Investigation on additive manufacturing processes performed by collaborative robot

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Abstract. The additive manufacturing (AM) applications using collaborative robots (cobot) are rapidly increasing in the manufacturing field. The integration of AM with a cobot abilities can help prototyping and manufacturing custom-made parts in a more efficient way. This paper relies on manufacturing cell that combines a fused deposition modeling (FDM) extruder with a 6-axis cobot controlled by IoT edge computing devices. The production processes are designed in a robot simulation software, where digital twin (DT) of the manufacturing cell is available. Direct and reverse communication between the simulation software and the physical manufacturing cell allows for implementing the real industrial cases. The manufacturing cell has been tested to demonstrate the viability of replacing traditional 3D printers in the industrial sector while taking advantage of working in a complex and dynamic environment. According to this approach this paper promotes the enlargement of the set of robot-abilities by adding additive manufacturing capabilities.

Keywords: Additive manufacturing, Cobot 3D printing, Industry 4.0/5.0, Smart manufacturing.

1 Introduction

In recent years Additive Manufacturing (AM) technology has been applied in different fields, including automotive, aerospace, food, bioengineering, architecture and manufacturing [1].

AM is defined as the process of joining materials to make parts from three-dimensional (3D) model data, whereas 3D printing is a technique that builds 3D objects layer by layer from a 3D digital model (either by computer-aided design or by scanning the object) [2]. A print head, extruder, nozzle, or other printer technologies are used in the 3D printing process to build components by deposing material.

Fused Deposition Modeling (FDM) is the most widely used 3D printing technique. FDM uses a heating chamber to liquefy polymer that is fed into the system as a filament. The filament is pushed into the chamber by a tractor wheel that generates the extrusion pressure. [3]. Typical FDM equipment has three degrees of freedom to describe the shape of the object by moving deposition head.

This approach is easy to implement due to the declining prices of FDM machines, which have become affordable for individuals, but it has some drawbacks in introducing manufacturing constraints, such as production speed, material options, material density and accuracy. Additionally, it can result in a stairwell effect on the surface. The FDM manufacturing process deposits material layer by layer resulting in significant product anisotropy. Due to layering, the sloping surface of printed parts will suffer from the staircase effect, which affects surface quality and leads to stress concentration. These issues weaken the FDM product's strength and limit its application scenarios, prompting the researchers to conduct extensive exploratory work.

Multi-axis robot-manipulated manufacturing methods, which are widely used for assembly, welding and handling or pick and place tasks, provide high quality and consistency, maximum productivity, safety and accuracy for repetitive task, and low labor cost [4][5]. Cobots' adaptable and flexible functionalities fulfill the dynamic demands of manufacturing. The use of multi-axis robot systems in combination with additive manufacturing technologies enables multi-axis additive manufacturing and the fabrication of complex geometries in a variety of industrial environment.

Nevertheless, the path planning of multi-axis 3D printing end-effector is more complex and less developed task [6]. The majority of multi-axis printing researches aim to reduce or eliminate support. There are few research studies on 3D toolpath planning and fabrication strategy for printing parts with complex geometry and mechanical properties. The deposition direction of multi-directional printing differs from traditional 3D printing, which deposits material in a series of parallel planes, therefore the mechanical properties of the multi-axis printed parts requires deeper analyzes. Moreover, there are no general control languages available for multi-axis printing. Finally, different platforms typically use different scripting languages to control the hardware, making software development more difficult.

This paper proposes a platform integration for multi-axis cobot assisted additive manufacturing with FDM. It describes the manufacturing process where a CAD model, embedded into Cyber-Physical System, drives 3D multi-axis printer, based on open source architecture, which produces the physical object. The rest of the paper reviews related works of existing multi-axis 3D printing systems and demonstrates various case studies of 3D printed objects using robotic-assisted additive manufacturing before presenting and discussing results.

2 Related works

The use of robots to perform 3D printing is a research question currently under development.

Robotic manipulators have been used to print complex 3D geometries without the use of supporting materials, and many research efforts are being directed toward the development of a robotic arm assisted 3D printing platform [7].

Yoa et al. propose a framework for 6-DOF robot arm based 3D printing and continuous toolpath planning method to improve the strength and surface quality [8]. The continuous toolpath planning method enables full use of robot arm-based additive manufacturing, achieving smooth printing on surfaces with high curvature while avoiding the staircase effect and collision in the process. 3D printing path planning has been investigated to improve the structural rigidity of manufactured parts [9].

Other authors proposed a 3D printing simulator based on an off-line robot programming system. This method usually requires data transfer to the real robotic system as well as adjustments to various parameters related to both robot operation and the AM process itself [10].

Ščetinec et al. recommended on-line layer height control and in-process toolpath replanning to improve geometric accuracy for tall shell parts [11].

Another research proposes an integrated framework for collaborative robot-assisted AM using fused deposition modeling (FDM) as an AM sub-process. This is a generic platform with position and orientation control that can be easily integrated (hardware and software) in any robot or multi-axis machine [12].

The integration of collaborative robot and AM systems present some challenges: in terms of technology integration, the definition of interconnected robot and AM parameters needs improvement, especially regarding availability of paths that are collision-free and reduce the stair scale effect on the complex surfaces. Like CNC machines, the ordinary 3D printer follows G-code instructions for positioning, but G-code does not specify how the robot should move to avoid collisions. Simulation are necessary to address this issue. Although there are a few route generation software options for multi-axis robot AM available in the market, they cannot fully unleash their potential. Additionally, the real time control of the collaborative robots introduces relevant difficulties in managing the whole system.

3 Development of the additive manufacturing robotic cell

The AM robotic cell was developed in the Mind4Lab laboratory of Politecnico di Torino to demonstrate the innovative robot-abilities in additive manufacturing.

The proposed additive manufacturing workstation includes a collaborative robot UR10e from Universal Robots, an On-Robot RG6 flexible dual finger robot gripper with a wide stroke (160 mm) and a gripping force range from 25 N to 120 N, a NEMA 17 stepper motor to drive the filament extruder, an Arduino board (Uno R3) to control and communicate with the robot controller, a heated nozzle, a heated bed to perform printing and RoboDK software to design the Digital Twin (DT) of the AM workstation.

The UR10e, a 6-axis cobot with force accuracy of 5.5 N in the axes (x,y,z) of the tool flange and position repeatability of ±0.05 mm, has a maximum payload capacity of 12.5 kg and a spherical workspace. The cobot working distance is 1300 mm radius and 300 mm radius around the robot base (Figure 1) with 0.05 mm pose repeatability, making it more suitable for complex AM applications while maintaining machining accuracy.

The 3D printing device is composed of a NEMA 17 stepper motor that drives a filament extruder and a heated nozzle with diameter 0.4 mm taken from a commercial 3D printer, that performs a fused deposition modelling (FDM) process.

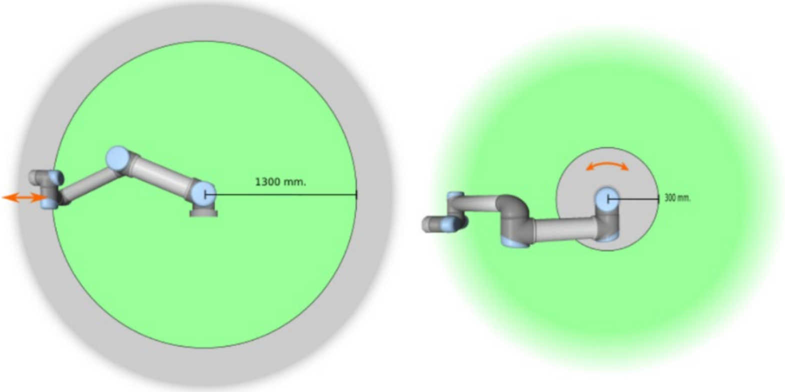


Fig. 1. UR10e working area.

All the components are fastened to the bracket and the On-Robot RG6 dual finger gripper fixes the structure to the cobot flange through its quick exchange connector resulting in a payload of 1.850 kg for the end-effector prototype. Figure 2 depicts the 3D printing end-effector prototype integrated on the UR10e cobot

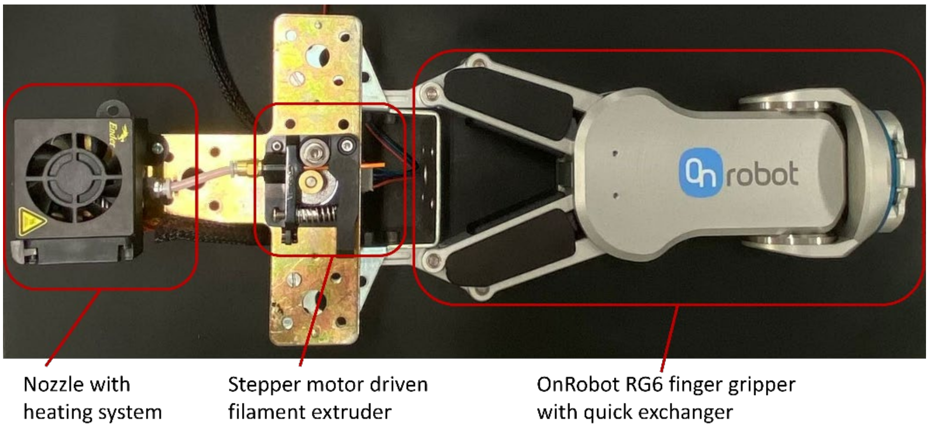


Fig. 2. A prototype of the end effector.

Digital Twin, IoT communication and hardware control system of the AM cell is logically divided into several functions as shown in Figure 3. The teach pendant and UR10e control box are used to receive the printing program and control the movements of the cobot, while sending ON/OFF signals to the Arduino board, synchronizing the extrusion process with the cobot motion. The nozzle temperature control is a separate system operated by the motherboard from the commercial 3D printer.

In the RoboDK software, a virtual AM cell, including the cobot, its accessories and the cell structure, is created by arranging all necessary Computer Aided Design (CAD) models of the components. Then, the CAD model of the ready-to-produce object is imported and placed in the desired position.

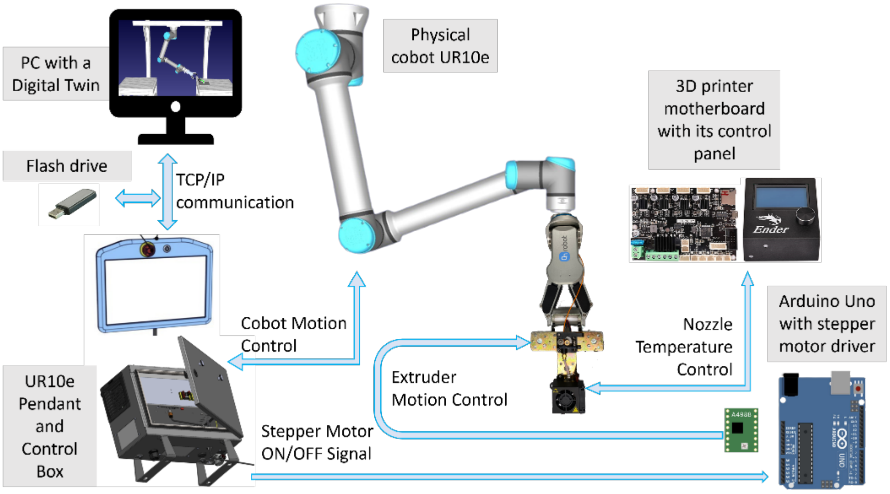


Fig. 3. Robot based AM work cell, IoT communication and control system.

Figure 4 summarizes the complex activities for AM production. RoboDK software allows for creating and simulating the tasks that contain the manufacturing path.

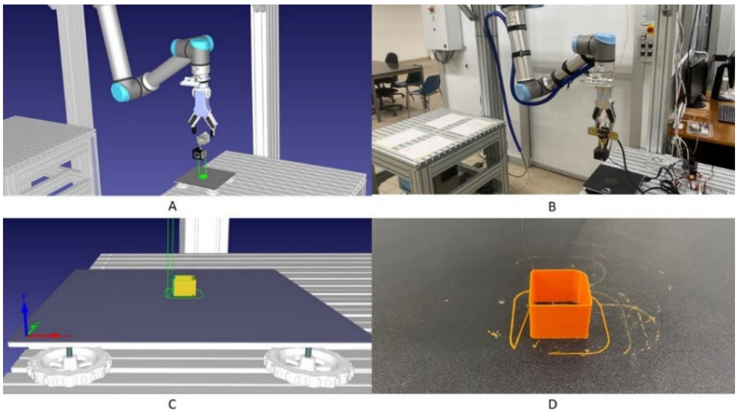


Fig. 4. A) CAD model of the AM cobot cell; B) Physical model of the cell; C) 3D printing of the simulated environment; D) 3D printing of the workpiece.

The RoboDK tasks are converted to robot programs through a dedicated postprocessor and, finally, the robot programs are executed on the integrated HW platform.

Figure 4A and 4C show virtual environment and simulation of AM cell, while Figure 4B with 4D illustrate physical environment of the cell and 3D printing of the workpiece.

4 Case studies

Three different objects have been designed in CAD software and printed in robot additive manufacturing cell. The Slic3r application available in RoboDK software converts 3D models into printing instructions. The objects are sliced into multiple layers 0.35 mm thick parallel to the predefined reference coordinate system. The tool path is defined and optimized by RoboDK to prevent collisions during printing. To minimize excess vibration, the cobot printing speed is set to 10 mm/s.

Case A: The task evaluates the multi-planar printing capabilities of the AM work cell. A tube-shaped object is divided into four parts, each with a unique reference coordinate system. The first part is created on the hotbed using conventional methods. The subsequent parts are then created on the surface of the previous part, with the printing reference system being elevated 15mm and inclined -20° along the Y-axis for each part. The printing process is shown in figure 5, where CAD model of the workpiece, 3D printing simulation and CAD model of the workstation are demonstrated.

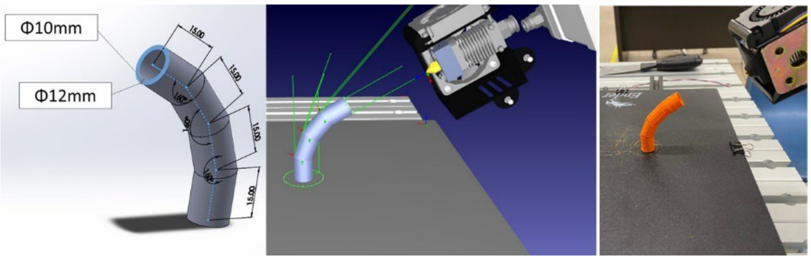


Fig. 5. Case A: On the left, CAD model of the workpiece and its dimensions, in the middle CAD model of the workstation, on the right side the printed tube.

Case B: A box with a hole is created to evaluate the performance and accuracy of the system when producing a simple and basic shape. The dimension of the box is 20x15x 20 mm, and the diameter of the through hole is 10 mm. Figure 6 shows the original CAD model, the CAD model in the virtual environment and the physical environment during printing.

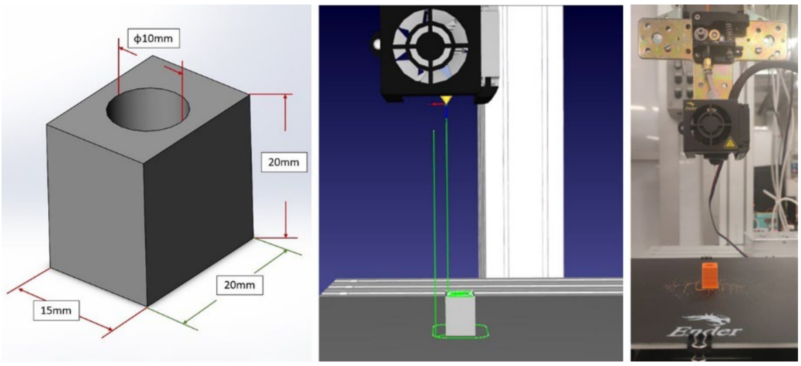


Fig. 6. Case B: CAD model of the workpiece with dimensions (left), CAD model of the workstation (middle), and printed box with a hole (right).

Case C: A thin wall shape object is used to analyze the adhesion of each single layer and the vertical printing quality. The inspection of the object allows for analyzing the material flow and evaluating its uniformity. Figure 7 shows the thin wall shape printed object: the CAD model of the object, and its workstation in digital and physical realization.

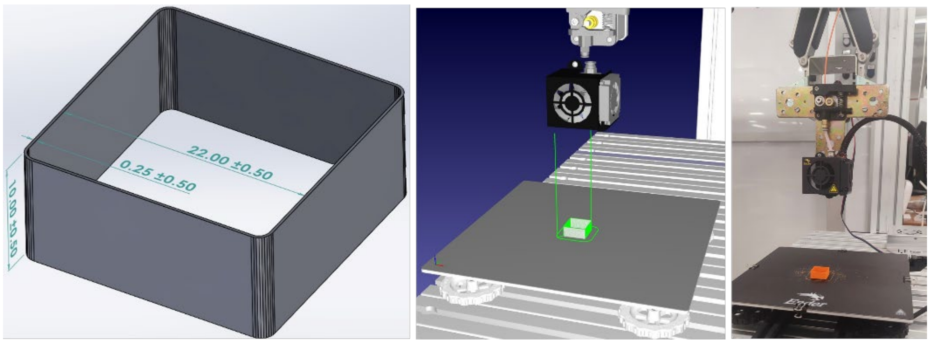
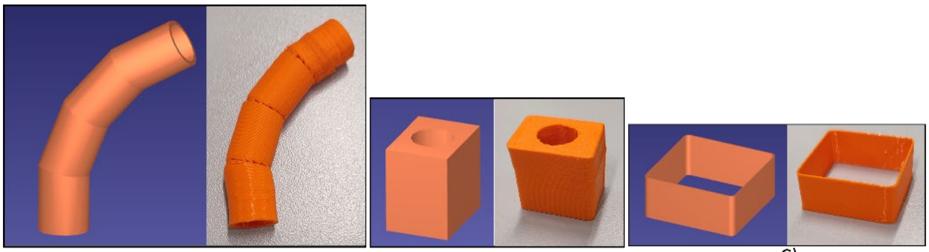


Fig. 7. Case C: CAD model of the workpiece with dimensions (left), CAD model of the workstation (middle), and real system of printed object and devices (right).

5 Results and discussions

The printed objects in Cases A, B and C, were tested on their simulation environment and measured using caliper. The simulation environment allows to simulate a workstation and to evaluate the system in real-time through online programming. The setup of the simulation environment of the workstation supports the online and offline programming.

Figure 8 shows the simulation results and real printed objects from the three case studies.

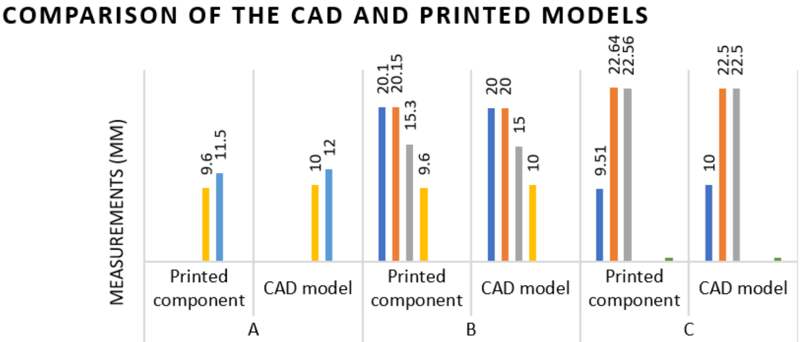


A) B) C)

Fig. 8. A) Tube 3D model (left) and Cobot printed Tube (right); B) Holed Cube 3D model (left) Cobot printed cube (right); C) Squared thin wall 3D (left) and Cobot printed workpiece.

Figure 9 summarizes the measurement results for each of the three scenarios. The measured data highlight an observable difference between nominal and physical dimensions.

According to the results, the performances of the multi-axis 3D printing system are comparable with performances of an ordinary 3D printing machine using FDM technology.



	A		B		C	
	Printed component	CAD model	Printed component	CAD model	Printed component	CAD model
■ Height (mm)			20.1	20	9.51	10
■ Width(mm)			20.15	20	22.64	22.5
■ Length(mm)			15.3	15	22.56	22.5
■ Diameter (internal) (mm)	9.6	10	9.6	10		
■ Diameter (external) (mm)	11.5	12				
■ Thickness(mm)					0.52	0.5

Fig. 9. Measurement results of the CAD and printed objects.

The proposed system has several limitations that require investigation to improve important characteristics of the system itself.

Robot speed: The printing speed is set to 10 mm/s to achieve high positioning accuracy, but this results in a slower printing process, about 4-6 times longer than conventional 3D printing process whose maximum speed is 60 mm/s when PLA (Polylactic Acid Resin) is used.

Quality of the printed objects: Despite the low printing speed, we observed noticeable oscillation and layer shifting in the finished products. This is believed to be caused by the length of the end effector, which causes the nozzle to shake when the cobot arm comes to a sudden stop.

Additionally, the weight of the extrusion system may contribute to layer shifting, especially when the extrusion system is working in an inclined position. Redesign of bracket supporting the extruding system could increase the structural robustness and reduce the nozzle vibration.

Complex geometry structures: Multi-planar printing has the potential to print more complex objects than conventional methods, but the complexity of the generated structures is currently limited by the building material and tool path generation software.

The AM work cell has the potential to build structures with a continuously varying coordinate system, but further research is needed to fully realize this potential and make it easier to use.

Cost of the system: Replacing a conventional AM system with a cobot arm is economically viable only if the quality or complexity of the generated objects reaches a level that cannot be achieved by existing solutions on the market.

Despite these limitations, the proposed system demonstrated its potential for AM in increasing its flexibility within the other processes of manufacturing. The proposed system is capable of generating products on any plane, whether parallel to the ground or fixed.

Additionally, with the use of replaceable tools, AM can be integrated with other processing techniques and applied to a wider range of scenarios, resulting in the production of more complex structures with improved quality.

Overall, the system showcases that AM can be no longer considered as a fixed processing step but as a flexible technology able to cooperate with other ones.

6 Conclusions

This paper demonstrates the use of cobots to manage AM processes and proposes a physical tool with a digital setup to create a cyber physical system of printing process. Cobot's end-effector for additive manufacturing demonstrated its effectiveness in producing quality parts of various dimensions and geometries.

A cobot-based AM workstation integrates both software and hardware applications and assists the manufacturing process from the CAD model to the final part production. Design and simulation of AM properties in the CAD model of the workstation allows for controlling the cobot end-effector orientation, thus improving the production of higher quality parts with no stair-like structure on their finished surface.

Furthermore, the system improves the appearance, mechanical properties, and load support in specific directions.

Finally, the proposed solution replaces a 3D printing machine with a printing robot and opens up the possibility of new solutions that take advantage of the flexibility of the robot. On the other side the proposed solution requires further investigations in order to improve its reliability, manageability and productivity.

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