Grasshopper-Based Design and Optimization of Mechanical Systems for Robotic Continuous Carbon Fiber Additive Manufacturing

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Abstract. This study focuses on solving problems in traditional three-axis 3D printing, such as the stair-stepping effect, excessive support structures, and poor mechanical performance. It uses continuous carbon fiber as the printing material and designs an automated additive manufacturing system based on a KUKA multi-axis robotic arm. The study chooses a multi-degree-of-freedom robotic arm as the motion platform. It uses Solid Works to design and 3D print the printing structure, which includes a hot end, a cooling part, and a throat tube. To improve cooling, the system uses spiral cooling blades and compressed gas. For software, it uses Grasshopper to create visual printing paths. It controls the Marlin firmware through serial communication to automate the printing process. In final tests, the results show that the software makes the printing path clearer and flexible. It also improves system integration and printing accuracy. For the hardware, the new print head can print complex shapes. The cooling tower helps improve cooling. It prevents the continuous carbon fiber material from melting in the upper part of the throat tube. This avoids blockage in the material path.

Keywords: Multi-Axis 3d Printing, Continuous Carbon Fiber, Robotic Additive Manufacturing

1 Introduction

With the rapid development of modern industry, higher requirements have been placed on manufacturing technology. 3D printing technology, also known as Additive Manufacturing (AM), has demonstrated its great potential for application in a variety of fields, such as industrial, medical, aerospace and construction, thanks to its advantages in design freedom and material utilization.3D printing technology breaks through the 3D printing technology breaks through the limitations of traditional manufacturing processes, allowing designers and engineers to create complex structures and shapes that would be difficult to achieve with traditional methods, greatly contributing to the innovation and productivity.

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Although 3D printing technology has significantly transformed the manufacturing industry, limitations remain in the range and performance of applicable materials. At present, most 3D printing techniques predominantly utilize engineering plastics as the primary printing materials. However, these materials exhibit constrained mechanical properties—such as limited strength, stiffness, and durability—which hinder their suitability for high-performance applications, particularly in environments requiring high load-bearing capacity and resistance to harsh conditions.

With ongoing technological advancements, continuous carbon fiber-reinforced composites are emerging as a preferred material for additive manufacturing due to their superior mechanical characteristics. Notably, their exceptional strength, stiffness, and durability make them especially well-suited for demanding applications in fields such as aerospace, automotive engineering, and precision instrumentation [1]. The integration of continuous carbon fiber-reinforced materials into 3D printing processes enables the production of components that are not only stronger and more durable but also better aligned with the performance requirements of high-end manufacturing [2]. This development represents a significant step forward in advancing additive manufacturing toward more robust and industrially viable solutions [3].

The common 3D printer machine on the market is usually a 3-axis gantry printer. This 3-axis AM process slices in the X-Y plane and then stacks layer by layer along the Z-axis in a fixed direction, so the paths therein are restricted to a specific 2D plane, which results in the 3-axis AM process having a number of limitations due to limitations in the number of degrees of freedom of the system and the process planning. Firstly the layering and path limitations of the 3-axis AM process make it impossible to print parts with complex geometries. Secondly, the 3-axis AM process molds the part layer by layer along the z-axis, creating a stepping effect on the high curvature surfaces of the part. The step effect affects the dimensional accuracy and surface roughness of the part being produced. Second, the 3-axis AM process molds layers along the z-axis, which creates a step effect on the high curvature surfaces of the part. The step effect affects the dimensional accuracy and surface roughness of the manufactured part. In addition, the 3-axis AM process requires the construction of additional support structures to prevent layer collapse when the part is suspended. Construction of the support structure will result in increased part fabrication time, increased material consumption, and reduced surface quality. In addition, the need to remove the support structure after construction of the overhanging part makes post-processing (e.g., stripping the support structure, cleaning, etc.) more difficult. The fill paths (serrated fill and contour) of the 3-axis AM process do not take into account the mechanical properties of the part, resulting in a part that is manufactured with less than optimal mechanical properties due to anisotropy. Finally, three-axis AM machines are not capable of manufacturing large parts due to their limited degrees of freedom and cavity volume [4].

To overcome these challenges, continuous carbon fiber 3D printing with multi-axis robotic arms has received increasing attention in research. With its redundant degrees of freedom, the multi-axis robotic arm performs surface layering and prints from multiple angles. This not only eliminates the weakening of mechanical properties due to step effect, support effect, and anisotropy to a certain extent, but also enables the printing of parts with complex geometries. In addition, in large-scale manufacturing, multi-axis AM machines can be designed for the extension direction of large-size parts, making it possible to 3D print large parts [5].

In the research and design of the multi-axis 3D printing system by the team from Beijing University of Aeronautics and Astronautics (BUAA), they chose a six-degree-of-freedom robotic arm and mounted the print head on the flange of the actuator at the end of the robotic arm. Since the ROS and the printing system work independently of each other, they designed a system to make the two work together. First, the robot arm is controlled to move along the planned route, and then the content of the corresponding G-code is calculated based on the movement information of the robot arm and sent to the firmware via serial communication to control the printing system [6].

The three-axis motion scheme widely used in the current continuous fiber composite additive manufacturing (CFRP-AM) system is not only difficult to manufacture medium- and large-sized components due to the limited molding space, but also only able to arrange continuous fibers in a two-dimensional plane, resulting in weaker performance of the components along the direction of the material stacking. Xiong Yi, assistant professor team of Southern University of Science and Technology for the above problems, developed a set of robot-assisted continuous fiber composite materials based on co-conformal additive manufacturing system, and used the system to successfully fabricate a complex fiber spatial arrangement of the grid reinforced shell structure. Compared with the existing process methods, the system achieved a significant improvement in the mechanical properties of the components, demonstrating a new paradigm of continuous fiber composite additive manufacturing and its great potential [7].

On this basis, this study developed a multi-axis robotic arm type continuous carbon fiber automated 3D printing system. In terms of hardware, a KUKA multi-axis robotic arm was selected as the motion platform, and the printing mechanism including the hot end, cooling, and throat was built. In order to adapt to the workspace of the six-degree-of-freedom robotic arm and avoid interference between the hot end and the printed parts, the hot end adopts a long and thin design, and at the same time integrates a compact cooling system, arranges the fan and radiator above the hot end, and optimizes the wiring of the pipelines and cables. For the cooling system, water cooling and air cooling are both selected in this study. Firstly, the water-cooled 3D printing nozzle was referred to [8], because the water has a large specific heat capacity, which can play a good role in cooling effect, and the use of cooling circulating water can effectively make the temperature lower. However, since the sealing effect could not be well ensured and safety hazards appeared, air cooling was finally adopted. For my study, the traditional fan is removed and a compressed gas cooling mechanism is used. The cooling structure is innovative, with spiral cooling blades and a tower cooling structure designed so that the compressed gas flows along a spiral path to improve heat transfer efficiency and enhance the cooling effect.

In terms of software, this study abandons the traditional 3D printing path generation tool and uses Grasshopper for visualization programming and control of the robot arm motion path. Grasshopper generates G-code and utilizes its serial communication function to send commands to the Marlin firmware control system in real time, which completes the automated linkage control of the printing subsystems such as extrusion, shearing and pre-extrusion. This solution not only enhances the intuition and flexibility of path generation, but also improves system integration and printing accuracy.

Multi-axis 3D printing technology not only significantly improves the performance of components, but also provides designers with greater design space, enabling them to create more innovative and optimized products. Multi-axis robots can be used for the printing of complex rotating parts such as propeller blades. In the field of aviation, the application of this technology will help reduce the weight of aircraft [9], improve fuel efficiency and reduce operating costs, while the use of large robotic arms will make it possible to manufacture large-scale aviation parts, which is important for improving the performance of aircraft and reducing manufacturing costs.

In addition, the robotic arm continuous carbon fiber 3D printing technology will bring multiple advantages such as reducing material waste [10], shortening the production cycle, and improving the flexibility of production, which foretells its great potential and application prospects in the modern manufacturing industry. With the continuous progress and improvement of technology the technology will play a more critical role in the future manufacturing industry, provide new manufacturing solutions for the high-end manufacturing industry, and promote the further development and innovation of the manufacturing industry.

2 Detailed Design

2.1 Design of automated printing systems

Extrusion Systems. Select any curve and use curve segmentation to divide the curve equally into 50 segments; each extrusion should be the length of each segment. Design a general switch that is connected to the relative side of the python statement that sends the final G-code, for example, to send G91 (so that all subsequent movements are relative to the current coordinates). Connect a counter behind the master switch to act as a timer, and send “G1 E ‘+str(E_value)+’ F700” every second after the counter starts counting, where str(E_value) is the value of the current motion as calculated by the where str(E_value) is the distance between the current point and the next point calculated by python. The counter is controlled by connecting a judgment python statement after the counter so that the extrusion statement is only enabled for a specific period of time.

Figure 1 shows how to get 3 curves from Rhino. Using Merge to combine them into a list of curves. Select a curve in the list. Extract the curve for length calculation.

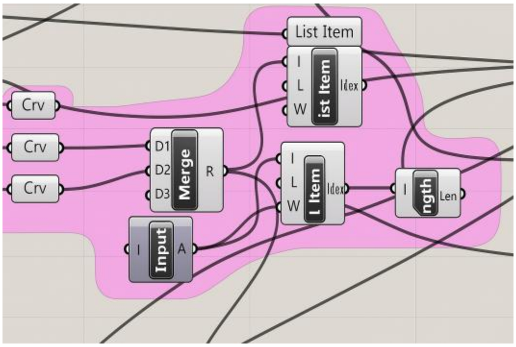

Fig. 1. Curve merging and selection process in Rhino(Picture credit : Original)

Shearing and Pre-Extrusion Systems. The length of the pre-extruded curve is calculated from the difference between the length of the nozzle and the length of the printed curve. Then design a length accumulator as in Figure 3, whose function is to first divide a curve into equal parts according to a set number of segments, output multiple points, and then extract the current point and the next point from the point list. Calculate the Euclidean distance between these two points. Finally, in the accumulator in the yellow panel at the bottom right corner, the length of each section will be added up step by step to get the total length. Use the python statement on the left side of Figure 2 to determine if the current extrusion has reached the cut length, and if it has then enabled the counter connected behind it. As shown in Figure 2 connect 3 python statements after the counter to delineate 3 points in time, they send M280 P0 S95, M280 P0 S105, M280 P0 S95 in turn (the instructions sent control the rotation of the servo tool and the shear action). Connect 1 more python statement on the bottom right side of Figure 2 to divide a time point in the above counter to enable the pre-extrusion end and send G01 X60 F600 one more time.

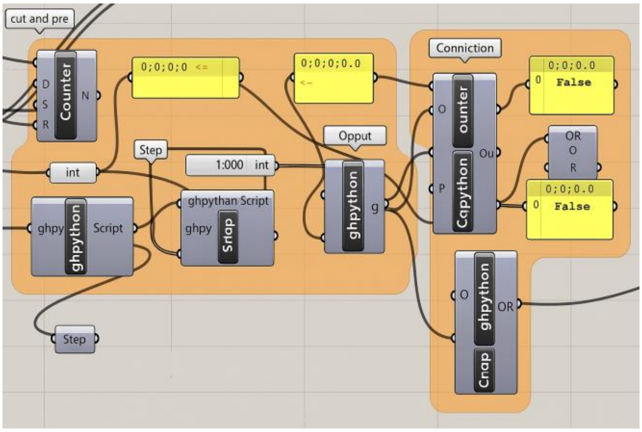

Fig. 2. Conditional judgment and Boolean logic for curve segmentation in Python (Picture credit: Original)

Figure 2 By determining the position of the current curve segment, working with Python scripts to make conditional judgments (e.g., whether it is in the shear region or needs to be prepossessed), and using Boolean logic (to integrate multiple judgments, thus outputting a Boolean list for subsequent operations (e.g., cropping, extruding).

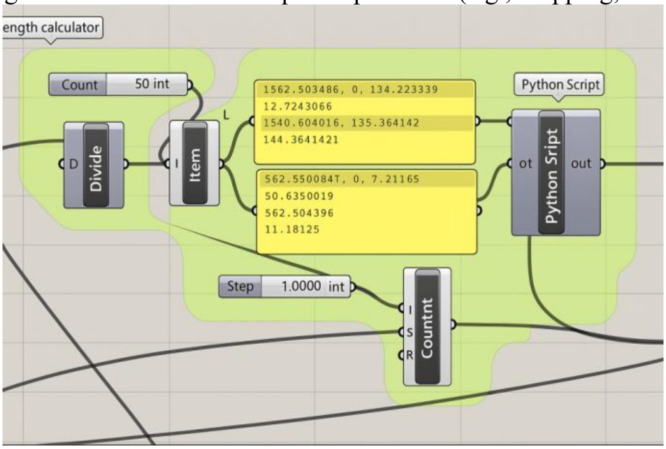

Fig. 3. The length accumulator with the segmented curve entering the counter from the left side (Picture credit: Original)

Figure 3 shows the length accumulator with the segmented curve entering the counter from the left side.

Switching Lines and Resetting the System. And then design a counter 2, its Set input by the total switch control, the value of every second increased by 1. Because the curve segmentation curve into 50 sections, so when the counter 2 value reaches 50, as the print head has printed a whole curve, to reach the conditions of line change. After reaching the condition of line change, through the python program driver file, the Reset input of counter 2 will be set to 1, so that its Set input and Reset input end are both 1 and reset, and after reset, the Reset input will be set to 0, so that it can continue to print. Design another counter 3. after reaching the line change condition, the python program outputs a negative pulse, which is converted to a positive pulse by a non-gate and connected to the Set input of counter 3, the positive pulse will increase its value by 1. after the value of counter 3 is increased by 1, the information of the next curve is fed into the curve segments through the list and file so that the system will start to print the next curve. Add a switch to the Reset input of Counter 3 and connect it to the S terminal through an or gate. When the switch is manually opened, both the Reset and Set inputs are set to 1 at the same time and Counter 3 is reset.

Robotic arm synchronization system. Enter the curve into the moving end of the robotic arm. The position of the robot arm (print head) when the Slider value is 0 is roughly estimated to be (775, -20,150). The coordinates of the start of a curve are obtained from the curve endpoints and converted to three numeric outputs using a list, and the distance between (775, -20,150) and the start of the curve is calculated using a python program. Divide this distance by the total length the print head should move when printing this line (i.e., it is this distance added to the length of the curve), and the resulting ratio is the initial value of the Slider. Write a python program so that each time the value of the counter increases by 1, the value of the Slider also increases. When the counter value reaches 50 (i.e., the line change condition is reached), the Slider value is 1. Figure 4 shows the initial position of the robotic arm. Figure 5 shows the robotic arm at the beginning of the curve

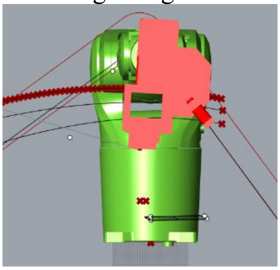

Fig. 4. The initial position of the robotic arm (Picture credit: Original)

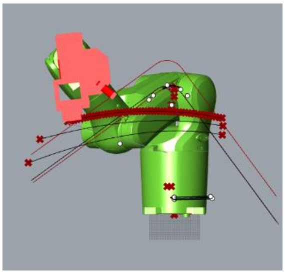

Fig. 5. The robotic arm at the beginning of the curve (Picture credit: Original)

2.2 Design and drawing of 3D printing head

For the drawing of the heating block, this study minimizes the projection area of the heating block on the z-axis as much as possible, i.e., the heating block shown in Figure 6, with a projection area of 15mm*9.5mm, which avoids collision with the printed object. The internal structure can be seen through the sectional view in Figure 7. The small hole on the side is used to clamp the heating bar using a set screw.

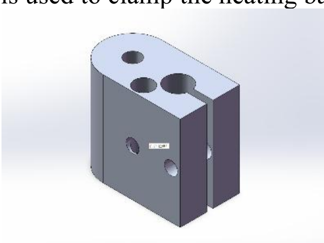

Fig. 6. Three-dimensional view of the heating block (Picture credit: Original)

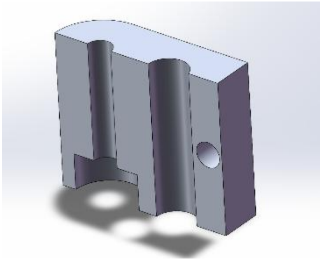

Fig. 7. Section view of the heating block (Picture credit: Original)

The spiral vane cooling section shown in Figure 8 is partially made of brass, and the advantage of the spiral vane is that it allows the surface area of the cooling vane to be enlarged and come into contact with as much compressed gas as possible. The compressed gas enters the air chamber in Figure 9 through the gas holes and moves along the spiral cooling vanes towards the outlet below, carrying away as much heat as possible along the way. Figure 10 shows an assembly of the cooling tower and air chamber and a cross-section thereof, with the connection portion being threaded. Figure 11 is section view.

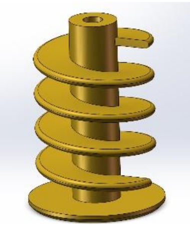

Fig. 8. Brass cooling tower (Picture credit: Original)

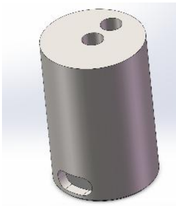

Fig. 9. Air chamber (Picture credit: Original)

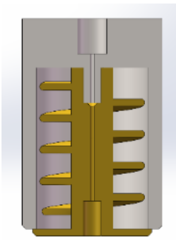

Fig. 10. Assembly diagram (Picture credit: Original)

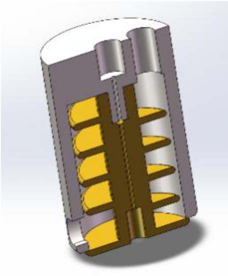

Fig. 11. Section view (Picture credit: Original)

Due to the difficulties that may be encountered in the machining of the spiral blades such as excessive cost and long lead time, a common cooling section as shown in Figure 12 was also designed in this study. The thickness of the blades are all 1mm and the material is also chosen as brass. Figure 13 shows its section view.

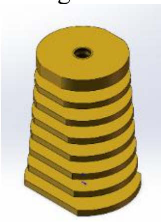

Fig. 12. 3D model of common cooling section(Picture credit : Original)

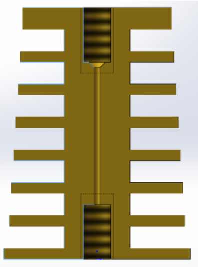

Fig. 13. Section view(Picture credit : Original)

Finally, there is the component that connects the cooling section to the heating block. In order to use continuous carbon fibers and to ensure that the consumables (continuous carbon fibers) are as free from clogging as possible, the connectors shown in Figure 14 were designed with a through hole in the middle foreseen to be 1.8 mm (as shown in the section in Figure 15) and using PTFE (Polytetrafluoroethylene) or stainless steel as the material of the inner tube with a polished surface to reduce friction. It is also ensured that the inner wall of the connector is smooth to avoid sharp bends to reduce the risk of fiber breakage.

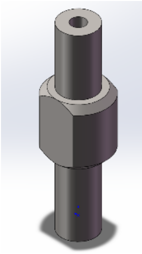

Fig. 14. Connection component (Picture credit: Original)

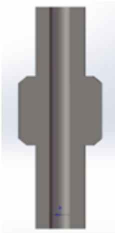

Fig. 15. Section view (Picture credit: Original)

The parts designed were fit in solid works with a threaded M3 connection and the results are shown in Figures 16 and 17 below.

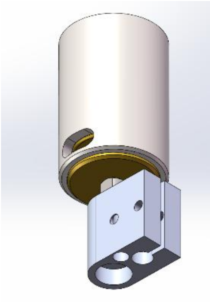

Fig. 16. Assembly diagram (Picture credit: Original)

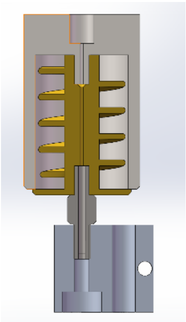

Fig. 17. Section view (Picture credit: Original)

The figures 18 and figure 19 shows the physical finished product of this study, printed from metal. The fast-heating material is alloy steel and the cooling part is brass.

Fig. 18. Actual finished product (metal print) (Picture credit : Original)

Fig. 19. Finished product with air chamber (and placed in the hand for easy observation comparison of actual size)(Picture credit : Original)

3 Discussion

3.1 Visualization Programming

As a visualization programming plug-in, the linkage between Grasshopper and Rhino gives it a lot of room for development in the field of designing mechanical systems. This project only shows the more basic programming functions in Grasshopper. In the foreground, the future programming trend may be a combination of visual programming and text programming, using visual tools to lower the entry barrier and increase development efficiency, while relying on text programming for more complex and high-performance applications when needed. Visual programming tools make it easier for professionals in different fields (e.g., designers, data scientists) to program, which improves the efficiency of cross-disciplinary collaboration. They also help developers to quickly create and adapt prototypes for rapid iteration and testing, and their intuitive nature reduces the learning curve so that beginners can get up to speed quickly. How to better utilize visual programming plug-ins such as Grasshopper is an issue that needs to be researched in the field of E&M in the future.

3.2 A more comprehensive 3D printing head

With the rise of continuous carbon fiber 3D printing, manufacturing has been revolutionized. In addition to considering the materials and applications of 3D printing, the 3D print head - the most critical part in determining the quality of 3D printing - needs to be constantly revolutionized. High-precision print heads are capable of achieving micron-level accuracy, making it possible to print complex structures and precision parts. This is particularly important in areas such as electronics components. In the near future, smart print heads can be integrated with sensors and AI technology. Smart print heads can monitor the printing process in real time, automatically adjust parameters to optimize print quality, and detect and repair printing defects. This not only improves printing efficiency and quality, but also reduces material waste. It can be said that the technological advancement of 3D print heads can greatly promote the development of the 3D printing industry.

3.3 Accuracy problems

At present, most 3D printing systems use robotic arms for manufacturing, and the accuracy problem limits the wide application of multi-axis robots in the field of 3D printing. Although the repeatability of industrial robots is already very high (0.1~0.5 mm), the actual positioning accuracy is low due to manufacturing errors, measurement errors and calibration errors, which in turn affects the printing accuracy [11].

3.4 Reflections on hardware

For the heating block of this study chose alloy steel, but after getting the physical object, it was found that the hardness of alloy steel was too high to be clamped with the tightening screws, which resulted in the heat of the heating rod could not be well conducted. For this problem, this study consulted the relevant information, that the following materials can be selected: (1) aluminum alloy has a lower hardness. Take 6061 aluminum alloy as an example, its Brinell hardness (HB) is about 95, while the Brinell hardness of 7075 aluminum alloy is about 150. aluminum alloy is lightweight, easy to process, and inexpensive, but it is relatively soft and prone to wear and deformation. (2) Copper has a Brinell hardness of about 35, the lowest of the common materials, but commonly used in heating block fabrication is chromium-zirconium copper, an alloy with a much higher hardness, typically around HB 110. Excellent thermal conductivity, but softer and easier to scratch and deform.

In addition, when combining parts this study found that there is a risk that the threads may break due to the thinness of the connecting part. In this regard, the main reasons may include: the root of the threads of the thin screws has less material and is subjected to concentrated stress, which can easily exceed the strength limit of the material and lead to breakage. And when tightening a fine screw, if the torque applied is too high, exceeding the design capacity of the screw, it will lead to excessive force on the thread and fracture. In order to reduce the risk of fracture of fine screw threads, the following measures can be taken: the use of high-strength materials to manufacture screws, such as alloy steel, stainless steel, etc.. And you can improve the geometry of the thread to reduce stress concentration, using a larger radius of the thread root fillet.

4 Conclusion

In this study, a continuous carbon fiber 3D printing system based on a KUKA multi-axis robotic arm is designed and implemented. In terms of hardware, this study designs and draws the skinny hot end and spiral blade cooling structure, as well as designing a new cooling scheme. It also improves the safety of printing and reduces the possibility of the hot end touching the printed part. In terms of software, Grasshopper was used for visual path planning, generating G-code, and sending commands to control the Marlin firmware through the serial port, which realized the automatic control of the processes of extrusion, shearing, and wire changing. The whole system can print complex geometries, which reduces the step effect and the use of support structures that occur in traditional 3-axis printing, and also improves the mechanical properties of the parts. The research not only presents a new solution, but also provides a technological basis for high-performance 3D printing. This technology has great potential for application in aerospace, automotive manufacturing and precision instruments. In the future, such systems can further incorporate sensors and intelligent control functions to realize automatic adjustment and fault repair of the printing process. At the same time, the joint printing of different materials will also become a development direction, which is expected to create more multi-functional composite structures. In addition, with the continuous development of visual programming tools, the design of print paths will become simpler and more efficient, facilitating the participation of engineers from more fields in research and development. The standardization of printing equipment and software will also help this technology to spread more quickly and promote further upgrading of the manufacturing industry.

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