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# *Exploration and Practice of 3D Printing Technology Experimental Teaching*

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***Abstract:*** 3D printing technology is an advanced manufacturing technology developed based on the principle of layered manufacturing. With the increasing popularity of 3D printing technology, cognitive and operational experiments related to 3D printing have been carried out in the experimental teaching of mechanical engineering disciplines, but they have not yet met the urgent demand for cultivating high-end talents in 3D printing. In the process of experimental teaching of 3D printing technology at the School of Mechanical Engineering, University of Shanghai for Science and Technology, the teaching objective is determined to enable students to master 3D printing, an advanced manufacturing technology and method, from the level of mechanism, and achieve this objective through three steps of teaching design: 3D printing principle analysis, 3D printer structure analysis and innovative design teaching and practice, and 3D printing effect analysis and printing operation countermeasure teaching and practice. This progressively extended teaching process can prompt students to start thinking about the mechanism of 3D printing, understand the functions of printer components, master functional component design methods, correctly configure the optimal 3D printing parameters, and complete the design of support structures required for 3D printing, thus fully mastering this advanced manufacturing technology and method. The experimental teaching of 3D printing technology in recent years has verified the applicability of this teaching method to undergraduate students and the operability in the teaching practice process.

## 1. Introduction

3D printing technology, formally known as Additive Manufacturing (AM) technology, is a method of forming parts by accumulating points to form surfaces and stacking layers to form bodies. Its manufacturing process integrates many cutting-edge technologies such as information technology, data modeling, electromechanical control, materials science, and chemistry. Its applications span various fields including aerospace, precision machinery, automotive manufacturing, and agricultural engineering. Based on the principle of directly manufacturing solid parts layer by layer according to CAD data, 3D printing technology solves the manufacturing challenges of complex structures and has become a hot technology pursued by manufacturing powerhouses worldwide[1-3].

In recent years, 3D printing technology has entered a period of rapid development. For students in universities, understanding and mastering 3D printing technology has become an urgent issue in experimental teaching, especially for disciplines such as mechanical engineering. Universities at home and abroad are gradually changing traditional educational content and experimental teaching methods, continuously exploring feasible experimental teaching schemes and measures for 3D printing technology[4-5]. In mechanical design majors, it is relatively easy to achieve cognitive teaching of 3D printing by combining it with mechanical principles and mechanical design courses, using 3D printing technology to fabricate structures into physical objects, giving students an intuitive impression of the structures, and enabling them to grasp cumbersome theoretical knowledge simultaneously[6]. As for experimental teaching, it can typically be achieved through three methods: firstly, guiding students to assemble a 3D printer themselves to understand its working principle[7]; secondly, demonstrating the 3D printing process to students; thirdly, assisting the students in independently completing the 3D printing process[8].

The aforementioned teaching content and methods make it possible for students to have a direct understanding and preliminary operation of 3D printing and 3D printers. However, with the increasing demand for cultivating innovative abilities among university students, cognitive education and operational learning alone are far from meeting the needs of universities to cultivate high-end talents in 3D printing during their undergraduate studies. Students' mastery of new processes, methods, and equipment now requires a deeper understanding, including understanding the reasons behind them, and subsequently developing the ability to independently design and develop new products with autonomous intellectual property rights, as well as the ability to design reasonable process parameters for new processes.

Based on these considerations and relying on the Ministry of Education of the People's Republic of China's Industry-Education Cooperation Collaborative Education Project, the School of Mechanical Engineering at the University of Shanghai for Science and Technology has established a 3D printing simulation experimental teaching curriculum system during undergraduate education, and has conducted some explorations and practices in 3D printing simulation experimental teaching. The specific content includes cognitive perception, comprehensive application, and innovation improvement modules. Among them, the innovation improvement module, which includes experiments on functional design of 3D printers and simulation analysis of 3D printing parameters, is a characteristic experimental course for the mechanical design and manufacturing major at the School of Mechanical Engineering. The objective of experimental teaching is to enable students to fully master 3D printing, an advanced manufacturing technology and method, from the level of mechanism, including understanding the principles of 3D printing, the functions of printer components and their design methods, and the principles of printer parameter setting.

## 2. Experimental Course System

3D printing technology is an integrated technology involving disciplines such as mechanical engineering, electronic engineering, materials science, and industrial design, and it represents a novel manufacturing method. Drawing from existing experience in 3D printing technology experimental teaching, the teaching of 3D printing technology at the Mechanical Engineering College of Shanghai Institute of Technology begins with fundamental cognitive perception teaching. It covers basic theories and operational knowledge, such as the fundamental principles, technical characteristics, process workflow, printer usage, and advantages of 3D printing. Emphasis is placed on the importance of three-dimensional data modeling, introducing students to the basic modeling concepts of three-dimensional software, familiarizing them with the use of simple commands, and allowing them to grasp the fundamental principles of modeling while autonomously learning complex modeling operations.

Building upon students' grasp of the basic theories and operational knowledge of 3D printing, the Mechanical Engineering College of Shanghai Institute of Technology focuses on guiding students to contemplate the design principles and methods of 3D printer functionality. Based on students' understanding of the principles behind 3D printer functionality, they are guided through the analysis of 3D printer structures and innovative design practices.

Additionally, within the context of innovative design courses for students, practical courses analyzing the printing effects of 3D printers and implementing printing operation strategies are offered, referred to as printing analysis teaching and practice. In this course, rather than simply enhancing printing effects through slicing, students are guided to find printing methods that are most suitable for improving the quality of printed parts based on principles. Consequently, students are able to design innovative products according to the functional requirements of different components. Throughout the entire process, students take charge of design requirements, design processes, and manufacturing processes, understanding the characteristics of the design products, enhancing their engineering awareness, fostering independent learning, and developing the ability to adapt to new phenomena, enabling students to understand new technologies thoroughly and comprehensively.

The overall experimental course system for 3D printing is illustrated in Figure 1. Since the incorporation of 3D printing technology into the experimental teaching activities of universities, the development of cognitive, perceptual, and comprehensive application experiments by various universities has shown initial success. The following sections focus on exploring and practicing innovative enhancement experiments in the course system.

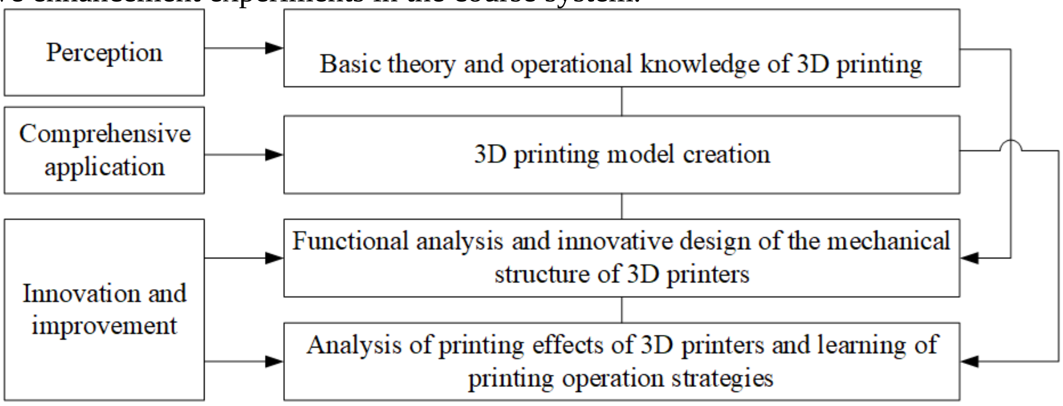



Figure 1: 3D Printing Experiment Course System

## 3. Teaching and Practice of Innovative Mechanical Structure Design

To realize the mechanical operations involved in the 3D printing process, the mechanical structure of a 3D printer is typically designed through three main components: the external frame, the base platform, and the motion mechanism of the printhead. Students can be grouped to work on the design of different mechanical structures such as the external frame, base platform, axial motion mechanism, and printhead motion mechanism.

Taking the design of the 3D printer frame as an example to illustrate mechanical structure design, after understanding the basic functions of the printer and studying common frame design schemes, students can analyze the advantages and disadvantages of existing designs and even propose their own design solutions. For instance, two frame design schemes for the 3D printer are presented below. In Figure 2, an open-frame structure is adopted for the external frame design. This scheme mainly consists of two trapezoidal feet, a gantry frame perpendicular to the base, and two circular tubes at the bottom. In Figure 3, a box-frame structure is utilized, composed of 12 aluminum alloy profiles assembled together. Reinforcement at the joint corners is achieved using 90° multi-configuration die-cast corner brackets, while strong multi-configuration die-cast corner brackets are employed at the bottom of the frame to further enhance rigidity. This box-frame structure draws inspiration from the frame types commonly used in high-end 3D printers on the market, balancing stability and aesthetics, making it a feasible solution.

After completing the initial design, students conduct an analysis of the strengths and weaknesses of the structure. This analysis is based on the knowledge structure and numerical calculations cultivated during their university education.

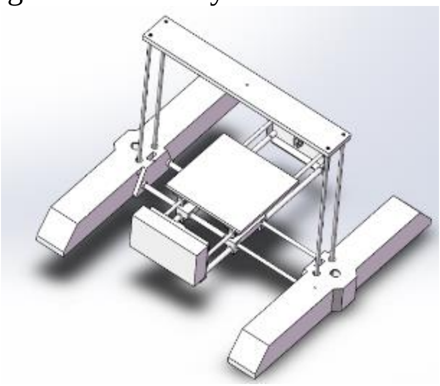


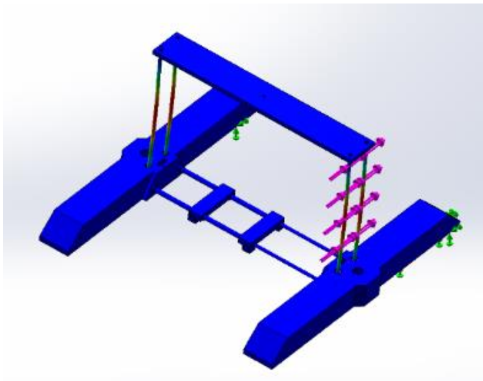
Figure 2: Open-framework structure

Figure 3: Box-frame structure

The open-frame structure design typically consists of several metal pipes forming a gantry frame and a base frame, with the two frames vertically connected to create a complete external frame. However, this design suffers from the instability of the gantry frame. Due to the gantry frame being constructed with relatively thin metal pipes and the need to ensure a considerable printing height for the 3D printer, the axial length of the metal pipes used is generally long. This leads to a weaker resistance to tipping for the upper gantry frame under external forces, resulting in instability and shaking during the printing process.

To address this issue, two A-shaped support brackets are added on both sides of the gantry frame, along with longer parallel base feet, to enhance the gantry frame's resistance to tipping. By employing simulation analysis methods to conduct static stress analysis on both the original gantry frame and the modified gantry frame with A-shaped support brackets and longer base feet, it can be observed from the deformation cloud maps in Figures 4 and 5 that, under the same material and external force conditions, the deformation of the modified gantry frame with A-shaped support brackets and longer base feet is smaller compared to the original gantry frame. This improvement enhances the precision during movement. The improved frame is superior to the original one and represents a viable solution. Similar analyses and improvement designs can be conducted for other schemes, such as Scheme Two or any other alternative designs.

Guiding students to compare the generated solutions based on the aforementioned analysis is crucial. Taking the two schemes mentioned as examples: both the improved open-frame structure scheme and the enclosed box-frame structure scheme can meet the operational requirements of the 3D printer.



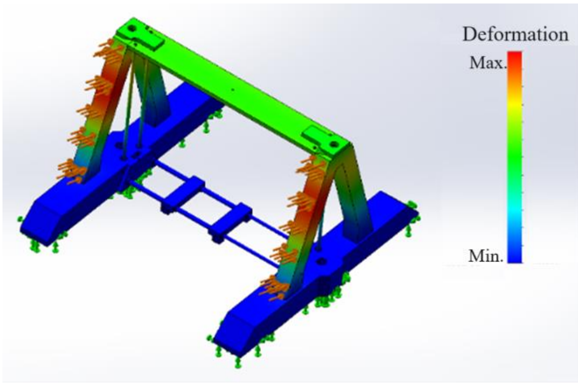



Figure 4: Original frame deformation  Figure 5: Modified gantry frame deformation

The distinguishing feature of the open-frame structure scheme lies in its reinforcement and improvement based on an open-frame structure. The overall structure is simple, easy to install, and simultaneously ensures a certain level of stability. On the other hand, the box-frame structure scheme features a modular cuboid frame, which provides better protection for the moving parts within the frame and offers higher strength and rigidity.

## 4. 3D Printing Analysis Teaching and Practice

Following students' understanding of the structure and design methods of 3D printers, teaching and practical exercises focusing on print analysis and operational strategies are conducted to enhance students' grasp of new concepts and foster innovative thinking.

In this segment of the teaching practice, students are tasked with designing various print components in groups. Utilizing additive manufacturing simulation software, primarily with metal as the main material and Selective Laser Melting (SLM) technology as the forming method, students adjust key printing parameters such as laser power, scanning speed, and substrate temperature. Through software calculations, the final deformation variables of the printed components are determined. A comparative analysis of simulation results is conducted using the contrast method to derive recommended printing parameters.

For instance, the frame of a heat dissipation fan, a component commonly found in 3D printers, serves as the printing object (Figure 6).

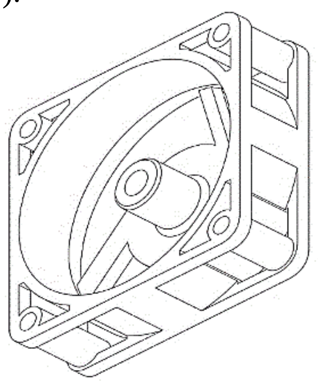


Figure 6: Basic structure of the cooling fan frame

### 4.1. Support Parameter Setting

Based on the current laboratory conditions, two different metal materials, CoCr cobalt-chromium alloy or IN718 nickel-chromium alloy, can be used to manufacture the aforementioned printed parts.

Firstly, students are required to predict and analyze the structural printing results to determine whether support is needed during the printing process. The decision to add support during printing significantly affects the stress situation in the parts where support structures come into contact. Taking CoCr material printing as an example, students should be able to independently obtain the final deformation of printed parts with and without support, similar to those shown in Figures 7, and provide a design proposal based on the analysis results. In this case, the conclusion students should draw is: considering that the printed part has fan blades installed internally, the circular part of the unsupported printed part exhibits significant deformation, which could potentially cause the fan to collide with the frame during operation. Therefore, for manufacturing this printed part using CoCr, it is recommended to add support.

Secondly, the correctness of students' structural analysis is verified through actual printing. Due to the long printing time and high cost of 3D printing, consistent basic structures are preferably used for overall analysis and prediction. After comparing the analysis and prediction results of several groups, a unified printing verification is conducted. Typical cases from each session can be retained as guiding examples for the next session of student practices to reduce experimental costs.

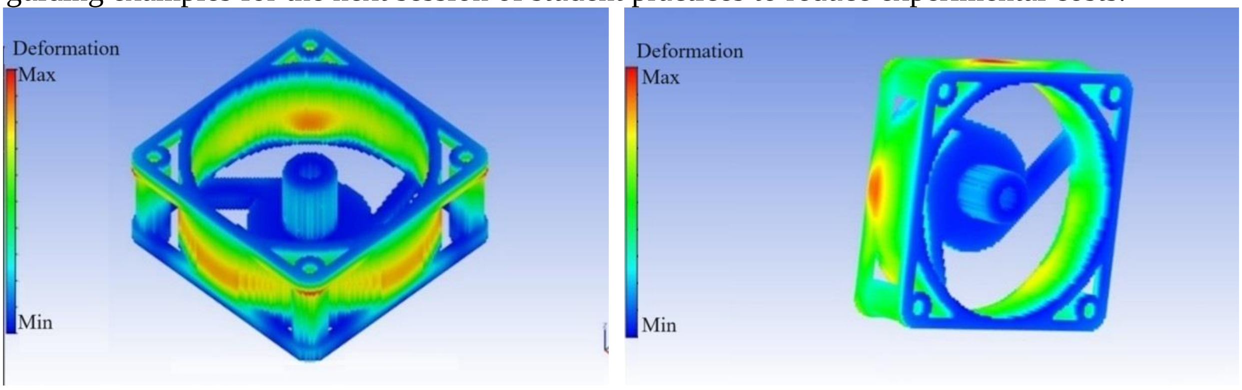



Figure 7: CoCr Print deformation (left: with support, right: unsupported)

### 4.2. Laser Parameter Setting

The laser selective melting technology achieves rapid prototyping of complex metal parts by layer-by-layer melting and spreading fine metal powder on a substrate using a laser beam. During the process of metal powder transitioning from solid state to molten state and then cooling back to solid state, localized shrinkage inevitably occurs. Excessive shrinkage can lead to warping and deformation of the printed part. Metal materials are sensitive to temperature changes during the 3D printing process, and the primary factors determining temperature changes are laser power and scanning speed.

Through setting different laser powers and scanning speeds for simulation analysis experiments, students learn how to set appropriate laser parameters for the printer. For the designed printed part, the optimal ratio of laser power to scanning speed is determined through data analysis and processing of the following three sets of experiments.

#### 4.2.1. Experiment (1)

Three nodes are set for scanning speed, namely: 300mm/s, 500mm/s, and 700mm/s. The same laser power, layer thickness, substrate temperature, scan angle, stripe width, and scan spacing are used as system presets. The printing material is CoCr cobalt-chromium alloy. The experimental setup is shown in Table 1.

Table 1: Relationship between shape variable and scanning speed at constant power (CoCr)

| Scanning speed (mm/s) | 300 | 500 | 700 |
|---|---|---|---|
| Maximum deformation of printed parts (mm) | | | |

### 4.2.2. Experiment (2)

Three nodes are set for laser power, namely: 100w, 140w, and 180w. The same laser scanning speed, layer thickness, substrate temperature, scan angle, stripe width, and scan spacing are used as system presets. The printing material is CoCr cobalt-chromium alloy. The experimental setup is shown in Table 2.

Table 2: Relationship between shape variable and power at constant scanning speed (CoCr)

| Laser power (w) | 100 | 140 | 180 |
|---|---|---|---|
| Maximum deformation of printed parts (mm) | | | |

### 4.2.3. Experiment (3)

Three sets of different laser powers and scanning speeds are respectively set as follows: 100w, 300mm/s; 140w, 500mm/s; 180w, 700mm/s. The layer thickness, substrate temperature, scan angle, stripe width, and scan spacing are all set as system presets. The printing material is CoCr cobalt-chromium alloy. The experimental setup is shown in Table 3.

Table 3: Deformation under different power and scanning speeds (CoCr)

| Scanning speed (mm/s) | 300 | 500 | 700 |
|---|---|---|---|
| Laser power (w) | 100 | 140 | 180 |
| Maximum deformation of printed parts (mm) | | | |

Through the aforementioned teaching experiments, students can master the method of optimizing support parameters for printed parts, correctly set the best printing parameters for 3D printing materials, and conduct reasonable data analysis and processing of experimental results.

## 5. Conclusions

In order to meet the urgent need for cultivating high-end talents in 3D printing in the discipline of mechanical engineering in higher education, the School of Mechanical Engineering at Shanghai Institute of Technology has defined the teaching objectives for 3D printing technology experiments. These objectives include enabling students to comprehensively master the advanced manufacturing technology and methods of 3D printing from the mechanistic level.

This is achieved through a three-step teaching design, which includes 3D printing principle analysis, analysis and innovative design teaching and practice of 3D printing machine structure, and analysis of 3D printing machine printing effects and teaching and practice of printing operation countermeasures. This method encourages students to think about the principles of 3D printing, understand the functions of printer components, master functional component design methods, and correctly configure the best 3D printing parameters and support component design methods needed for 3D printing.

In recent years, the experimental teaching of 3D printing technology has verified the applicability of this teaching method to undergraduate students and the operability in teaching practice.

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