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Temperature Control in 3D Printers using PID Controller

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***Abstract*—This paper presents the role of PID controllers for temperature control of the Nozzle for the Fused Deposition Modelling 3D printers. The stability, accuracy and appropriateness of the nozzle plays a crucial role in quality of the prints and melting of filaments without clogging. This paper focuses mainly on the nozzle of Fused Deposition Modeling (FDM) 3D printers, even though the temperature bed still uses a closed loop control system to detect and control the temperature. Although there is already a considerable amount of research focusing on temperature control and PID control for FDM 3D printers, many unresolved issues remain. For example, how to reduce energy consumption while ensuring print quality, how to minimize the impact of PID control on the lifespan of printer components, and how to design more advanced and intelligent control algorithms. The occurring issues require further research and discussion to promote the use of FDM 3D printing process in the manufacturing industry across the globe. This study demonstrates that PID controller can effectively improve the temperature control performance of FDM 3D printers, therefore ensuring stable and high print quality**.

***Keywords*—FDM 3D printers, PID controllers, Nozzle, Temperature control, closed loop control systems.**

I. INTRODUCTION

As the technology in the manufacturing industries become advanced day by day, one of its technique '3D printing' which is gaining popularity these days, have gotten mature in printing products with detailed accuracy and enhancing the quality of the print. Additive Manufacturing is a technique that, in contrast to traditional machining, creates an object by progressively layering material instead of cutting it from a solid block [1]. It was originally developed for quick prototyping, Additive Manufacturing quickly turned into mass production due to its high adaptability, less material waste and its ability to produce shapes that are hard to achieve. However, these benefits come along with certain drawbacks, such as lower ejection of the filaments, significant uncertainties, and a heightened susceptibility to defects.

Various Additive Manufacturing methods have been developed to process variety of materials, including polymers, metals, ceramics, and concrete. Different Additive Manufacturing technologies have emerged to process different materials, including polymers, metals, ceramics and concrete . Amongst them, the most mature ones are known as Fused Deposition Modeling (FDM), Powder Bed Fusion (PBF), Stereolithography (SLA), Direct Energy Deposition (DED) and Laminated Object Manufacturing (LOM)[8][5]. FDM is specialized in plastic materials and composites, making this technology extremely useful in a wide range of sectors. In general, the FDM process comprises the following subroutines slicing, path planning, motion control and extrusion control. Extrusion is defined as the process of enforcing the flow of a semi-solid filament under pressure and high temperature. In FDM, the raw material is usually powder, pellet or filament of different type of polymers. These polymers are compressed and heated until reaching the melting temperature. Then, they melt inside the extruder and it is extruded through the nozzle as a semi-solid thread like fluid. The block constituted by the extruder and the nozzle is called the printing head.[8]

Scott Crump developed FDM 3D printing in 1989 and have applied for a patent during that time. However, FDM became famous only because of its popularity among the non-commercial users later. In particular, the standard FDM process is different from other material extrusion processes, like food 3D printing. The standard FDM process uses thermoplastic material as feedstocks in the form of pellets or powder as mentioned above. A typical FDM 3D printer, takes a thermoplastic polymer based filament and forces it through a nozzle which has high temperature, which melts the material and deposits it in 2D layers on the build platform. While the nozzle is still warm, these layers fuse with each other to eventually create a three-dimensional part. This way is universally accepted as the simplest way to carry out 3D printing process. FDM is easily accessible, highly efficient, and popular world wide. FDM printers are used in more numbers the 3D printing market, being remarkably more straightforward than resin 3D printing. This paper demonstrates the working principle of FDM 3D printers and an analysis on different types of filaments used and their melting temperatures. The main focus is about the use of PID controller for temperature control of the nozzle using Matlab Simulink, which shows the temperature graph. The simulation was done using the transfer function of the nozzle.

II. WORKING PROCESS OF FDM 3D PRINTER

At it's core the FDM technique is relatively simple procedure and can be carried out easily. Its main functions are performed by two distinct systems. The first system is responsible for the extrusion and deposition and the other system is responsible for the printhead movement. The extrusion deposition has two amin assemblies- the 'cold end' and the 'hot end'. The cold end is responsible for the pushing of the filament into the nozzle. The hot end is responsible for the heating and melting of the filament which purge through the nozzle[1]. The cold and hot end must work collaboratively to

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extrude right amount of material at the right temperature and at the right time for the stacking up of layers. Another important process is that the controlling of nozzle head to move in specified positions during printing for which stepper motors are used. They are complex mechatronic systems that integrate mechanical, control and computer technologies. The control part is composed of the main control board and responsible for importing the model, inputting commands and running the program. The mechanical part consists of four-axis belt screw, linear axes and optical axes, which are mainly responsible for feeding the filament, plastic molding, etc. Finally, the most important part, the heating component, which is composed of the printer's nozzle, which controls the output of the filament in a molten state conducive to plasticity and also regulates the bed temperature ideal for printing.

A. Filaments and its type

The primary material for 3d printing are the filaments, they are generally made of pure polymer with a low melting point. The pure polymer filaments are manufactured through the process of extruding pellets or raw materials from polymers. It is carried out by using extruders which push or forces the material through holes in the dye to get the product as an extrudate. During this manufacturing process several factors affects the process like Die temperature, roller puller speed, spindle speed and inlet temperature, these parameters will affect the viscosity of the material which results in abnormal diameter of the filament from the nozzle. Filaments are divided into two categories, pure polymer filament and composite filament[5]. The pure polymer filament is completely made from a polymer compound without adding additive solutions. The composite filaments are the filaments where addtives like fibres are added according to the use. Some of the pure polymer filaments are PLA, ABS and PP. Some of the widely used filaments,

PLA - polylactic acid, in contrast to other filaments which contain petroleum but PLA is made from organic materials. This thermoplastic monomer is user friendly and environment friendly, it does not easily warp during printing. It is not soluble in water. The print temperature is from 130-180 degree Celsius and the bed temperature should be around 50 degree Celsius.[4]

ABS - Acrylonitrile Butadiene Styrene, or ABS, is one of the thermoplastics and a 3D printing filament type that’s tough and can hold itself at high temperatures which is just as well because printing with ABS uses high temperatures for both the hot end and the printer bed. ABS is popularly known for its durability and its ability to withstand wear and tear. The print temperature is from 220 – 250 degree Celsius and the bed temperature is around 95 – 110 degree Celsius.[4]

NYLON - Nylon (aka polyamide) is a popular engineering plastic which is capable of withstanding wear resistance and has high durability. Nylon is absorbs moisture easily hence it requires high print temperatures. The print temperature is around 225 – 265 degree Celsius and the required bed temperature is about 70 to 90 degree Celsius.[4]

PVA – PolyVinyl Alcohol is a type of plastic filament which is bio-degradable and user-friendly. It is mostly used as support material for PLA and it easily dissolves in water. The print temperature is about 185 – 200 degree Celsius and the bed temperature is around 45 – 60 degree Celsius.[4]

A. Nozzle

The nozzle is the core components of the printer to complete the fused deposition modeling, according to the requirements of the different printing one can choose single or double spray nozzle. FDM printer nozzles are typically made of high thermal conductive metal such as brass or copper. The metal qualities and thermal conductivity play a major role in the printed part's surface quality and accuracy[6]. To control the nozzle temperature and make sure the material does not cause leakage or clogging, a heat sink and a fan are installed directly above the nozzle. Therefore, most commercial 3-axis printers’ heads are short and wide. Adaptations to the extruder head have been proposed for different needs. As the main component of the printer, it is crucial to have a nozzle that meets different requirements in FDM, depending on filament feed, time consumption, materials and final quality finish. The FDM nozzle stru cture generally separated into structure control device, feeding mechanism, throat cooling unit, cooling device, pipe assembly and nozzle hot end parts[6].

V. TYPES OF 3D PRINTERS

A. Gantry Type

Gantry-type 3D printers are based on traditional numerical control machining technology. As shown in figure 1, they use a three-axis control system, consisting of the X, Y, and Z axes to control the movement and positioning of the print head on the worktable[3]. The print head of a gantry-type 3D printer is movable and the three-axis control system precisely positions the print head's location and movement path, allowing the print head to move freely in three directions, thereby realizing the printing of complex three-dimensional structures. The gantry 3D printer can withstand larger weights and inertial forces with help of this structure, therefore resulting in higher printing accuracy and faster printing speeds[8]. During printing, the gantry structure controls the X and Z axes, while the baseplate controls the movement of the Y axis. The advantages of this structure are its simplicity, ease of assembly, and convenience of maintenance[3]. However, the disadvantages include insufficient Y-axis control precision, average print quality, relatively high noise, and limited choices of printing materials.

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Figure 1: ELEGOO Neptune 4 max

B. Box Type

As shown in figure 2, Box type 3D printers are the printers which are partially or fully enclosed around the printing area. The drive in the X and Y-axis directions is controlled by two synchronized motors working together. The two motors are fixed to the surrounding frame and connected to the print head by belts, allowing it to move freely within the same plane[3]. The enclosed form helps to create a stable environment for printing and also keeps the dusts and contaminants away from sensitive parts like nozzle or the print head. The closed structure is also helpful for maintaining the temperature. The main advantage of using Box type printers over Gantry is to reduce noise and improve precision but ends up having higher cost and maintenance on the other hand

VI. FDM WITH OPEN LOOP CONTROL

In early FDM 3D printers, the open-loop control method involved heating the print head using fixed-power heating elements. This made the open loop control system relatively simple and inexpensive. However, there are some apparent drawbacks to open-loop control systems. The main drawback was lack of feedback due to which the open loop control cannot correct errors or cope with environmental changes like voltage fluctuations, room temperature and other factors.[3] Open loop control systems do not provide more accuracy than closed control, it is limited by the precision of the pre-set parameters. The stepper motors might miss some steps because of mechanical resistance. Open loop control system cannot adjust to the variation in filaments as the temperature is not controlled well[7]. Moreover using open loop control system will require manual calibration for bed levelling, Extruder's steps per mm, any mistake or unsuitable values could lead to uneven printing, clogging of nozzles.

Figure 2: BAMBU P1P

VII. CLOSED LOOP CONTROL

Closed-loop control, in contrast to open-loop control, closed-loop control systems monitor output results in real-time, compare them with expected results and automatically adjust control parameters to correct errors. This makes closed-loop control systems more stable and accurate. Compared to open-loop systems, closed loop control systems have many advantages. The first is higher accuracy, Through real-time feedback and automatic adjustment, closed-loop control systems can improve system accuracy and stability. Second, they have excellent anti-interference capabilities. Closed-loop control systems can cope better with environmental changes and external disturbances, such as voltage fluctuations and temperature variations[3]. However, closed-loop control systems also have some drawbacks. Compared to open-loop control, closed-loop control systems require more complex hardware and software designs, which results in higher cost of the system.

A. PID Control

PID control is currently the most widely used type of controller in engineering, with its principle block diagram shown in figure 3.

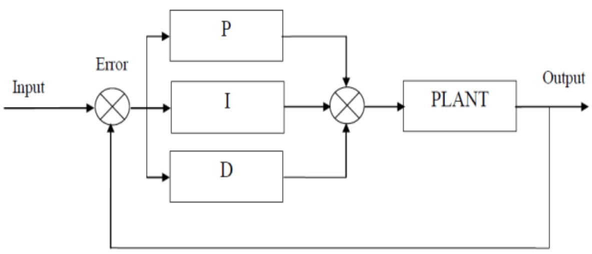

Figure 3: Schematic Diagram of PID Controller

It is a control system composed of proportional(P), integral(I), and derivative(D) units. It is a linear controller that can adjust the input value according to the deviation between the desired and current states, enabling it to achieve the desired state and maintain stability. It has the characteristics of a simple structure, clear principles, easy-to-adjust parameters, and stable system maintenance. The mathematical expression of the PID controller is:

$$u(t) = K_p e(t) + \frac{1}{T1}\int_0^t e(t).dt + T_d\frac{de(t)}{dt}$$

$$\mathrm{G(s)} = \frac{\mathrm{U(s)}}{\mathrm{E(s)}} = K_p\left[1 + \frac{1}{T1s} + T_D s\right]$$

In the formula: kp is the proportional coefficient; $T1$S(ki) is the integral time constant; TdS(kd) is the derivative time constant; $u(t)$ represents the output and $e(t)$ represents the error. Compared to the temperature control of early FDM 3D printers, PID control has improved FDM 3D printers in the following aspects:

Stability: The PID controller can maintain the target temperature more stably. Traditional control methods may cause temperature fluctuations, while PID controllers reduce fluctuations by continuously adjusting the power of heating elements. Response speed: PID controllers can reach the set temperature more quickly. By adjusting the proportional, integral, and derivative parameters, the PID controller can reach the target temperature in the shortest possible time. Adaptability: PID controllers can automatically adjust parameters to adapt to different working conditions. This means that PID controllers can maintain good performance in various environments without the need for manual intervention.
The size of the proportional coefficient in PID control affects the system's response speed and stability. When the proportional coefficient is large, the system has faster response speed but chances of oscillations and overshooting are likely. Likewise the integral gain determines the ability to eliminate static errors, but it also may lead to integral saturation. Hence the performance of the PID controller is crucially dependent on the tuning of the PID parameters.

XI. PID IN TEMPERATURE CONTROL

As the extruder head and heated bed of a fused deposition modeling 3D printer need to be maintained at a constant temperature, heating resistors are used to heat them and then thermistors are used for temperature monitoring. The 3D printer's microcontroller has a ADC module that can collect the voltage values in real time[2]. The interface-connected thermistor realizes the voltage variation with temperature change through voltage division. Moreover, the controller's ADC-collected analog voltage and the temperature change on the thermistor have a good linear relationship and specific parameters can be calibrated through temperature calibration. The microcontroller converts the collected voltage into a temperature value, compares this temperature value with the system's set target temperature, and performs PID adjustment. The microcontroller keeps the temperature fluctuations of the extruder and heated bed within a certain range through PID control, forming a closed-loop temperature control system.

X. SIMULATION AND RESULT

In this study, the PID control method was employed to control the temperature of the FDM 3D printer's extruder head, and the extruder head temperature control system was modeled and simulated using SIMULINK. Through data analysis of the simulation results, a deeper understanding of the advantages and limitations of PID control in temperature control can be achieved. Here the set temperature is 200 degree Celsius. Two graphs are to be obtained, one graph is plotted with the values obtained without the PID controller and the other graph is plotted with the help of the values obtained while using PID controller. The graph plotted in red colour is plotted while using PID controller and the blue colour graph indicates the values obtained without using PID controller. Their comparison, advantages and disadvantages have been discussed in the later part.

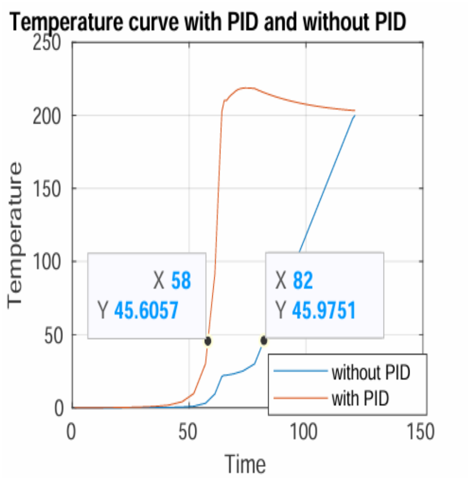

Figure 4: Temperature rise curve comparison between with PID controlled nozzle and without a PID control nozzle

The characteristics of the graph at different values are discussed in order to compare and understand their behaviour clearly. It is shown in figure 4 that with the help of PID controller temperature rises within a short span of time and exceeds the set temperature which is due to the absence of damping and settles down at the set temperature. Without PID control as shown in figure 4, the temperature takes some time to rise and the temperature will not be settled at the set temperature as precisely as using PID. In figure 4, the time taken for reaching 45 degrees using PID and without using PID is compared, the time taken without PID is 82 seconds but while using PID controller, the temperature reached 45 degrees in 58 seconds. Hence the time taken to reach 45 degrees without PID is more when compared to using with PID controller.

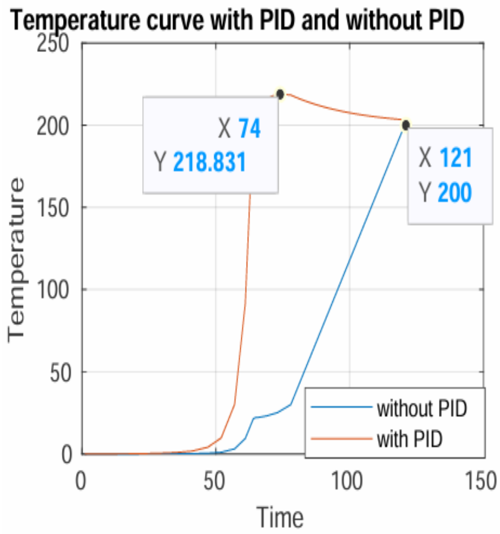

Figure 5: Peak temperature of the nozzle with PID and without PID controller

Figure 5 shows the peak temperature values with and without using PID controller, the peak value obtained with PID control is 218.831 degree Celsius at 74 seconds which shows quick heating response but with some overshoot due the improper tuning of the PID controller, the temperature could be controlled precisely with proper tuning of the PID controller. Meanwhile, without PID control the peak temperature is the set temperature 200 degree Celsius at 121 seconds which shows stability but with slower response rate, this could make the nozzle less responsive to the external disturbances. Even though the temperature might reach the set temperature without using the closed loop control, the main disadvantages are that the temperature might fluctuate due to external disturbances and it cannot be corrected as it does not have any feedback which could eventually affect the print quality. Other one is the overshoot, the temperature rises very steeply in open loop which could damage some parts, meanwhile with proper tuning of PID the overshoot can be controlled.

XII. OPTIMIZATION AND IMPROVEMENT

We have discussed in detail the current issues with nozzle temperature control in FDM 3D printers and the effectiveness of PID controllers. By comparing experimental data, we found that the PID controller demonstrates a significant advantage in improving system stability and temperature accuracy.

A. Optimizing PID parameter tuning methods: To achieve better temperature control performance, more advanced PID parameter tuning methods can be tried, such as simulated annealing algorithms, genetic algorithms[9].
B. Introducing adaptive control and intelligent control algorithms: Considering factors such as environmental disturbances and equipment aging during the actual printing process, adaptive control and intelligent control algorithms can be introduced. For example, adaptive PID control and fuzzy PID control can automatically adjust PID parameters according to actual working conditions, making temperature control more stable and precise[10].
C. Dual PID loops for faster response: Dual loop PID technique is quit useful, where one loop controls the initial heating and the other loop takes over once the temperature reaches around the set temperature. This helps in reducing the initial heating time and the secondary loop reduces the overshoot and maintains a stable temperature, ensuring high quality prints.

XIII. CONCLUSION

This Paper discusses on the FDM 3d printing, its type and working process in detail. The importance of closed loop control in 3D printers for achieving better quality. Also an analysis on closed loop temperature control of the nozzle using PID controller and have showed the significant impact of using PID temperature control over standard temperature control. The main result is that using PID controller have significantly reduced the heating time of the nozzle of 3D printer when compared to the open loop temperature control. However, this improvement also has some drawbacks, such as excessive overshoot. In order to tackle these drawbacks several optimization strategies have been developed and envision the future of temperature control in FDM 3D printers.

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