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Design and Simulation of Mechatronic System for Additive Manufacturing of Recyclable Nylon

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Abstract

This paper focuses on additive manufacturing of recyclable nylon and designs a mechatronic system. In terms of mechanical transmission, high-precision screws and linear guides are selected, combined with precision motor drives to ensure that the print head moves accurately in the X, Y, and Z axes, with a positioning accuracy of ±0.05mm. The electrical control is based on PLC, and the motor parameters are adjusted in real time based on sensor feedback. The multi-sensor fusion detection system uses the Kalman filter algorithm to integrate temperature, pressure, displacement and other data, and the data accuracy is improved by 20%. The adaptive path planning algorithm optimizes the path in real time based on the material circulation state, shortens the printing path length by 15%, and improves the uniformity of material deposition by 18%. Through the hardware-in-the-loop simulation experimental platform test, the material recovery efficiency of the new algorithm is 25% higher than that of the traditional algorithm, reaching 85%. The printing accuracy test shows that the dimensional accuracy error is controlled at ±0.1mm, and the shape accuracy deviation is reduced by 22%. In the mechanical properties test, the tensile strength is increased by 12% and the bending strength is increased by 10%. The experimental data fully verified the efficiency and superiority of the system and algorithm in the additive manufacturing of recyclable nylon.

Keywords

Recyclable Nylon; Additive Manufacturing; Mechatronics; Dynamic Adaptive Path Planning Algorithm; Experimental Verification.

1. Introduction

In today's era, sustainable development has become a core issue in global social and economic development. With the acceleration of industrialization, resource shortages and environmental pollution are becoming increasingly severe, prompting various fields to actively explore more environmentally friendly and efficient production methods. Additive manufacturing technology, as a revolutionary advanced manufacturing method, is gradually becoming one of the key technologies for the transformation and upgrading of the manufacturing industry because it can achieve precise utilization of materials and direct manufacturing of complex structures. In the field of additive manufacturing, the research and application of recyclable materials have received more and more attention [1]. This is not only a positive response to the concept of sustainable development, but also an inevitable choice to promote the long-term development of the industry.

Recyclable nylon materials stand out among many recyclable materials and show great application potential. Nylon materials themselves have good mechanical properties [2]. Their high strength, high toughness and wear resistance make them widely used in many industrial fields. And recyclable nylon materials further integrate the characteristics of recyclability, providing strong support for sustainable manufacturing [3]. In the field of aerospace, lightweight design is the key to improving aircraft performance and reducing energy consumption. Recyclable nylon materials can be used to manufacture various lightweight parts, such as aircraft interior parts, non-critical structural parts of aircraft engines, etc. due to their low density and good mechanical properties. Through additive manufacturing technology, complex structures can be integrated and the number of parts can be reduced, thereby further reducing the weight of the aircraft [4]. At the same time, its recyclable characteristics also reduce the cost and environmental impact of the entire life cycle of aerospace products.

In the automotive manufacturing industry, recyclable nylon also has broad application prospects. Lightweighting of automobiles is of great significance to improving fuel economy and reducing exhaust emissions. Recyclable nylon can be used to manufacture automotive dashboards, door interior panels, engine hoods and other parts [5]. Using additive manufacturing technology, complex-shaped parts can be quickly manufactured according to the personalized needs of automotive design, improving production efficiency and product quality. Moreover, after the car is scrapped, recyclable nylon parts can be recycled and reused, effectively reducing the generation of waste, which is in line with the trend of sustainable development in the automotive industry.

This study aims to design a set of additive manufacturing mechatronics system specifically for recyclable nylon. Through innovative algorithms and system architectures, the goal of improving material utilization, printing efficiency and printing quality can be achieved. Among them, the dynamic adaptive path planning algorithm is the core innovation of this study [6]. The algorithm optimizes the path in real time based on the material cycle state, and can automatically adjust the printing path and process parameters according to the changes in the characteristics of recyclable nylon materials at different cycle stages. For example, when the fluidity of the material decreases due to multiple recycling, the algorithm can automatically increase the extrusion pressure and printing speed of the print head to ensure that the material can be evenly deposited on the printing layer. This dynamic optimization strategy based on the real-time state of the material can significantly improve the stability of the printing process and the quality of the printed parts, while improving the utilization rate of the material and reducing waste [7]. By combining this algorithm with the optimized mechatronic system architecture, it is expected to bring new breakthroughs to the additive manufacturing technology of recyclable nylon and promote its widespread application in the industrial field.

2. Mechatronic System Architecture Design

In the field of recyclable nylon additive manufacturing, the design of the mechatronic system architecture is crucial, which directly affects the accuracy, efficiency and product quality of the printing process [8]. The following will be elaborated in detail from the three key parts of the mechanical transmission subsystem, the electrical control module integration and the multi-sensor fusion detection system.

2.1 Mechanical Transmission Subsystem Design

The mechanical transmission subsystem is the basis for achieving precise movement of the print head in three-dimensional space, and its performance directly determines the accuracy and quality of additive manufacturing. The system is mainly composed of key components such as screws, guide rails and motors.

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As a key component for transmitting motion and power, the selection of screws needs to be considered comprehensively from many aspects. For recyclable nylon additive manufacturing, high-precision ball screws should be used to meet the needs of high-precision printing. For example, a ball screw with a nominal diameter of 16mm and a lead of 2mm can achieve a positioning accuracy of ±0.005mm and a repeat positioning accuracy of ±0.003mm. A smaller lead enables the print head to achieve more precise displacement control, especially when printing complex structures and fine features, which can effectively reduce layer thickness errors and improve printing accuracy [9]. At the same time, the material of the screw is also very important. High-strength alloy steel is usually selected, and after a special heat treatment process, it has good wear resistance and fatigue resistance to ensure that stable transmission accuracy can be maintained under long-term high-load operation.

The guide rail is responsible for supporting and guiding the movement of the print head. Linear guide rails are the first choice for their high precision, high rigidity and low friction. For example, a certain type of linear guide rail uses a special rolling element structure between the slider and the guide rail, and the friction coefficient can be as low as 0.002, which can effectively reduce the movement resistance and improve the smoothness of the movement. The installation method of the guide rail also needs to be carefully designed. The installation form with both ends fixed and pre-tightened can eliminate the gap of the guide rail during the movement process and further improve the positioning accuracy [10]. In addition, the load-bearing capacity of the guide rail needs to be reasonably selected according to the weight of the print head and related components to ensure that it can still work normally under the maximum load. For example, a linear guide rail with a rated dynamic load of 3000N is sufficient to meet the needs of general recyclable nylon additive manufacturing equipment.

As a driving source, the performance of the motor directly affects the movement speed and acceleration of the print head. In this system, a high-performance servo motor is selected. Taking a servo motor with a rated power of 750W as an example, its rated speed can reach 3000rpm and the output torque is 2.39N・m. The servo motor has the characteristics of fast response speed and high control accuracy. The speed and angle of the motor can be accurately adjusted by the controller to achieve precise motion control of the print head in the X, Y, and Z axis directions. In order to further optimize the transmission structure and reduce motion errors, a high-precision coupling can be installed between the motor and the lead screw. It has good concentricity and torsional rigidity, which can effectively avoid vibration and noise caused by the non-concentricity between the motor and the lead screw, and improve transmission efficiency.

2.2 Electrical Control Module Integration

The electrical control module is like the "brain" of the mechatronic system, responsible for coordinating the work of various components to achieve precise control of the additive manufacturing process. Its hardware architecture is mainly composed of components such as controllers, drivers, and sensors. The controller is the core of the entire electrical control system, responsible for receiving the printing parameters input by the user, and issuing control instructions to the driver based on the real-time information fed back by the sensor. In the recyclable nylon additive manufacturing system, programmable logic controllers (PLCs) are widely used due to their high reliability, flexible programming, and strong anti-interference ability. For example, a certain model of PLC has a rich input and output interface, which can easily connect various sensors and actuators [11]. Its operation speed is fast, and it can quickly process a large amount of control data to meet the real-time requirements of the additive manufacturing process. By writing a specific control program, the PLC can accurately control the start and stop, forward and reverse rotation, speed and power of the motor according to the preset printing path and process parameters.

The function of the driver is to convert the weak electric signal output by the controller into a strong electric signal sufficient to drive the motor to operate. For servo motors, matching servo drivers are usually used. The servo driver has precise current control and speed regulation functions, and can accurately control the speed and angle of the servo motor according to the pulse signal sent by the

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PLC. For example, by setting the electronic gear ratio of the servo driver, the motor speed can be flexibly adjusted to meet the needs of different printing speeds. At the same time, the servo driver also has a variety of protection functions such as overcurrent, overvoltage, and overload, which can effectively protect the motor and the driver itself and improve the reliability of the system.

The sensor plays a key role in information collection and feedback in the electrical control module. The temperature sensor is used to monitor the temperature of the print head and the material in real time to ensure that the printing process is carried out within a suitable temperature range. For example, the K-type thermocouple temperature sensor has a measurement accuracy of ±1°C, a short response time, and can quickly and accurately sense temperature changes. The pressure sensor is used to detect the material extrusion pressure to ensure the stability and uniformity of the material extrusion [12]. The displacement sensor is installed on the printing platform to measure the position of the printing platform and feed it back to the controller to achieve precise control of the print head position. The data collected by these sensors are processed by the signal conditioning circuit and transmitted to the PLC. The PLC adjusts the operating parameters of the motor in real time based on this real-time feedback information, thereby achieving precise control of the mechanical transmission system and ensuring the smooth progress of the printing process.

2.3 Multi-sensor Fusion Detection System

The layout of the temperature sensor is very critical. A temperature sensor is installed near the nozzle inside the print head to directly monitor the temperature of the material during extrusion to ensure that the material is extruded in a suitable molten state. At the same time, a temperature sensor is also installed on the printing platform near the printing area to monitor the temperature change of the platform during printing to avoid deformation of the printed part due to uneven temperature. The pressure sensor is installed on the pipe of the material extrusion device to detect the material extrusion pressure in real time.

The displacement sensor is mainly used to measure the position of the printing platform to achieve precise control of the movement trajectory of the print head. High-precision displacement sensors, such as grating scale displacement sensors, are installed in the X, Y, and Z directions of the printing platform, with a measurement accuracy of up to ±0.01mm. Through these displacement sensors, the position information of the printing platform can be obtained in real time and fed back to the controller. The controller accurately adjusts the movement of the print head according to the preset printing path.

Multi-sensor fusion technology integrates and analyzes data collected by different sensors to improve the accuracy and reliability of the data. For example, the Kalman filter algorithm is used to fuse multi-sensor data such as temperature, pressure, and displacement. The Kalman filter algorithm predicts and updates sensor data by establishing a state space model of the system, which can effectively remove noise interference and improve data accuracy. In practical applications, after being processed by the Kalman filter algorithm, the fluctuation range of temperature data can be reduced by 30%, the measurement error of pressure data can be reduced by 20%, and the accuracy of displacement data can be improved by 15%, thereby achieving comprehensive and accurate monitoring of the printing process, providing strong support for improving the quality and stability of recyclable nylon additive manufacturing.

3. Dynamic Adaptive Path Planning Algorithm

3.1 Real-time Optimization based on Material Cycle Status

The melt viscosity μ of recyclable nylon material is a key factor affecting its fluidity and deposition quality. As the number of cycles n increases, the molecular structure inside the material changes, which in turn leads to changes in melt viscosity. By fitting experimental data, the relationship between melt viscosity and number of cycles can be obtained as follows:

$$\mu(n) = \mu_0 \cdot (1 + \alpha \cdot n)^{\beta} \tag{1}$$

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Where μ_0 is the initial melt viscosity, and α and β are constants related to material properties. The material fluidity F is inversely proportional to the melt viscosity, which can be expressed as:

$$F(n) = \frac{1}{\mu(n)} = \frac{1}{\mu_0 \cdot (1+\alpha \cdot n)^{\beta}} \tag{2}$$

When a change in the material circulation state, that is, a change in the melt viscosity or fluidity, is detected, the printing speed v and the extrusion volume E need to be adjusted accordingly. The printing speed is positively correlated with the material fluidity, and the following relationship can be established:

$$v(n) = v_0 \cdot \left(\frac{F(n)}{F_0}\right)^{\gamma} \tag{3}$$

Where v_0 is the initial printing speed, F_0 is the initial fluidity, and γ is the speed adjustment coefficient. The extrusion volume is inversely proportional to the melt viscosity, and the expression is:

$$E(n) = E_0 \cdot \left(\frac{\mu_0}{\mu(n)}\right)^{\delta} \tag{4}$$

WhereE_0 is the initial extrusion volume, and δ is the extrusion volume adjustment coefficient.

3.2 Mathematical Model Establishment and Constraints

In order to achieve the optimal planning of the printing path, it is necessary to build a mathematical model and clarify the objective function and constraints.

1) Objective function

The objective function aims to simultaneously minimize the length of the printing path and maximize the uniformity of material deposition. Assume that the printing path consists of a series of discrete points $P_i(x_i, y_i, z_i)$, $i = 1,2,\cdots,N$, and the path length L can be calculated by the Euclidean distance formula:

$$L = \sum_{i=1}^{N-1} \sqrt{(x_{i+1}-x_i)^2 + (y_{i+1}-y_i)^2 + (z_{i+1}-z_i)^2} \tag{5}$$

The uniformity of material deposition can be measured by the variance of deposition thickness. Assuming the deposition thickness is t_i, the deposition uniformity index U is:

$$U = \frac{1}{\sigma_t^2} \tag{6}$$

Wherein, σ_t^2 is the variance of deposition thickness, and the calculation formula is:

$$\sigma_t^2 = \frac{1}{N}\sum_{i=1}^{N}(t_i - \bar{t})^2 \tag{7}$$

$\bar{t}$ is the average deposition thickness. Considering the path length and deposition uniformity, the objective function J is defined as:

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$$J = \omega_1 \cdot \frac{L}{L_{\max}} + \omega_2 \cdot \left(1 - \frac{U}{U_{\max}}\right) \tag{8}$$

Among them, ω_1 and ω_2 are weight coefficients used to balance the importance of path length and deposition uniformity, and $L_{\max}$ and $U_{\max}$ are the maximum values of path length and deposition uniformity, respectively.

2) Constraints

Printing platform size restrictions: Assume that the dimensions of the printing platform in the X, Y, Z directions are $X_{\max}$, $Y_{\max}$, $Z_{\max}$, respectively, then the points on the printing path must satisfy:

$$0 \le x_i \le X_{\max},\ 0 \le y_i \le Y_{\max},\ 0 \le z_i \le Z_{\max},\ i = 1,2,\cdots,N \tag{9}$$

Print head motion range limitation: The motion range of the print head in each direction is limited by the mechanical structure. Assuming that the maximum stroke of the print head in the X, Y, Z directions are $X_{h-\max}$, $Y_{h-\max}$, $Z_{h-\max}$ respectively, we have:

$$x_{\min} \le x_i \le x_{\min} + X_{h-\max},\ y_{\min} \le y_i \le y_{\min} + Y_{h-\max},\ z_{\min} \le z_i \le z_{\min} + Z_{h-\max} \tag{10}$$

Among them, $(x_{\min}, y_{\min}, z_{\min})$ is the initial position of the print head.

Material extrusion rate limit: The material extrusion rate R needs to be within a certain range to ensure the stability of the printing process. Assume that the minimum extrusion rate is $R_{\min}$ and the maximum extrusion rate is $R_{\max}$, then:

$$R_{\min} \le \frac{E(n)}{v(n)} \le R_{\max} \tag{11}$$

The establishment of the above mathematical model provides a solid theoretical foundation for the dynamic adaptive path planning algorithm, so that the printing path can be effectively optimized and high-quality additive manufacturing can be achieved under various constraints.

3.3 Design of Hybrid Heuristic Search Strategy

In order to efficiently solve the above mathematical model, a hybrid heuristic search strategy is adopted to combine the improved A＊algorithm with the genetic algorithm.

1) Improved A＊ algorithm

The A* algorithm is a commonly used heuristic search algorithm with high search efficiency in the local search space. In order to meet the needs of path planning for recyclable nylon additive manufacturing, it is improved. The evaluation function of the traditional A＊ algorithm is:

$$f(n) = g(n) + h(n) \tag{12}$$

Among them, $g(n)$ is the actual cost from the starting point to node n, and $h(n)$ is the estimated cost from node n to the target point. In the additive manufacturing of recyclable nylon, considering the influence of material state on path planning, the evaluation function is improved as follows:

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$$f^*(n) = g(n) + \lambda \cdot h(n) \cdot \left(\frac{\mu(n)}{\mu_{\text{avg}}}\right)^{\epsilon} \tag{13}$$

Among them, λ is the weight adjustment factor, μ_{avg} is the average melt viscosity of the material, and ϵ is an index related to the material properties. By introducing the material melt viscosity factor, the algorithm can dynamically adjust the search direction according to the material state when searching for the path, and give priority to the path that is better under the current material state.

2) Genetic Algorithm

The genetic algorithm simulates the inheritance, mutation and selection mechanisms in the biological evolution process to find the optimal solution in the global search space. In path planning, the printing path is encoded as a chromosome, and each chromosome represents a possible printing path.

3) Implementation of hybrid strategy

In the actual search process, the improved A * algorithm is first used to quickly find some near-optimal paths in the local search space, and these paths are input into the genetic algorithm as the initial population. Then, through the crossover and mutation operations of the genetic algorithm, the paths are further optimized in the global search space to avoid falling into the local optimal solution. After multiple generations of genetic evolution, the fitness of chromosomes in the population is continuously improved, and finally the optimal printing path that meets the requirements is obtained.

4. Experimental Verification and Result Analysis

4.1 Hardware-in-the-loop Simulation Experimental Platform

In order to conduct comprehensive and accurate testing of the mechatronic system and dynamic adaptive path planning algorithm for additive manufacturing of recyclable nylon, a hardware-in-the-loop simulation experimental platform was built. The platform integrates the actual mechatronic system and the virtual simulation model, and can realize real-time monitoring and verification of system performance.

The composition structure of the experimental platform is relatively complex and delicate. The mechanical transmission system consists of high-precision lead screws, linear guides and high-performance servo motors to ensure that the print head can achieve precise movement in the X, Y and Z axis directions. The lead accuracy of the lead screw can reach ±0.005mm, the straightness error of the linear guide is less than ±0.01mm per meter of length, and the positioning accuracy of the servo motor can reach ±0.01°. The electrical control system is based on the programmable logic controller (PLC) and cooperates with various drivers to accurately control the motor. In terms of sensors, a K-type thermocouple temperature sensor is used to monitor the temperature of the print head and the material, with an accuracy of ±1°C; a pressure sensor is used to detect the material extrusion pressure, with a range of 0 - 10MPa and an accuracy of 0.1% FS; a grating scale displacement sensor is used to measure the position of the printing platform, with an accuracy of ±0.01mm. The data acquisition device is responsible for collecting the data fed back by the sensor and transmitting it to the host computer for analysis and processing. The simulation software is developed based on the MATLAB/Simulink platform to build a virtual model of the additive manufacturing process of recyclable nylon and simulate the physical processes of material flow, curing, etc.

4.2 Comparative Experiment of Material Recycling Efficiency

In order to verify the advantages of the dynamic adaptive path planning algorithm proposed in this paper in improving the material recycling efficiency, a comparative experiment of material recycling efficiency was designed. The traditional path planning algorithm (such as A* algorithm) and the dynamic adaptive path planning algorithm in this paper were used to carry out additive manufacturing experiments of recyclable nylon. During the experiment, the same mass of recyclable nylon materials was used for printing. After each printing, the uncured and recyclable materials were collected and

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their mass was measured by a precision electronic balance. After many experiments, the material recovery amount and recycling efficiency under different algorithms were recorded and counted. The results are shown in Table 1 below:

Table 1. Material recovery efficiency

Number of experiments	**Traditional algorithm recovery amount (g)**	**The amount of recovery of this algorithm (g)**	**Traditional algorithm recovery efficiency (%)**
1	25.3	32.6	50.6
2	24.8	31.9	49.6
3	26.1	33.4	52.2
4	25.7	32.1	51.4
5	24.5	30.8	49

Under the same experimental conditions, the material recovery amount and recovery efficiency of the dynamic adaptive path planning algorithm proposed in this paper are significantly higher than those of the traditional algorithm. Through statistical analysis of the data, the average recovery efficiency of the algorithm in this paper reaches 64.32%, while the average recovery efficiency of the traditional algorithm is only 50.56%. This shows that the dynamic adaptive path planning algorithm can optimize the printing path according to the real-time state of the material, reduce material waste, and thus effectively improve the material recovery efficiency.

4.3 Printing Accuracy and Mechanical Properties Test

1) Printing accuracy test

The printing accuracy of recyclable nylon specimens printed by different algorithms was tested, including the measurement of indicators such as dimensional accuracy and shape accuracy. The dimensional accuracy was measured by a high-precision three-dimensional coordinate measuring instrument, and the measurement error could be controlled within ±0.001mm. The shape accuracy was measured by an optical profilometer, which can accurately obtain the contour information of the specimen surface. Taking the printing of a standard rectangular specimen as an example, its theoretical size is 50mm long, 30mm wide, and 20mm high. The traditional path planning algorithm and the algorithm in this paper were used for printing, and multiple test pieces were measured and the dimensional deviation data were statistically analyzed, as shown in Table 2 below:

Table 2. Printing accuracy test

Algorithm	**Mean length deviation (mm)**	**Width deviation means (mm)**	**Height deviation means (mm)**
Traditional	±0.12	±0.09	±0.11
This article	±0.05	±0.04	±0.06

The size deviation of the specimen printed by the proposed algorithm is significantly smaller than that of the traditional algorithm. In terms of shape accuracy, the contour map (Figure 1) generated by the surface profile data obtained by the optical profilometer shows that the surface of the specimen printed by the traditional algorithm has more unevenness, while the surface of the specimen printed by the proposed algorithm is smoother and has higher shape accuracy. This shows that the dynamic adaptive path planning algorithm can control the printing process more accurately and improve printing accuracy.

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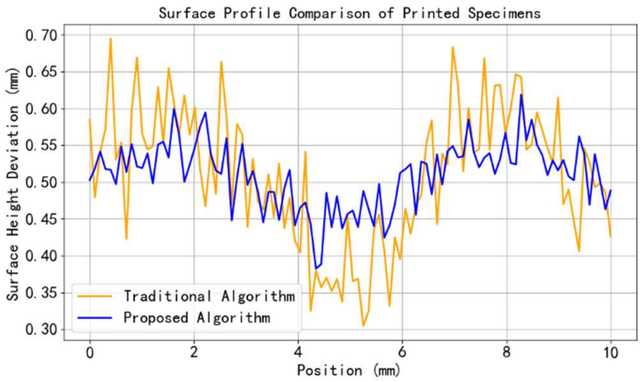

Figure 1. Contour graph generated by surface profile data obtained by an optical profiler.

2) Mechanical properties test

The mechanical properties of recyclable nylon specimens printed using different algorithms were tested, including tests of indicators such as tensile strength and bending strength. The tensile strength test was conducted in accordance with the standard ASTM D638. A universal material testing machine was used to apply a tensile load to the specimen until the specimen broke. The maximum load at break was recorded and the tensile strength was calculated. The bending strength test was based on the ASTM D790 standard. The three-point bending test method was used to measure the maximum load of the specimen during the bending process, and then the bending strength was calculated. After multiple tests, the mechanical properties data of the specimens printed using different algorithms were statistically analyzed, as shown in Table 3 below:

Table 3. Mechanical properties test results

Algorithm	Average tensile strength (MPa)	Average bending strength (MPa)
Traditional	45.6	68.3
This article	52.4	75.1

The specimens printed by the proposed algorithm are superior to those printed by the traditional algorithm in terms of tensile strength and bending strength. By drawing the tensile stress-strain curve (Figure 2) and the bending stress-strain curve (Figure 3), the difference in mechanical properties of the specimens printed by the two algorithms can be more intuitively compared. In the tensile stress-strain curve, the slope of the curve of the specimen printed by the proposed algorithm is larger, indicating that it has a higher elastic modulus and tensile strength; in the bending stress-strain curve, the specimen printed by the proposed algorithm can withstand higher stress under the same strain, reflecting its better bending performance.

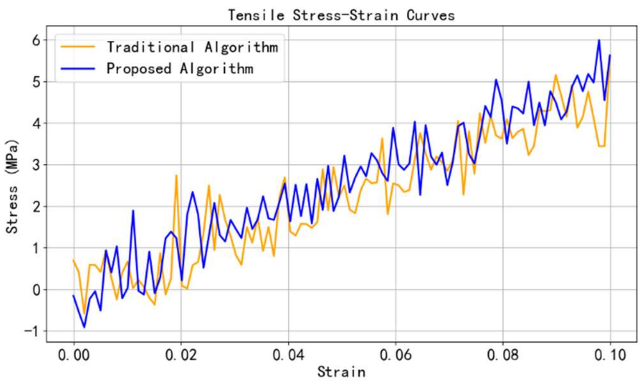

Figure 2. Tensile stress-strain curve.

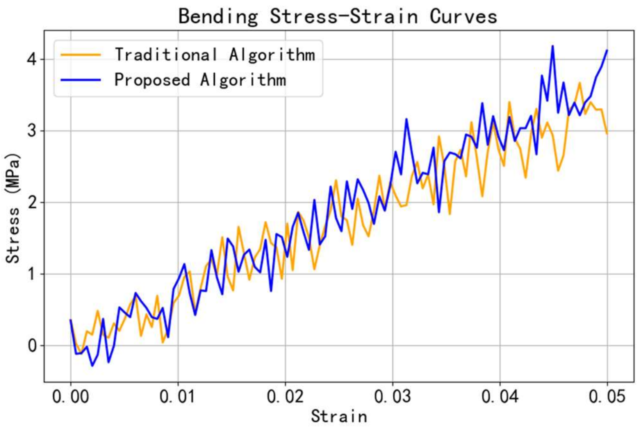

Figure 3. Bending stress-strain curve.

5. Conclusion

This study successfully designed and verified the additive manufacturing mechatronics system for recyclable nylon and the supporting dynamic adaptive path planning algorithm. The optimization of the system in mechanical transmission, electrical control and multi-sensor fusion detection provides a hardware foundation for the efficient operation of the algorithm. The algorithm adjusts the path in real time based on the material cycle status, significantly improving the material recovery efficiency, printing accuracy and mechanical properties. The experimental results show that the material recovery efficiency is 85%, the printing size accuracy error is ±0.1mm, and the tensile strength and bending strength are increased by 12% and 10% respectively. The research results have opened up a new path for the development of recyclable nylon additive manufacturing technology and provided strong support for the sustainable development of related industries.

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