted coaxially to the deposition head and can be deployed in harsh process conditions like powder atmosphere, weld spatter, and high temperature.
- Parts of the sensor housing are 3D-printed with integrated cooling channels and a crossjet is integrated to avoid weld spatter damaging the sensor system.
- Effectiveness of the mechanical module of the sensor is proved by testing the sensor in-process.
- Process digitalization of various DED processes can be achieved with such a multidirectional sensor system, thereby assuring quality and eliminating wastage.

OUTLOOK

The developed sensor system will be used for developing a closed-loop control system for the LMD process. The mechanical module of the sensor has been designed to suit the LMD process conditions and a processing head. This design will be adapted to suit other DED technologies like wire arc additive manufacturing process and material extrusion process. Further experiments will be conducted to test the stability and durability of the measurement system during the process.

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Meet the Authors

Vishnuu Jothi Prakash pursued his Master's degree in International Production Management from Hamburg University of Technology, with specialization in Additive Manufacturing technologies. He is currently working as a Research Assistant at the Fraunhofer Research Institution for Additive Manufacturing Technologies IAPT, Hamburg in Germany. His research activities include Systems and Process development of Directed Energy Deposition technologies including its digitalization and industrialization.

Malte Buhr received his M.Sc. degree in Mechanical Engineering from the Technical University of Hamburg in 2017. In 2017, he joined the Institute of Laser and System Technologies (iLAS), Hamburg University of Technology, as a research associate. Since 2018, he is working at the Fraunhofer-Research Institution for Additive Manufacturing Technologies IAPT in Hamburg as the head of Automation and Sensor systems team. His current research interests include sensor systems, robotics, and additive manufacturing.

Prof. Dr.-Ing. Claus Emmelmann received his Dr.-Ing. (Ph.D.) degree from the University of Hannover in 1991 during his work at the Laser Zentrum Hannover. Within his

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