Fuzzy PID Control on Temperature Field of Vascular 3D Printing Forming Regional

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Abstract —The clinical medical application of three dimensional (3D) printing is popular among scientific researchers at home and abroad in recent years. In order to improve the prototyping quality and the activity of vascular 3D printing, according to the high precision double nozzle six axis vascular 3D printing equipment developed independently, the subject mainly studies on temperature field control of forming region by researching design and simulation calculation of the temperature field, the temperature control process, BECKHOFF temperature self-tuning PID algorithm and the program redevelopment based on self-tuning fuzzy PID algorithm. SIMULINK software was used to simulate the program redevelopment based on the BECKHOFF temperature control, and the results show that by compared with the self-tuning PID control, the robustness and the dynamic & static performance has a great improvement. When the temperature field reaches the stable state, delay time is 12s, steady time is 310s, overshoot is 1.2% and the anti-interference ability has been enhanced significantly. The experimental date indicates that this program redevelopment can effectively meet the temperature requirements of the vascular rapid prototyping.

Keywords-Vascular 3D printing; Forming regional; Temperature field; Self-tuning fuzzy PID; SIMULINK

I. INTRODUCTION

Compared with milling, lathe, grinding, planning, casting and other traditional processing reduction material manufacturing technology, three dimensional (3D) printing is also called Additive Manufacturing (AM) or Rapid Prototyping (RP). 3D printing is an advanced manufacturing technology with the big significance of the industrial revolution rise in recent 30 years and has received more and more attention [1]. The forming principle based on the manufacturing ideas of discrete accumulation forming, directly driven by computer 3D digital model, through the methods of hierarchical processing and super position forming to print a real object by building up successive layers of material and can realize the complicated shape outline object. The technology has a broad market application prospect in mechanical engineering, clinical medical, industrial design, aerospace industry, construction engineering, art culture and so on [2].

The clinical medical application of 3D printing is a emerging technology that development based on the multidisciplinary cross fusion and makes the human organ and tissue regeneration dream come true [3].Now, the congenital diseases, cardio- vascular diseases, cancer, organ defects and other symptoms caused by industrial pollution, environmental pollution and traffic accidents has greatly promote the clinical application of human organs 3D printing [4]. According to the WHO statistics, in the whole world there are about nearly 20 million people died of heart disease each year, which claim the lives of millions of people in the Europe and America developed countries [5]. In our country, cardiovascular diseases keep increasing state year by year, tens of thousands of patients need artificial blood vessel and valve with vascular channels [6]. Revascularization not only is the basis of tissue regeneration, but also is the prerequisite for the clinical medical to treat cardiovascular diseases and organ repair & transplantation. Using the 3D printing technology to rapid forming the transplantation vascular and vascular net repair material is becoming a popular direction for scientific researchers at home and abroad [7].

In the technology research and clinical application of vascular 3D printing, America and Germany and other developed countries are in a leading position, however China is still in the initial stage. The University of Pennsylvania MILLER by casting method of composite load cell hydrogel forming tubular blood access [8].American Columbia University NOROTTE use the self-research biogel ball of 3D printing technology developed rapidly prototyping a no stent small diameter vascular [9]. Germany Fraunh of research uses in 3D printing and "Multiphoton polymerization" rapid prototyping "vascular prosthesis" [10]. Singapore Nanyang Technology University LEONG by selective laser sintering manufacture stent structure [11]. Chinese Wuhan University Zhongnan Hospital vascular surgery uses the selectivity of liquid photosensitive resin curing technology to produce a selective tissue engineering venous valve stent model [12]. Organ manufacturing center in Tsinghua University formed the cell survival rate reached more than 90% of the three-dimensional structure of vascularization adipose tissue through compounding cell growth factor in the nutrient Fluid [13].

For the 3D printing of vascular and vascular net, the prototyping quality and the activity of vascular 3D printing still is an important barrier to the rapid prototyping and its clinical application [14]. In the overt relevant documents of rapid prototyping, for cell printing most of the emphasis on the low temperature environment, but did not explain the concrete control method of temperature field. Although the Fengchao team of Tsinghua University discloses a low-temperature ice type dispersed spray rapid prototyping on 3D printing, the accuracy of manufacture is not high and still remains to be further research on the application of vascular 3D printing [15]. In view of the high precision double nozzle six axis synergic control vascular 3D printing equipment which Cooperative R & D with the regenerative medicine research center of West China Hospital of Sichuan University, the subject studies on the control method of forming regional temperature field

II. DESIGN PROCESS

The high precision double nozzles six axis vascular 3D printing equipment use the structure of Long men, in the X and Z directions, two rotary motors driven by two linear motors and rotary motor drives two print nozzles. In the Y direction, the forming regional of vascular 3D printing is placed in the fixed platform of the linear motor, forming regional adopts hydraulic loop, firstly using the servo pump to make the nutrition into the microporous rotating rod, then microporous rotating rod throw out the nutrition driven by the servo motor, at the same time the nutrition back into the nutrition trough, finally through the special print nozzle and microporous rotating rod to complete the effective package and rapid prototyping of vascular cell printing under the temperature field control. Fixed platform Chooses the fast heat conduction aluminum material, the external jacketed insulation layer, the inner cavity using the access into the circulation of the constant temperature liquid medium slot design, around the forming regional design and install the semi-closed microporous steam cooling device, all loop pipe are choose corrosion resistant 316 stainless steel pipe and jacketed insulation layer in its external, in the hydraulic loop of microporous rotating rod exit end installation PT100 temperature sensor so that to make the temperature real-time collection and feedback for temperature field when printing cell. The forming regional 3d structure diagram and the temperature field design of planar graph as shown in figure 1, 2, respectively.

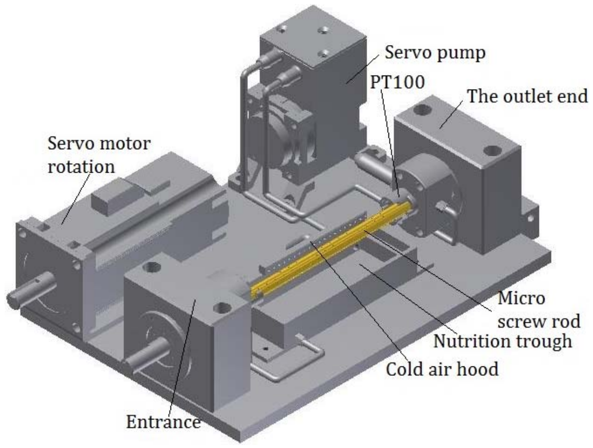

Fig.1 3D Structure of Forming Regional

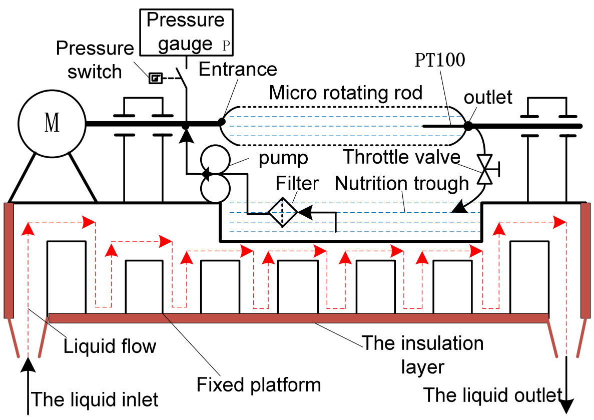

Fig.2 Two-Dimensional Design Diagram of Temperature Field

III. PREPARATION CONTROL PROCESS

A. *Temperature Field Control Process*

Forming regional temperature field control theory is based on the metal aluminum good heat conduction and insulation layer good insulation effect, by receiving the real-time temperature signal collected by PT100 sensors and using PID control algorithm to real-time control liquid medium temperature of the external incubator, the liquid medium of incubator through the servo pump and pipeline loop to cycle access constant temperature liquid into platform, using heat conduction transfer heat to the forming regional. Because the forming regional has a small heat capacity and good heat insulation, the microporous rotating rod is φ10 mm×100 mm, so the heat conduction rate is fast and transmission efficiency also is very high. Constant temperature of the liquid medium inside the coil is cooperative controlled by the compressor output constant low temperature and semi- conductor silicon heating, touching type HMI shows real- time temperature signal and the input control instructions. Temperature control process is shown in figure 3.

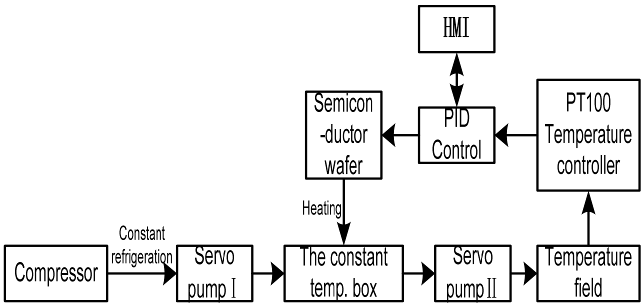

Fig.3 Control Flow Chart of Temperature Field

B. *Temperature Sampling Module*

Forming regional temperature field closed loop control system with PT100 temperature sensor as temperature collection and feedback unit, it has strong sensitivity, resolution, stability, oxidation- resistivity and anti-interference ability in the temperature range of -50 ~ 600 □ [16]. The relation- ship between platinum resistance and temperature is:

$$R_t = R_0\left[1 + 3.90802\times10^{-3}t - 5.80195\times10^{-7}t^2 - 4.2735\times10^{-12}(t-100)t^3\right] \quad (\text{-200～0℃})$$

$$R_t = R_0\left(1 + 3.90802\times10^{-3}t - 5.80195\times10^{-7}t^2\right) \quad (0～850℃)$$

PT100 temperature sensor temperature sampling circuit use the two ends of PT100 resistor constant current to realize the linear relationship between PT100 resistance and output voltage, in this way it is beneficial to the temperature calculation and correction. PT100 resistance temperature sampling circuit is shown in figure 4. In the PT100 sampling process, op-amp LM258 converts input of reference voltage *Vref* into constant current source and incent PT100 resistance. After the two ends of PT100 resistance voltage cross LM258, the signal is magnified 10 times, that is the output temperature sampling signal [16].

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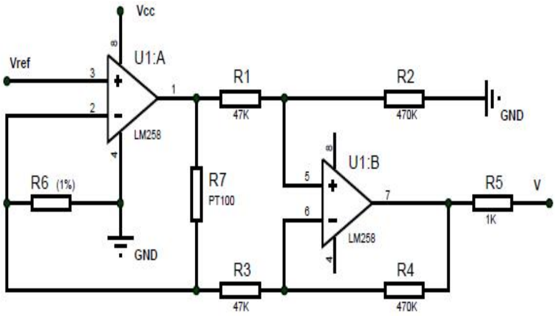

Fig.4 The Sampling Circuit of PT100

C. Simulation Calculation

According to the heat transfer theory, there are three heat transformation methods between the objects: conduction, convection and thermal radiation. Forming regional temperature field is mainly through the convective heat transfer of circulation constant temperature liquid medium and good heat conduction of metal aluminum to transfer heat. External incubator circulating convey constant temperature liquid to platform inner cavity by compressor cooling and semiconductor silicon heating, under the action of servo pump, using liquid medium forced convection and metal aluminum heat conduction to control the nutrition temperature of forming regional microporous rotating rod. According to the principle of conservation of energy, convective heat transfer formula is [17-18]

$$Q = fS\Delta T(t) \quad (1)$$

$$f = 2041(1 + 0.015T')v^{0.87}/D^{0.13} \quad (2)$$

$$S = \pi DL \quad (3)$$

$$Q' = cm\Delta T(m) \quad (4)$$

Where Q is convective heat energy, J. f is convection heat transfer coefficient, $W/m^2 \bullet$℃. S is the total area of convective heat transfer, m^2 . $\Delta T(t)$ is temperature difference after the convective heat transfer, ℃. T' is the average temperature of the liquid medium, ℃. v is the flow velocity of the liquid medium, m/s. D is transmission pipeline diameter, m. Q' is the heat energy required to release of incubator liquid medium, J. c is the specific heat capacity of incubator liquid medium, $W/kg\bullet$℃. m is the total quality of incubator liquid, kg. $\Delta T(m)$ is temperature difference after heat release of incubator liquid, ℃.

According to the heat transfer theory, the conditional equation for forming regional meet temperature field convective heat transfer is [17-18]

$$cm\Delta T(m) \geq \int_0^{\tau} fS\Delta T(t) \quad (5)$$

Where τ is the time when convective heat transfer achieve stable constant temperature, min.

Using software Inventor and the Laplace equation for the temperature field modeling scanning, get three-dimensional steady-state temperature field for [17-18]

$$\kappa\left(\partial^2 T/\partial x^2 \bullet \partial^2 T/\partial y^2 \bullet \partial^2 T/\partial z^2\right) = 0 \quad (x, y, z) \in A \quad (6)$$

Where x , y , Z are three-dimensional coordinate. A is modeling regional. k is the thermal conductivity of metal aluminum. T is temperature.

For the Laplace equation to determine the temperature of the forming regional steady state temperature field, for formula (6) can use the weighted residual method and discrete area boundary to achieve the three-dimensional steady temperature and heat energy, then obtain the required to release the heat capacity and the coil size in order to maintain constant temperature state for incubator. [17-18]

IV. PID CONTROL ALGORITHM

A. Self-tuning PID Algorithm

BECKHOFF temperature self-tuning PID algorithm is optimized from the conventional PID algorithm, it supports manual and automatic adjustment temperature control, has the incomplete differential, differential first, an integral saturation and other functions. Self-tuning PID control adopts Chien, Hrones and Reswick method, this method under the action of step response, according to the anti-jamming capability optimization, using tangent method to determine the delay time Tu , stability time Tg and proportionality coefficient of the system Ks . Temperature self-tuning PID control process is shown in figure 5 [19-20]. BECKHOFF temperature self-tuning PID controller formula is

$$G(s) = K_P\left(1 + 1/T_n s + T_v s/T_d s\right)$$

Where K_P is self-tuning amplification coefficient. T_n

is self-tuning integral time constant (I component). T_v is self-tuning differential time constant (D component). T_d is self-tuning damping time.

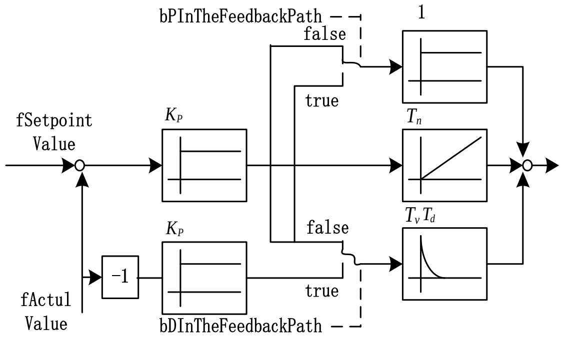

Fig.5 BECKHOFF Temperature Self-tuning PID Control Process

B. Self-tuning Fuzzy PID algorithm

Temperature self-tuning PID control could automatically adjust the proportionality coefficient K_P, integral K_I and differential coefficient K_D according to the actual circumstance of temperature field, temperature field temperature change was adjusted real time by self-tuning function module [21-23]. Self-tuning fuzzy PID control system block diagram is shown in figure 6.

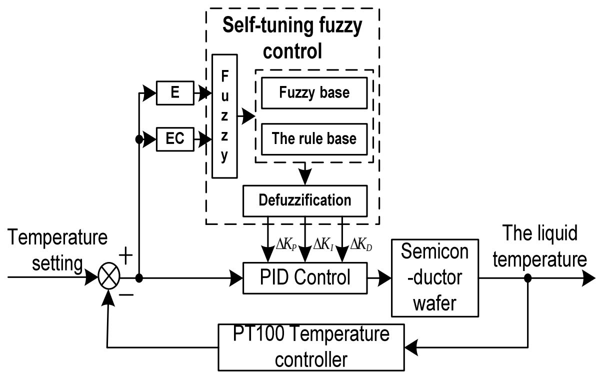

Fig.6 Self-tuning Fuzzy PID Control System Diagram

Self-tuning fuzzy PID control algorithm is through PT100 temperature sensor collect and feedback temperature changing to calculate the microporous rotating rod nutrition temperature deviation E and deviation rate EC, E and EC as the input language variable, semiconductor silicon voltage variation ΔU as the output language variable, according to the requirement of the vessels rapid prototyping to temperature, the physical domain of E is [-0.5, 0.5], the physical domain of EC is [-0.01, 0.01]. Physical domain multiplied by quantification factor K_E=6, K_{EC}=60, could consistent with fuzzy domain [-3, 3]. Selecting 7 fuzzy subsets and the corresponding language value is PB, PM, PS, ZO, NS, NM, NB. To improve the stability and robustness of the control algorithm, selects the membership degree of [0, 1] triangle membership function, and carries on the fuzzy processing, as shown in figure 7. Based on the system real time step response, making the self-tuning fuzzy PID control rule table is shown in table 1-3. Fuzzy output the precise value of ΔK_P, ΔK_I and ΔK_D must multiply by its initial value could get the actual should add PID parameters [21-23].

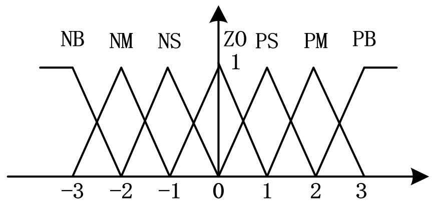

Fig.7 Membership Function of Fuzzy Set

TABLE I. FUZZY CONTROL RULE TABLE OF ΔK_P

ΔU / E	EC						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB	PB	NM	NM	NB	NS	ZO
NM	NB	PB	NS	NS	NM	NM	ZO
NS	PS	PS	PS	NS	ZO	PM	PM
ZO	PS	Z0	PS	ZO	PS	Z0	PS
PS	PM	PM	ZO	NM	PS	PS	PS
PM	ZO	NM	NM	NS	NS	PB	NB
PB	ZO	NS	NB	NS	NM	PB	NB

TABLE II. FUZZY CONTROL RULE TABLE OF ΔK_I

ΔU / E	EC						
	NB	NM	NS	ZO	PS	PM	PB
NB	NB	NS	NM	NS	NS	ZO	ZO
NM	NB	NS	NS	NS	ZO	ZO	ZO
NS	NM	NM	NS	NS	ZO	NS	NM
ZO	NM	NM	PS	ZO	PS	NM	NM
PS	NM	NS	ZO	NS	NS	NM	NM
PM	ZO	ZO	ZO	NM	NS	NS	NB
PB	ZO	ZO	NS	PS	NM	NS	NB

TABLE III. FUZZY CONTROL RULE TABLE OF ΔK_D

ΔU \ E	EC						
	NB	NM	NS	ZO	PS	PM	PB
NB	PB	PM	PM	PS	PM	PM	PB
NM	PB	PM	PM	PS	PM	PS	PM
NS	PM	PS	NS	ZO	ZO	NS	ZO
ZO	PS	NS	ZO	ZO	ZO	NS	PS
PS	ZO	NS	ZO	NS	NS	PS	PM
PM	PM	PS	PM	PS	PM	PM	PB
PB	PB	PM	PM	PS	PM	PM	PB

V. DEBUGGING AND SIMULATION

A. *Debugging*

The high precision double nozzle six axis vascular 3D printing equipment in self-research use the BECKHOFF CX2030-0123 controller, and carry on self-tuning PID temperature control module which based on TwinCAT. BECKHOFF open temperature control system is shown in figure 8 [19-20].

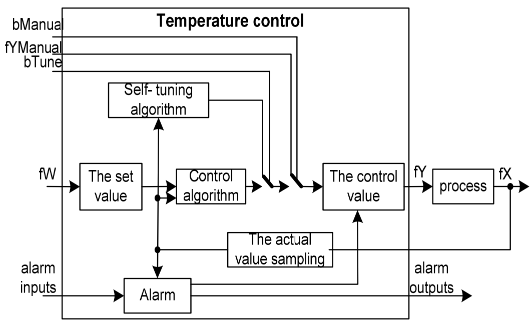

Fig. (8). The Diagram of BECKHOFF Open Temperature Control System

In order to satisfy the prototyping quality and the activity of vascular 3D printing, require the temperature controlled in 4 □. BECKHOFF temperature self-tuning PID algorithm debugging step is, add and create TcTempCtrl.lib self-tuning library function, FB_Temp Controller function block and ST_Controller Parameter structure instance. Complete all external hardware connection of temperature field control system and by structure instance accomplish parameter settings, specifies the PWM cycle time, task cycle time and sampling time. Configure Twin CAT observer value, actual value and analog control values. Close the alarm function, use amplitude f_Y_Tune as step values to trigger and complete adjustment of PID parameters [19-20]. Under the BECKHOFF temperature self-tuning PID algorithm debugging the temperature curve of temperature field is shown in figure 9. We can see when the temperature field reaches the stable state, delay time is 17s, steady time is 550s, overshoot is 12.7%, and there is some interference fluctuation.

B. *Program redevelopment simulation*

Because there are some interference factors in the process of temperature field debugging which based on the BECKHOFF temperature self-tuning PID algorithm, delay time and steady-state time is too long, overshoot is on the high side. Through the analysis for temperature field closed loop control system circuit, interference factor is found time compressor refrigerating capacity and semiconductor silicon heating capacity does not match in the same, there's no feed forward control and override control in closed loop control circuit. Based on self-tuning fuzzy PID control rules table, by writing the self-tuning fuzzy PID temperature control program to change fTune Kp, fTune Tn, fTune Tv and fTune Td values in the ST_Controller Parameter structure, then on the basis of BECKHHOFF software library to do program redevelopment of temperature control, and under the action of step response, using Simulink software simulate the temperature change of the temperature field to get the temperature change performance index of temperature field. The temperature curve of temperature field under the program redevelopment debugging is shown in figure 10. When the temperature field reaches the stable state, delay time is 12s, steady time is 310s, overshoot is 1.2%, and there is no obvious interference fluctuation in the heating process.

C. *Analysis of Results*

Through the simulation of BECKHOFF temperature control program redevelopment which based on self-tuning fuzzy PID control algorithm, obtain the temperature field temperature curve and actual heating effect chart. Compare with the self-tuning PID control, the robustness and the dynamic & static performance has great improvement,

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specific performance in delay time has reduced 5 s, steady time has reduced 240 s, overshoot has reduced 11.5%, and anti-interference ability has been enhanced significantly when the temperature field reaches the stable state. The experimental date indicates this program redevelopment can effectively control the forming regional temperature and improve the prototyping quality and the activity of vascular 3D printing.

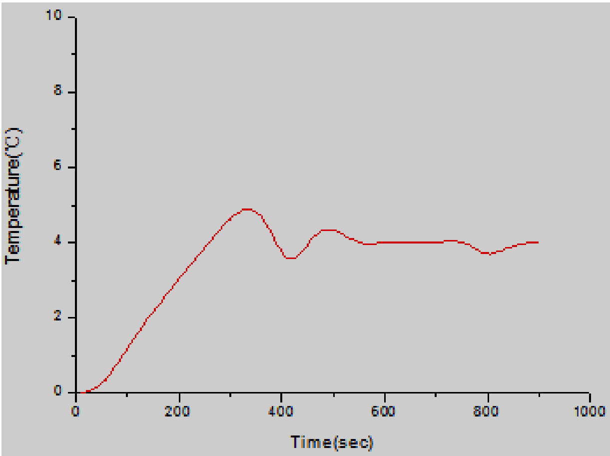

Fig.9 The Temperature Under Self-tuning PID Debugging

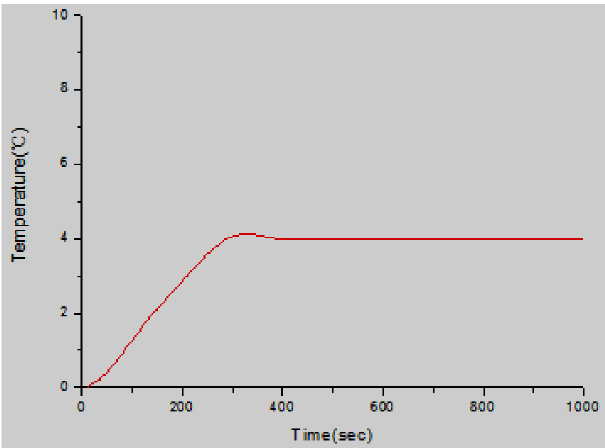

Fig.10 The Temperature Under Program Redevelopment Debugging

VI. CONCLUSIONS

Revascularization is the basis of the clinical medical application for 3D printing, to improve the prototyping quality and the activity of vascular 3D printing related to whether vascular 3D printing could be effective applied in clinical medical. According to the high precision double nozzle six axis vascular 3D printing equipment in self-research, the subject studies on temperature field control of forming regional from the temperature field design and simulation calculation, the temperature control process, BECKHOFF temperature self-tuning PID algorithm and the program redevelopment based on self-tuning fuzzy PID algorithm. Through the program redevelopment of the simulation results show that the BECKHOFF program redevelopment temperature controller which based on self-tuning fuzzy PID control can improve the robustness and the dynamic & static performance, reduced the delay time, steady time and overshoot when the temperature field reaches the stable state, meanwhile enhance the anti-interference ability, can effectively meet the temperature requirements of the vascular rapid prototyping. This article aims to provide a control method for vascular 3D printing temperature field control, and promote the clinical application of vascular 3D printing come true as soon as possible.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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REFERENCES

[1] HE Jiankang, LIU Yaxiong, LIAN Jin, etal, “Biofabrication of vital parenchymal organs,” *China Biotechnology*,32(9), pp.76-81. (Chinese), 2012.

[2] LIU Yuanyuan, ZHANG Fuhua, and CHEN Weihua, “CAD/CAM System and Experimental Study of Biological 3D Printing Composite Process,” *JOURNAL OF MECHANICAL ENGINEERING*, 50(15), pp.147-154. (Chinese), 2014.

[3] LIPSON H, and KUMAN M, “Fabricated: The new world of 3D printing,” *Beijing: Zhongxin Press*, (Chinese), 2013.

[4] MELCHELS F P W, DOMINGOS M A N, KLEIN T J, etal,

"Additive manufacturing of tissues and organs," *Progress in Polymer Science*, 37, pp.1079-1104, 2012.

[5] WANG X H,YAN Yongnian, and ZHANG Renji, "Recenttrends and challenges in complex organ manufacturing," *Tissue Eng. Part B*, 16, pp.189-197, 2010.

[6] WANG X H, and ZHANG Q Q. "Overview on "Chinese–Finnish workshop on biomanufacturing and evaluation techniques," *Artificial Organs*, 35(10), pp.E191- E193, 2011.

[7] JIANG Jing, QI Wen-Jun, and Moming-Adli. "Application of rapid prototype technology in medicine," *Machinery Design &Manufacture*, 5(5), pp.254-256. (Chinese), 2011.

[8] MILLER J S, STEVENS K R, YANG M T, etal, "Rapid casting of patterned vascular networks for perfusable engineered three-dimensional tissues," *Nature Materials*, 11, pp.768-774, 2012.

[9] NOROTTE C, MARGA F S, NIKLASON L E, etal, "Scaffold-free vascular tissue engineering using bioprinting," *Biomaterials*, 30, pp.5970-5917, 2009.

[10] Gu Yong-quan, and Wu Xin, "The application of 3D printing technology in vascular surgery," *Chinese Journal of Reparative and Reconstructive Surgery*, 28(3), pp.276-278. (Chinese), 2014.

[11] LEONG K F, CHEAH C M, and CHUA C K, "Solid freeform fabrication of three-dimensional scaffolds for engineering replacement tissues and organs," *Biomaterials*, 24, pp.2363 – 2378, 2003.

[12] LIU Yang, and TAN Zui, "Study of Scaffold on Tissue Engineered Blood Vessel," *Medical Journal o f Wuhan Unive rsity*, 27(1), pp.124-129. (Chinese), 2006.

[13] WANG X H, HE K, and ZHANG W M, "Opimizing the fabrication processes for manufacturing a hybrid hierarchical olyurethane- cell/ hydrogel construct," *J. Bioact. Compat. Polym.*, 28(4):303-319, 2013.

[14] WANG Jiayin, CHAI Teps, LIU Libiao, etal, "Progress in Three-dimensional (3D) Printing of Artificial Organs," *JOURNAL OF MECHANICAL ENGINEERING*, 50(23), pp.119-127. (Chinese), 2014.

[15] FENG Chao, YAN Yongnian, and ZHANG Renji, "Study on the Jetting Technology Used in Rapid Ice Prototype Forming." *China Mechanical Engineering*,13(13), pp.1128-1130. (Chinese), 2002.

[16] FU Bo, and CHEN Shu-fen, "Research on driving control of SFS used in FOG," *OPTICAL TECHNIQUE*, 33(5), pp.785- 787. (Chinese), 2007.

[17] LU Zhongliang, ZHOU Jiangping, YANG Dongsheng, etal, "Rapid fabrication method of pre-research turbine blade wax precision mould based on 3D printing technology," *Acta Aeronauticaet Astronautica Sinica*, 36(2), pp.651-660. (Chinese), 2015.

[18] Cui S B, Zhou H M, and Li D Q, "Study on key algorithms of numerical simulation in the cooling process of injection molding," *China Plastics*, 19(4), pp.96-97, 2005.

[19] Beckhoff Automation Co., Ltd, "TwinCAT PLC Programming Manual," Zhou Yao-gang, Translation, *Beijing: BECKHOFF China technical support department*, (Chinese),2011.

[20] Beckhoff Automation Co., Ltd, "Temperature controller software library for use: Solutions of temperature control based on PC," *http://www.docin.com/p-394420890.html*, 2015-03-08.

[21] Yang Fan, Chen Maolin, Ma Xinwen, etal, "Purify air conditioning control system based on fuzzy PID algorithm," *J. Huazhong Univ.of Sci. &Tech. (Natural Science Edition),* 42 (1), pp.120-123. (Chinese), 2014.

[22] Dai Junke, Jiang Haiming, Zhong Qirun, etal, "LD temperature control system based on self-tuning fuzzy PID algorithm," *Infrared and Laser Engineering*, 43(10), pp.3287-3291. (Chinese), 2014.

[23] Zhang Hua-guang, and He Xi-qin, "The Fuzzy Adaptive Control Theory and Application," *Beijing: Beihang University Press*, (Chinese), 2002.