Robotic System for Additive Manufacturing of Large and Complex Parts

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Abstract—**In this paper the use of industrial robots in combination with additive manufacturing technologies for the production of large parts is presented. The paper summarizes the results of an ongoing major joint project being completed by industrial companies and research organizations. The objective is to develop a "genuine" three-dimensional additive robotic system that cost effectively builds large models and molds from any thermoplastic material with volumes of 1.000x1.000x1.000 mm³. The system combines hereby the advantages of both worlds – flexible and cost effective industrial robots with high innovative additive manufacturing. In particular, the manufacturing technology, the system architecture and the motion planning are presented.**

Keywords—industrial robot; additive manufacturing; robot machining

I. INTRODUCTION

Manufacturing competitiveness depends largely on its productivity, flexibility and agility to react to market demands. Additive manufacturing is a key element to achieve such competitiveness, especially if they are able to produce large parts in short times. Existing additive manufacturing systems generates only models with limited size and slow build rates in thin layers that strongly restrict the fields of applications. The production of large parts is enormous time-consuming or still not possible with existing technologies. Thick-layer deposition could be an alternative to the common used thin layers to reduce built-up times, but it requires an intensive post-processing.

On the other side, robot machining is changing the way the production system are designed in general. Industrial robots offer a proven alternative technology for the development of high productive and flexible manufacturing systems realizing various manufacturing tasks from common handling to welding, milling and painting. Thus, the addition of robots to manufacturing processes is constantly increasing worldwide.

II. STATE OF THE ART

A. Robot Machining

The use of robotic systems to build large prototype has been the focus of numerous research projects [1]. Robotics has primarily been used to mill large parts. Drawbacks are the reduced absolute accuracy over CNC milling machines and the stiffness of the robot kinematics [2]. Established additive applications use gantry robots to foam PU into pre-milled (polystyrene) models. Nowadays, multi-robot systems - operated from a single control point - are common in many applications with repetitive manufacturing tasks, such as large-component welding or multi-processing cells [3]. By contrast, most machining processes with strongly varying tasks are performed by single robot systems.

B. Additive Manufacturing

Their different advantages notwithstanding, additive manufacturing systems have only become established for mass production to a limited extent. In terms of their engineering, powder-based systems (metal, polymer, ceramic) primarily have deficits related to production speed and build space. Moreover, key part properties such as surface finish and strength or consistency and process reliability are need of improvement [4].

Most of the existing additive manufacturing machines are based on the principle of thin-layer deposition. The surface quality of objects produced with this approach is a function of layer thickness. Very thin layers, usually in the range of 50 - 200 microns, are required to guarantee proper surface quality and to minimize reworking [5]. Since thin layer deposition processes typically have low build rates, the size of parts that can be produced is limited or build times for large objects are very long.

Additive manufacturing machines need highly accurate components to produce layers as thin as 50 microns or less. Since the cost of machinery rises significantly as the workspace increases, about 95% of additive manufacturing machines have workspaces as small as 300 x 300 x 250 mm³[6].

Most additive manufacturing machines are equipped with isolated chambers to maintain defined process conditions, particularly temperature and atmosphere. This also limits the workspace and the dimensions of parts. Some technological approaches promise to overcome the shortcomings of common thin layer deposition processes by increasing the layer thickness. Recent developments of large-scale printers can process thermoplastics with dimensions as large as 1100 x 900 x 850 mm³ and layer thicknesses as thick as 1 mm [7], [8].

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They also manufacture in 2½D, but at low manufacturing rates and comparatively poor surface quality. In 2010, [9] developed wire and arc additive manufacturing to produce large structural components for aircraft. This method entails using robots to apply welding beads layer by layer in a dimensional range of 2000 x 1000 mm at layer thicknesses as thick as 4 mm.

III. Design of the Manufacturing System

The joint research project is based on a new manufacturing approach that overcomes the existing deficits of current additive manufacturing systems by combining the advantages of additive manufacturing and universal industrial robotics in one high-performance system that manufactures geometrically complex large parts of thermoplastic material.

Therefore, a specially designed extruder will consistently apply the material vertically (in the direction of gravity) and ensure that beads have defined and reproducible geometries. Applying and cooling of the material will be constantly controlled to keep the viscosity of the plastics stable and to prevent parts from shrinking or deforming. A 6-axis industrial robot executes the 2½D build process by holding and guiding the build platform below the stationary extruder. A further robot integrates additional function elements (inserts) directly into the part in parallel with the build process. The system is designed for parts with volumes of 1.000x1.000x1.000 mm³ and maximum weights of 25 kg at first.

The manufacturing system includes the following essential components (Fig. 1):

- an industrial robot (1) with build platform that holds and handles the parts,
- a further robot (2) that positions the inserts,
- a base frame (3) that holds the extruder units,
- three extruder units (4) with needle nozzles,
- a scanner (5) that measures temperatures (part surface, melt temperature) and scans geometry data, and
- a control unit for the complete system with a collision detector

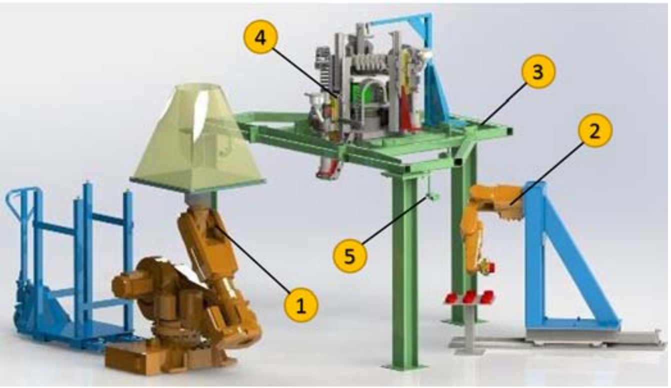

Fig. 1. CAD layout of the manufacturing system.

The system concept includes three extruder units, thus making it possible to build up parts of different materials from hard-soft combinations, different colors and glass and carbon fiber filled materials. Continuous online temperature measurement in the build space keeps the viscosity of the plastics stable. The use of multi-material systems and the integration of additional function elements (inserts) makes it possible to incorporate a multitude of specific demands in a plastic part.

A. Development of the Extruder Units

The extruder units are the core components of the manufacturing system. The units directly process standard thermoplastic plastic material in granular form. It replaces the filament material previously used in standard FDM systems, resulting in a substantial cost advantage of up to a factor of five. This facilitates cost effective manufacturing, which, in turn, should open up other uses for the new technology.

The extruder unit (Fig. 2) is designed for a maximum part build rate of 5 kg/hour from standard granulates (ABS, SAN, PMMA, PP, PC, PC / ABS, PLA, PVA). The extruder nozzle's diameter can be varied in a range of 1 to 3 mm.

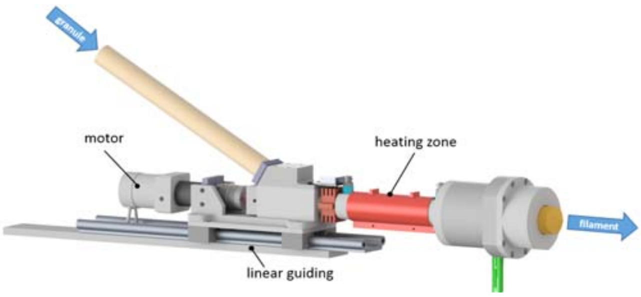

Fig. 2. Extruder unit.

The modular design of the extruder unit allows flexible response to system modifications base on building material and lead to minimize setup times (Fig. 3). The custom-designed needle nozzle (2) is installed in the extruder (1) to ensure a continuous and consistent flow of material. This prevents uncontrolled filament formation during the build process. The heated build platform (3) is clamped on the industrial robot (4), which interacts with the extruders through the control program.

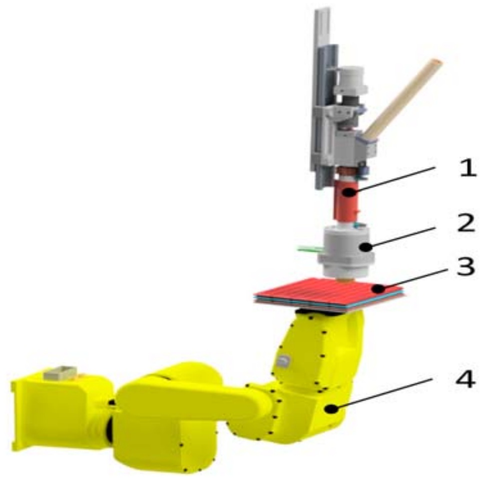

Fig. 3. Extruder unit and robot with build platform.

The three extruder units are arranged in a revolving magazine (Fig. 4 left). A set of pneumatic cylinders can move each of the extruders individually in a vertical direction to the working plane. This ensures a safe distance to the gantry and simultaneously increases the robot's operating range. Parts are built layer-by-layer on a build platform mounted on an articulated robot. Since the build platform has 6-axis movement to produce a three-dimensional part without anisotropy, the point where material is applied is always perpendicular to the extruder nozzle. A second robot places additional components (e.g. metallic inserts) in the part. This makes it possible to integrate other function elements automatically that can not be printed with the system (Fig. 4 right).

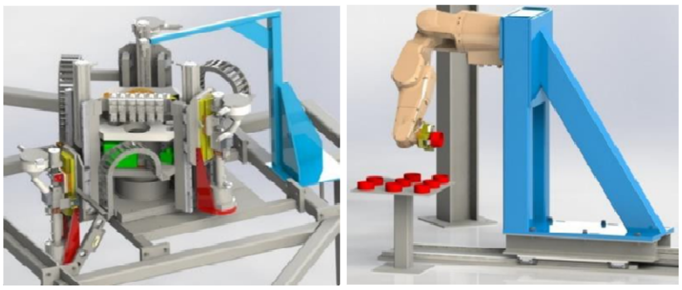

Fig. 4. Extruder magazine (left) and insert handling robot (right).

B. *Development of the Printing Material*

The 3D printing process needs suitable thermoplastic materials with specifications based on different polymers. A constant and reproducible material flow in the extrusion line is as important as the reduction of the thermal coefficients. A uniform quality of the building process is demanded over a broad range of temperature.

Preliminary tests with differently sized pellets determined that the extruder unit has the capability to process any standard pellets without additional modification. This made it possible to eliminate any need for complex and expensive custom designs to produce new mixtures. Current tests are dealing with the development of a material specification that combines hard and soft components. Since initial findings reveal that internal stresses especially cause cracking, different SEBS and TPE are being tested with the aim of using them as bonding material. Initial tests of extruding polymer foams are also being conducted (Fig. 5).

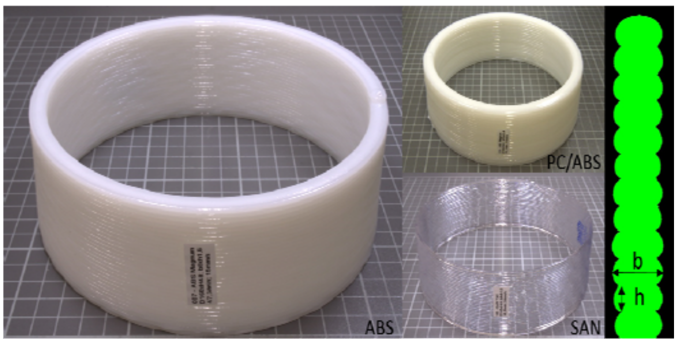

Fig. 5. Extruded polymer foam.

The next steps will cover the development and testing of special resins for water and/or alcohol-soluble substrates. Studies with water-soluble PVA mixed with and without release agents are being conducted at present. The influence of certain additives on the glass-transition temperature is of particular interest here.

C. *Process Control System*

Ensuring stable viscosity of processed granulates is an essential criterion for manufacturing homogeneous parts. This necessitates continuous monitoring of the manufacturing process. The system's individual subsystems, which are heated to different temperatures, have to be defined. While polymers are processed at temperatures of 150-300° C, a part has to be preheated to 50-100° C at the same time.

The monitoring unit must be heat resistant up to at least 70° C. These demands served as basis for developing a video pyrometer that scans a point with a diameter of 2 mm (at a distance of 600 mm from the build platform) at workspace temperatures of 150° C and withstands maximum ambient temperatures of 75° C.

D. *Design of the Build Platform*

The system will be used for different sized parts, which makes it necessary to easily exchange the build platforms depending on part dimension or to remove finished parts. This ensures a high flexibility of the entire building process. Since a part is built directly on a swivel platform held by the robot, a customized zero-point clamping system was developed to meet the demands for positioning accuracy. The platform can thus be combined consistently with the robot by an adapter with specific tolerances. The platform's first upgrade provides spots to mount four differently sized plastic plates and a maximum build size of 1.000x1.000x1.000 mm³.

IV. Motion Planning and Control of Multiple Robots

A. *Motion Planning*

A complex software architecture is necessary to run the manufacturing system in order to calculate the trajectories of a multiple robot system. This includes strategies for automatically generating of robot path from 3D CAD data of the part that are designed in a CAD system, or obtained from reverse engineering such as 3D scanners.

The CAD model has to be converted into the standard STL format and divided into different sections based on the information on the surfaces' physical location. It can be divided either interactively by selecting specific contour elements or by automatically detecting edges. Unidirectional slicing algorithm slices the STL model into a number of equidistant layers parallel to the build platform. Based on this slices, the toolpath is calculated according to the build strategies. The software detects and immediately corrects inconsistencies whenever radii are too small. Motion planning for offset surfaces, which have to be calculated very precisely, is an important task. Equidistant elements aligned with the tool direction are employed, thus forming a correct offset plane.

Further software routines are dealing with the generation of support structures as well as the 3D build strategies needed to do this.

B. *Control System for Multiple Robots*

A major priority in the project is the development of the control system for the manufacturing system. The components of the innovative control system design include component control, motion planning and machine monitoring and operation. In this subproject, the simulation is being coupled with the machine controller (PLC, robot control by a real-time interface) and a safety specification that prevents collisions in workspaces (eliminating incorrect machine states) is being developed. Moreover, workpieces and materials are being incorporated in all of the operations and the real-time capability of the models created are being demonstrated under real conditions. The integrated simulation and software tool VINCENT developed by the Fraunhofer IFF is being used to develop the control system for complex manufacturing operations (Fig. 6).

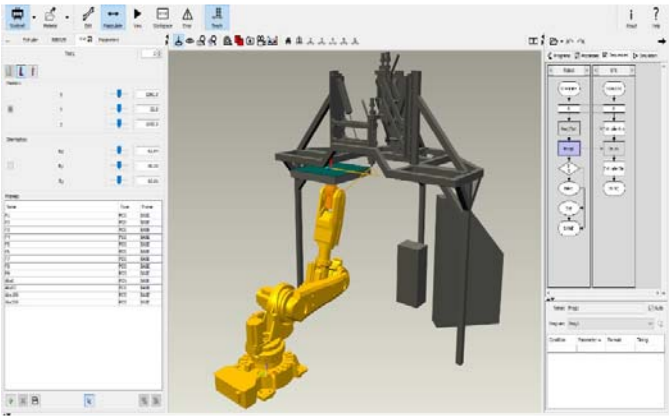

Fig. 6. Simulation-based development with VINCENT.

This new integrative approach to motion planning and event simulation makes it possible to test geometry and function even before the system starts being built. Machine and structural elements as well as the controller, assemblies and media can thus be developed and optimized in parallel. Connecting the virtual model of the system with the real control system online makes it possible to identify potential collisions between different system components and the complex part being manufactured before the task is executed. Both, short motion sequences and complete manufacturing programs lasting several hours can be tested in advance. The software tool interconnects established systems and standards (generating a program code compliant with IEC61131-3) and easily imports CAD data (STEP files).

One of VINCENT's major strengths is its rapid collision detection utilizing detailed CAD surface data without distorting bounding geometries and its capability to analyze the range of motion completely and verifiably by generating the safety zone for every one of the system's components. The efficient program reliably and completely transfers knowledge from design engineers to control engineers. Sequences in the machine are defined easily from start to finish by using established standard formats to exchange data.

V. Validation and Outlook

The technologically feasibility of this novel approach and its cost-effective deployment was demonstrated in first tests with the prototype of the manufacturing system for large parts. Further tests to optimize the basic system components and the material composition are ongoing. It is essential to improve the materials' thermostability while parts are being built, e.g. by employing different additives. Another task is the optimization of build process and the enlargement of the build space as a function of the extruder units. The technical specification of the electrical components (drives, sensors, control loops, etc.) for the control module has to be compiled, incorporating the extruder's final gantry design and the insert handling elements, and adapted to the progressive engineering. Another important objective is reliable detection of any potential collision zones and real-time collision control.

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