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Automated Postprocessing of 3D-printed Multi-Material Polymer Parts Through a Robot-Based Modular System and Control Architecture

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Abstract

Automating the production of 3D-printed polymer parts must be based on a modular and highly flexible system and control architecture to meet the volatile demands of the customer market. Therefore, the additive-subtractive production system was integrated into an automated workflow with a customized user interface. The process chain includes postprocessing steps like support structure removal and smoothing. To enhance the automation potential, a modular control system architecture is proposed. This allows flexible integration and control of a wide range of different postprocessing modules. For functional parts with soluble support structures, the printer can process up to four materials simultaneously. The successful implementation of a printing process is shown. The integrated robot can access up to nine additional modules through a linear axis. A 3D scanner with a bin-picking application enables it to recognize and handle parts between different modules. Furthermore, an approach for the effective joining of additively manufactured parts within tight tolerances of 0.05 mm is shown.

Keywords: Additive Manufacturing; 3D printing; Automation; Modularisation; Postprocessing

1. Introduction

With the newly affirmed right to repair from the parliament of the European Union [1] and the ever-increasing demand for customized products, the flexibility of additive manufacturing processes makes them particularly suitable to meet these challenges. Especially polymer parts were rarely repaired up to now and therefore faced criticism regarding their sustainability [2]. Among the additive manufacturing processes, the fused filament fabrication (FFF) process has proven to be a comparatively simple machine technology and offers low production costs and short production times. Additionally, it wastes a lot of material and offers the possibility of producing parts close to the final state, only missing a finishing treatment. On the other hand, rough surfaces, insufficient dimensional accuracy, and the need for support structures in case of overhangs are disadvantages of this process. All of these issues result in time-consuming, often manual, postprocessing and a loss of part quality. Especially surface critical applications can induce an excessive amount of manual labor, which sometimes exceeds one of the conventional manufacturing methods [3]. The result is the limitation of FFF to prototyping. The potential in the field of cost-efficient mass or series production for highly individualized or functionalized products remains unused due to the high effort in manual postprocessing [4].

Due to critical requirements, many components are designed as functional, hybrid polymer parts. These functional components, however, often are inside the part and therefore are difficult to repair due to the restricted access. This contradicts the aim of a sustainable, long, resource-saving lifecycle with the possibility of reusing, upgrading, and repairing individual components. The FFF process is suitable as a primary approach, yet must be extended to include additional process elements [5], which are the automated

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integration of inserts (achieved in [6]), subtractive pre- and postprocessing (achieved in [7]), removal of support structures, integration of functional components, a variety of different materials as well as mechanical and chemical surface treatments.

Commercial postprocessing systems are widely available. Depending on the additive manufacturing process, different postprocessing is necessary. Powder-bed processes require at least some removal of the powder. Resin-based processes need a curing to link the remaining resin. FFF processes may require the removal of support structures. Depending on the tolerances demanded by function, a finishing surface treatment is necessary for all of the processes. Due to the focus on FFF processes, the reduction or removal of support structures and surface treatments are primarily considered within this work. The best and optimal design accounts for support structures and tries to avoid or at least reduce them by design. This reduces the need for time-consuming postprocessing. As this is often not possible, either removable structures, reusable support structures, or support structures made from soluble materials are used. The first faces the challenge of postprocessing, and the first and second face the challenge of handling, placing, and removing these structures [8]. Therefore, soluble material is used more commonly. To remove these soluble structures, the part is placed in a solution of solvent. This solvent then only attacks the support structures due to the materials used. The main advantages are to be listed here. Firstly, more complex support structures with limited accessibility can be removed, which leads to greater design freedom [9]. Then, an increased surface quality can be achieved by a residue-free removal of these structures [10]. Lastly, automation of this process is possible and feasible, as the process is independent of the geometry of the part [11].

To enhance surface quality several mechanical, chemical, and thermal procedures are available. Common mechanical procedures are milling and grinding. With milling being already integrated into the additive-subtractive process [7], grinding is going to be integrated into the postprocessing steps. Chemical procedures are normally used to smoothen the surface by bringing it into contact with a solvent. The elevations of the surface profile are thus washed away and the depressions filled. Once the solvent has evaporated, a solid surface is created again, which is also smooth and shiny. Thermal procedures are not considered in the future. Commercial solutions are available for example from AM SOLUTIONS, a brand by RÖSLER OBERFLÄCHEN-TECHNIK [12], which uses submerged tumbler grinding. Here, parts fixed on a tray are submerged by a kinematic system and returned after the grinding process. Loading can also be automated. Further automated options are mainly offered for powder-based processes due to their high relevance for industrial applications. AM SOLUTIONS, HP, EOS, DYEMANSION, and AMT POSTPRO offer solutions for powder removal. The latter three are followed by surface treatments by tumbling or surface blasting and finished by vapor smoothing or coloring [12], [13], [14]. These processes can also be automated, sometimes done in a single machine (AM SOLUTIONS) [12].

Automated additive manufacturing processes have just managed to be introduced in series production, yet regarding polymers only for laser-sintering [15]. Semi-automated individual modules are available in small numbers [16]. The state of the art clearly shows that a system for the fully automated production of ready-to-use FFF parts does not yet exist. Highly modular and agile additive-subtractive production systems propose a solution for all of these challenges stated above. Modules from different manufacturers can be combined with low costs and automated part handling can be achieved.

2. Modular System and Control Architecture

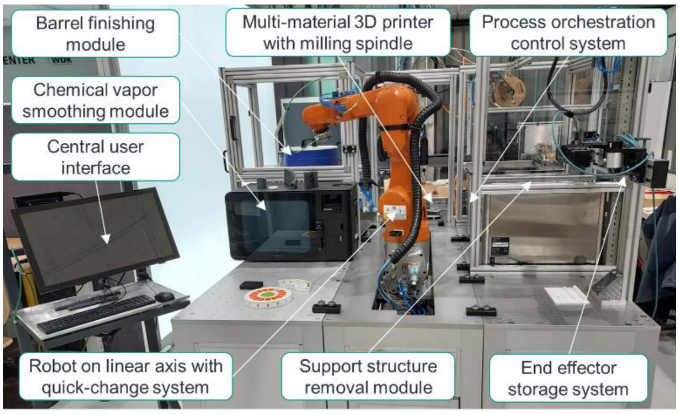

Fig. 1 Overview of current system layout

The system consists of a central elongated handling module, which integrates a linear axis capable of moving a KUKA KR6 -R900-2 robot, and 6 flexible, detachable modules. At the backside a self-designed multi-material printer is attached with an integrated milling spindle. The system setup currently offers different modules for postprocessing:

- Automated support removal through a heated alkaline solution bath Vortex EZ by XIONEER with drying option
- Table-top barrel finishing station by OTEC
- Chemical vapor smoothing with a ZORTRAX Apoller
- Module to store end effectors and inserts

A central user interface for process planning and monitoring can connect to any of the above-mentioned modules via ethernet connectors on their front side. Internal switches centrally connect all of the module's control systems.

2.1. Modular Control System Hardware Setup

The control system is realized by PLCs from BECKHOFF AUTOMATION. This guarantees compatibility between the different module controllers. As shown in Fig. 2, each module has a connection for power and compressed air as well as an RJ45 connector. This means that the modules can be connected to the central handling module, which serves as a distributor, alternatively to an external source. In addition, the modules have a main power switch, an emergency stop, and three buttons, one of which is used to reset the safety controller. Communication with the modules is established via an Ethernet port on the control units and a network switch in the handling module.

2.2. Control System Architecture

The manufacturing system is characterized by an efficient, flexible production environment. The system is therefore divided into three hierarchy layers (see Fig. 3).

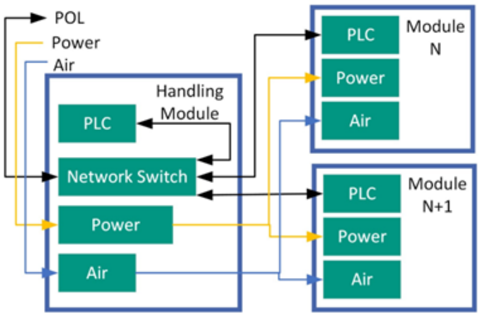

Fig. 2 Basic hardware setup of module configuration

Execution Layer
The execution layer of the system includes both the production modules and the transport system, which consists of a linear module and a robot. Each of these systems is controlled by an individual Programmable Logic Controller (PLC) and operates based on defined tasks. These tasks, identified by unique IDs, are precise sequences of instructions designed to achieve specific sub goals. Because of their modular nature, these tasks can be arranged in different sequences, resulting in different process outcomes and allowing a high degree of flexibility in process design. The transport and handling system plays a central role. It can perform three types of tasks: Positioning tasks to move components between different modules, module-specific tasks to pick up and place components, and special tasks that require direct assistance from the robot. This differentiated task distribution allows flexible use of the robot for material handling and process support while maximizing the efficiency and flexibility of the overall system.

Process Orchestration Layer
The various PLCs are connected to a central PLC that controls the entire system forming the Process Orchestration Layer (POL). It can assign the different tasks to the corresponding modules or the transport system based on the IDs. This controller also decides when a new task can be transferred. The PLC processes the tasks sequentially.

User Layer
The system's Process Planning and Control Interface (PPCI) integrates process planning, including the Hybrid Planner, and process monitoring into a single user interface. This integration offers improved efficiency by simplifying operations and allowing quick parameter adjustments even during the process. The PPCI allows users to define new modules and associated tasks, including the definition of specific parameters (see Fig. 3). It is also possible to change the module configuration and define the sequence of tasks and the components to be manufactured for a production run. When a task is added from the FFF printer, the system automatically switches to the Hybrid Planner, where the printing process, including milling and handling, can be precisely planned. Added milling or printing processes automatically result in the addition of corresponding tasks in the task sequence. After the planning phase, the PPCI allows the user to monitor the manufacturing process. The user can start and stop the process, respond to messages from the modules, and monitor process parameters. When the central controller is ready to receive a new task, it signals this to the PPCI via the communication protocol Automation Device Specification (ADS) by BECKHOFF AUTOMATION, which then transmits the next task. Parameter adjustments remain possible until the final transfer of the task, ensuring maximum flexibility in the production process.

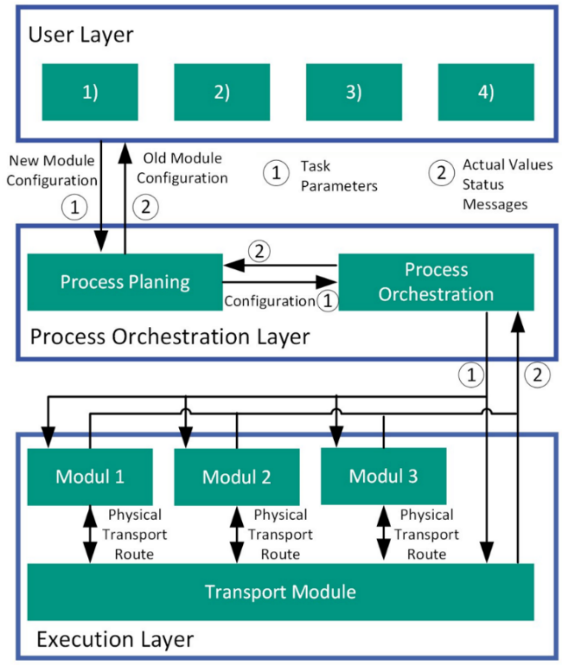

Fig. 3 Hierarchy layers

User/process Orchestration Layer Interface
In the system, ADS enables smooth data exchange between the PPCI in the user layer and the POL. During the planning phase, current module configurations are sent to the PPCI via ADS, and the newly configured settings are sent to the POL. When workflow planning is complete, the PPCI is notified when the central PLC is ready to receive new tasks. This allows the PPCI to sequentially transfer the prepared tasks to the PLC. In addition, the current actual values, status, and any messages from the modules are sent directly to the PPCI. The PPCI is informed as soon as values change and immediately receives the updated data from the POL.

2.3. Operation Status Model and Modular Safety

Each module has two different operating modes. The first operating mode is local operation. This mode is used if the module is used outside the modular system. The second operating mode is automatic operation. In this mode, the module executes the instructions of the Process Orchestration Layer (POL). Only one operating mode can be active at a time so that no competing instructions can be processed.

In the POL, the modules are implemented as objects. The attributes of the modules are divided into module attributes and process attributes. Module attributes are standardized in each module and are used for communication with the POL and module master file data. The process attributes describe module-specific process variables that can be configured in the process planner.

Communication between the POL and the module controller takes place via EtherCAT Automation Protocol (EAP) because this communication protocol enables real-time capable Master-To-Master communication and supports the open safety protocol FailSafe over EtherCAT (FSoE). This allows process parameters and relevant signals from the safety controller to be transmitted.

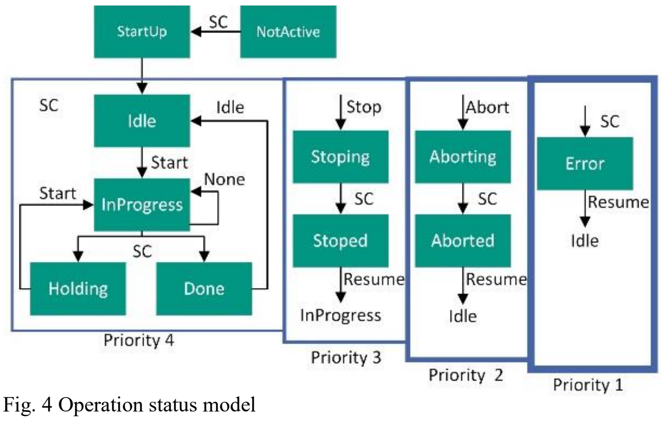

Fig. 4 Operation status model

Before the process orchestration begins, the last system configuration is loaded and compared with the new configuration. If the configurations are different, the new one is adopted. For safety reasons, this must be confirmed again. The connection to the configured modules is then ensured. Process orchestration does not start until all modules are connected to avoid misconfiguration.

The coordination of the individual modules in automatic operation follows the operation status model in Fig. 4, which was derived from [17]. The model has been extended with states and transitions that facilitate online diagnostics in the POL and map intermediate steps within a process task.

Within the POL tasks from the process planner are sequentially executed. For this purpose, the relevant process parameters are transmitted to the corresponding module based on the task ID. The task is started if the module is corresponding and the transmission has been confirmed as loss-free. Transitions outside of priority 4 are controlled by the operator and have priority over normal operation and can be requested at any time. Function-critical errors are detected in the module and handled by a TwinSAFE application as part of the safety technology of BECKHOFF AUTOMATION. The type and location of the error are reported back to the operator and handled automatically if possible.

In each module, the safety-critical controller is implemented by a TwinSAFE application. This communicates with the central safety controller in the POL via FSoE. The events of the modules are combined in the POL and sent back to the modules. To prevent a feedback loop, the local results of the module controller are sent to the POL before the signals from the POL are included in the safety controller. For a quick change between local and modular operation, each variable is sent as a FALSE by default and the existence of the opposite side is checked via the built-in watchdog.

3. Multi-Material Printing with Benchmark Test

The dimensional accuracy of the multi-material FFF process has been investigated by manufacturing a test workpiece with Nozzles 1, and 2 and a milling spindle [7]. The resulting manufacturing inaccuracy was decreased to 0.02 mm for the integration of functional components. However, for the scope of modular manufacturing abilities, it is crucial to have more material options for support structures or functionalization available. Thus, fused filament fabrication with four different materials (4K-FFF) has been a focus of this research. Furthermore, a part cooling system has been implemented to improve the print quality of overhangs, and a motion system has been implemented for each individual extruder. They can be raised and lowered individually with pneumatic cylinders and carriages on linear rails to increase the consistent manufacturing capabilities of the 4K-FFF module. The resulting stroke is approx. 5 mm. The z-coordinate in the lowered state can be varied using a grub screw and a lock nut from the underside of the print head. This allows the z-offsets of the nozzles to be set separately.

Table 1 4K-FFF M commands examples.

M command	Extruder E [1-4]	Example
Extruder temperature T control	M10E=T	M101=210
Part cooling	M121=E	M121=3
Disable part cooling	M122	M122
Lower extruder	M116=E	M116=2
All extruders up	M117	M117

To integrate this tool-changing-like routine in the used PLC with a computer numerical control (CNC) extension, custom g-code insertions must be made when slicing the model. The same principle is used to set up a milling process.Multi-extruder printing requires additional calibration of a work coordinate system. Extruder offset calibration in x- and y-directions were done by printing a test file. A model from the Printables.com platform was used to calibrate the nozzle offset [18]. This model is a multi-material model consisting of two STL files, which are merged in the slicer. Since the model was designed for IDEX printers, only two extruders can be calibrated to each other. Therefore, this print must be carried out several times for multi-extruder systems. The model helps to fine-tune the first layer for each extruder. When printing PLA filament, we ran into oozing problems that seemed to result from the comparatively slow travel movements of the portal machine construction.

As a result, two innovative approaches to prevent stringing defects were developed (see Fig. 6). The first variant uses the built-in slicer wipe tower as an object to clean the nozzle before the system switches to the next extruder. The extruder, which is still active, moves along the cleaning tower. This is intended to ensure that the filament, which is still molten, can run out of the nozzle without contaminating the workpiece. The problem with this approach is that unforeseen filament runs onto the cleaning tower the more material changes are made. This can further exacerbate the problem of stringing contamination of the workpiece, as the excess material can end up on the printing platform. The advantage, however, is that the material can be changed very quickly. If a model needs to be changed a few times or at intervals of several layers, this profile can be used without any problems.

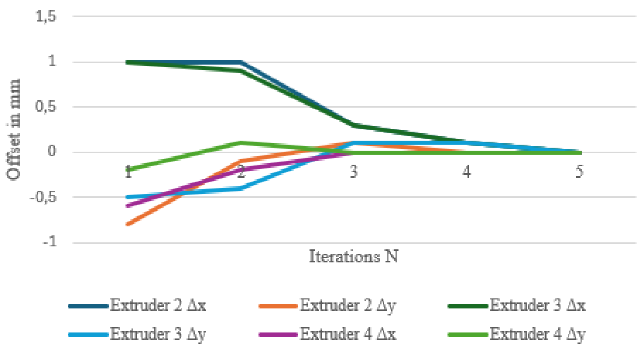

Fig. 5 Indirect measurement of extruder offsets in millimeter per iteration

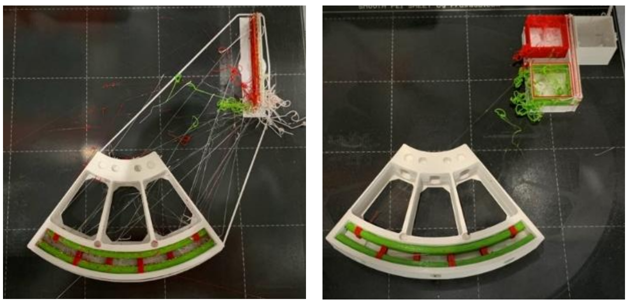

Fig. 6 Fast-Switch (left) and Safe-Switching (right) variant printing one fifth of the axial flux machine

In the second variant, the wipe tower has been extended to include cleaning containers that are generated dynamically during slicing. These are designed to completely prevent the nozzles from leaking. One container is assigned to each nozzle so that a maximum of four can be generated. If an extruder change is initiated, the active extruder prints a layer on the edge of the container and then continues to run in it for a few seconds so that the filament that runs out is wiped into the bucket. If no change is made for an extruder in a layer, the last active extruder per layer prints the missing walls of the containers so that they are complete. It should also be mentioned that when Ooze Prevention is activated in PrusaSlicer, the active extruder is cooled down during the wiping movements and the following extruder is heated up. This largely compensates for the additional time that the system needs to be ready. The problem with this approach is the significantly increased printing time and the additional material consumption on the walls of the containers. For each print job, a decision should be made as to which profile can more effectively reproduce the desired function. The advantage, however, is that tests have shown that this concept can work very reliably. Especially if the filament is highly hygroscopic or has not been dried before printing.

Table 2 Benchmark features for multi-material workpiece with inserts

Feature	Description (Values in Millimeters)
F0	Dimensional accuracy 65 x 65, Axes labeled
F1	Bridge 55mm
F2	Overhang (45, 40 and 35 degrees)
F3	Extruder offset (measurable with calipers)
F5	Milling different diameters on the outer surface; Cylindricity
F6	Milling different diameters on the outer surface; spindle offset
F7	Overlapping material 3; Tool changes per layer
F8	Heat Inserts; done by a special robot tool
F9	Tolerance Test Bearing; 30 mm diameter cavity

For further metrological analysis of the manufacturing process, a new custom workpiece was designed to incorporate valuable inspection features (Fig. 7). Manufacturing these complex additive-subtractive parts requires advanced process planning capabilities. In the past digital planning has been done via the Hybrid Planner [19], which integrates a graphical user interface (GUI) for layer-per-layer postprocess planning and g-code generation. To achieve the goal of a modular manufacturing environment, a higher abstraction layer of the control architecture is needed.

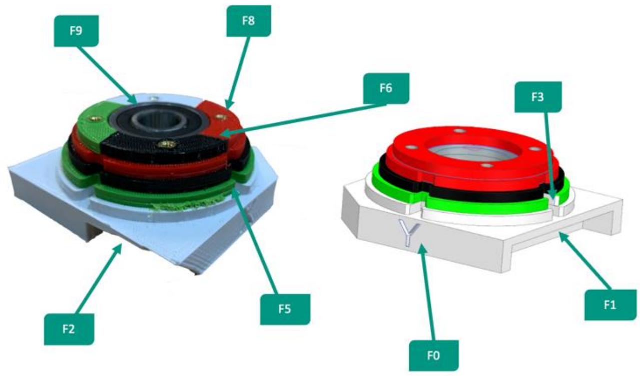

Fig. 7 Custom 4K-FFF workpiece for metrological analysis of manufacturing quality; Features highlighted and explained in Table 2

4. Handling and Joining of Individual 3D-Printed Parts

To integrate the individual modules, it is necessary to pick up components at one station and place them at another using the robot. To manufacture and repair products automatically the handling robot needs to be able to assemble and disassemble components too. A possible repair case is the replacement of a broken pole shoe in an electrical motor. Therefore, the robot needs to remove the broken pole shoes and insert new ones automatically.

The 3D scanning system PhoXi M from PHOTONEO and their bin-picking application is used to automate these handling processes. To enable a flexible working area, the 3D scanner is mounted above the quick-change system on the robot flange.

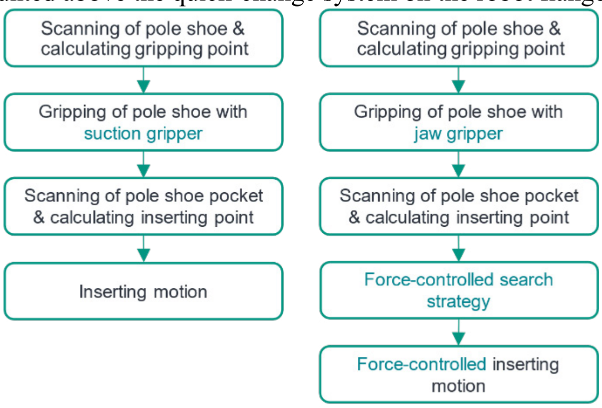

Fig. 8 Process with laser scanner and suction gripper (left); process with laser scanner, jaw gripper and force torque sensor (right)

The bin-picking application uses the 3D scan data to localize components, plan the robot's path and monitor collisions with its environment. Data on the gripper, the gripping objects and points are used to train the software’s algorithms. By integrating the 3D scanner system, automated handling and bin-picking of components is realized. The precise insertion of a new pole shoe by only using a 3D scanner to determine its starting and end position does not work with a bin-picking approach. The determined inserting point is too imprecise due to inaccuracies in the scanner, image processing, and gripping position of the suction gripper. Furthermore, the forces occurring during the joining process cannot be considered, which cause the pole shoe to tilt.

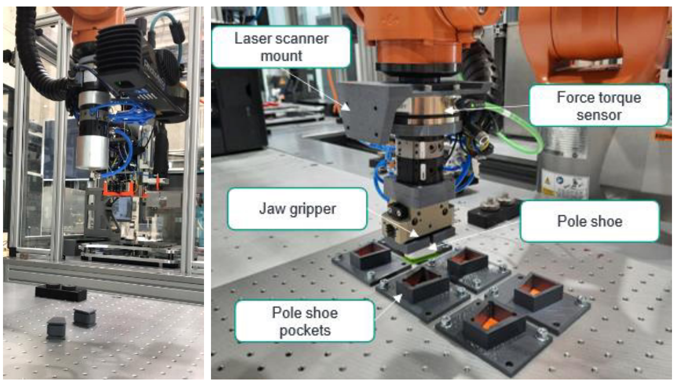

Fig. 9 Testing setup with 3D scanner and suction gripper (left) and jaw gripper (right) for insertion tests with force torque sensor

Instead, a jaw gripper is used to be able to transfer forces through form fit and to center the pole piece. Moreover, a force torque sensor was integrated into the system to be able to find a suitable inserting starting position with a search strategy and be able to do a force-controlled inserting motion. The KUKA ForTTran SG 500-20 was selected due to its compatibility with the robot KUKA KR6 -R900-2 and suitable force and torque range. To program force-controlled movements the ArtiMinds Robot Programming Suite (RPS) is used. The RPS was chosen because of its modular library of combinable robot skills and compatibility with the system. A force-controlled search strategy is used to compensate for the inaccuracy of the starting point determined by the 3D scanner. The robot moves according to a specific pattern, for example, a spiral, and presses with 5 N on the upper edge of the pole shoe pocket. As soon as the robot finds the pole shoe pocket, it slips in the z-direction due to the lack of resistance. Forces in the x- and y-directions can be controlled as well. Tests have shown that if the starting position of the search strategy is less than 1 mm away from the actual inserting point, controlling the x- and y-forces helps to find the position more quickly. If the starting position of the search strategy is more than 1 mm away in one spatial direction, the pole shoe may get stuck on the edge of the pole shoe pocket created by milling. In that case, the inserting position cannot be found, and the search strategy is not successful. In the case of search strategies without force control in x- and y-directions, it takes longer to find the insert point. However, the search strategy is successful at a starting position that is 2 mm away from the final inserting position.

Insertion tests were carried out to determine the fit of the pole shoe in the pocket. The fit between the pole shoe and its pocket was between 0.03 to 0.7 mm. The starting point for each test is a manually taught point that is as central as possible above the respective pole shoe pocket. During the joining movement, the robot moves the pole shoe up to 20 mm in the negative z-direction and regulates the lateral forces F_x and F_y between -0.5 and 0.5 N. The joining movement stops when the pole shoe has reached the bottom, and the force torque sensor measures a z-force between 10 and 40 N. During testing with fits between 0.7 mm and 0.05 mm and an offset rotation in z-direction of 1°, the pole shoe could be joined. The force curves plotted over the z-distance show that the x- and y-forces could be controlled during the insertion process and were kept within their ranges. At a distance of around 14.25 mm in z-direction, the pole shoe reached the bottom of the pocket. The force-torque sensor measures a force up to 27 N in the z-direction. Inserting tests with a fit of 0.03 mm showed higher forces during the inserting process as the robot was not able to compensate the z-rotation.

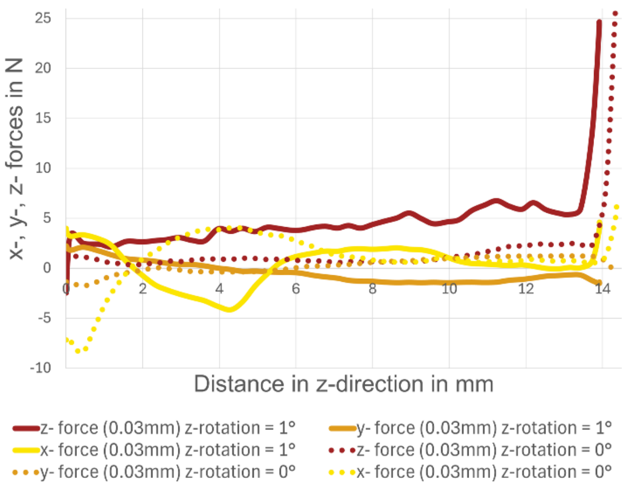

Fig. 10 Force in x-, y- and z-direction during inserting process in z-direction

5. Summary and Outlook

In this paper a system architecture for an additive manufacturing system with automated postprocessing through a robot is presented. The system and control architecture is highly modular and can integrate further modules flexibly. Multi-material printing with four different materials by four individual nozzles is implemented and methods for robust printing results were tested by a newly proposed benchmark piece. The joining of additively manufactured parts by the system with the robot and a 3D scanner were investigated. With a suitable searching algorithm and an integrated force-torque sensor, joining tolerances of down to 0.05mm could be fitted with a z-force of up to 27N.

In the future, the control system architecture could be further developed to parallelize different processes. With this enhancement, it would be possible to perform an optimization of the task order before the addition of the transport and handling tasks. The system would automatically calculate the most efficient sequence of tasks. The transport tasks could then be adjusted accordingly to ensure that the production processes run seamlessly and as quickly as possible.

Handling and joining of highly individual parts with robot kinematics have been shown for different tolerances after subtractive postprocessing. Nonetheless, for full automation of the handling process, it is necessary to autonomously detect gripping position strategies as well as secure path planning. Fragile and delicate parts should be grasped by form-fitting grippers to lower the actual gripping force and make joining possible. These can be 3D-printed in process with the parts and automatically exchanged by the robot's end effector as needed. Strategies and solutions are currently developed and will be presented in the future.

For postprocessing, chemical vapor smoothing and barrel finishing are industry standards for polymer parts. Automated modules using the versatility of the robot for un-/loading and the modular control architecture as the interface between different systems are presently built. A concept for a laser finishing module as an innovative, highly flexible, and geometrically independent postprocessing method as well as a module for quality inspection is under development.

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