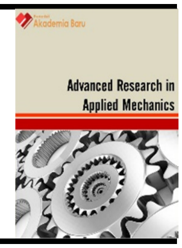
Penerbit Akademia Baru

Journal of Advanced Research in Applied Mechanics

Journal homepage: www.akademiabaru.com/aram.html
ISSN: 2289-7895



Fuzzy Controller Algorithm for 3D Printer Heaters

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ARTICLE INFO

Article history:
Received 5 June 2017
Received in revised form 4 July 2017
Accepted 4 December 2017
Available online 11 March 2018

Keywords:
3D printing, fuzzy control, temperature control, extruder, cartridge heater, heat bed

ABSTRACT

3D printing using fused filament fabrication technology requires the printer's heaters to operate within temperature ranges suitable for the used material, hence a closed-loop controller for the heaters is needed. PID controllers are the most widely used. To efficiently design this controller, parameter-tuning must be done which is a time-consuming process. To save time, tuning could be performed by simulation, but this requires the system's model. Some system models are difficult to deduce, thus other controllers that are independent of the system model and do not require multiple tuning iterations are used. An example of such controllers is the fuzzy like PI controller. This paper presents the design and implementation of a fuzzy like PI controller. The results for testing the controller are presented.

1. Introduction

There are many 3D printing techniques. The fused filament fabrication technology technique was used in this article to carry out the tests and consists of a heat bed and an extruder through which a filament of 1.75 mm or 3 mm diameter is fed [3]. The most common printing materials are ABS and PLA. The temperature of the hot end of the extruder ranges from 200-250 °C when using ABS [5] for printing and from 160-220 °C when using PLA [6]. Heat beds prevent warping and increase the print quality. The heat bed's temperature ranges from 100-110°C with ABS and from 50-70°C with PLA [7]. The most widely used controller for heaters is the PID controller [1].

To conduct this study, a 40-watt cartridge heater was used for the extruder and a 90-watt heater for the heat bed. Both heaters' parameters were unavailable which made building their models difficult. The heat bed's heater takes about 10 minutes to reach 100°C. Thus, system identification techniques are time consuming. Without the system model and with the time taken for the heat bed's heater to reach the set point temperature, tuning a PID controller can be time-

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consuming. The heaters' parameters could also be time-variant or have a dependency on other variables [4]. The aim of this study is to use a controller for the heaters that is easy to implement and fast to tune and can control a non-LTI system whose model is unknown. Thus, a model-free fuzzy like PI controller is selected [2] [8].

2. Fuzzy Like PI Controller

A fuzzy like PI controller was designed and implemented to control the temperatures of both the heat bed and the extruder heater of a 3D printer, Figure 1 shows the block diagram of the system.

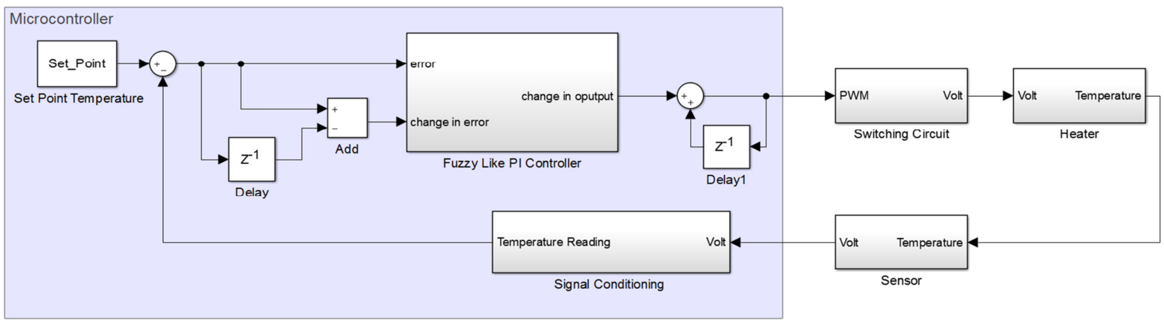

Fig. 1. System block diagram

2.1 Fuzzy Like PI Controller Algorithm

The implemented fuzzy controller is a Mamdani type fuzzy logic controller implemented in a manner that gives the user flexibility in choosing the number of membership sets of the error and the change in error (n), the user also inputs the ranges of the values of both the input and the output, and the operational set point. The membership sets are isosceles triangular shaped except for the two outer most sets which are shaped as a trapezium, the membership sets are numbered from 0 at the most negative set and n-1 at the most positive set, the zero set is numbered at (n-1)/2, then both the error and the change of error are normalized (from 0 to 100) and fuzzified.

For each fuzzy set three values are calculated: a, b and c; where b represents the center of the set, a and c represent the two outer ends of the set as shown in Figure 2, br is the value between a and b or b and c, it is also the value between the current b value and the b value of the previous -or the next- fuzzy set.

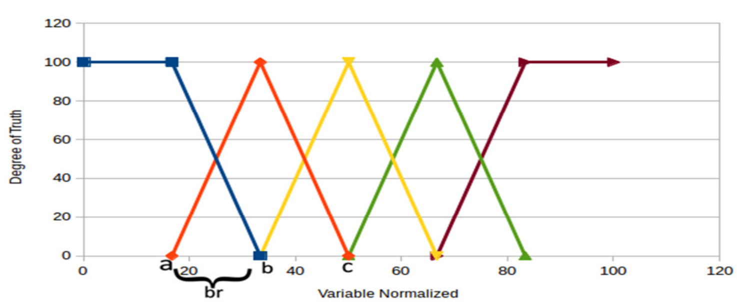

Fig. 2. 5 Fuzzy Sets example

2.1.1 Simplified change in output sets determination

The number of membership sets in the change in output is (2n -1), the membership sets numbers of the change in output is determined by summing the membership sets of both the errors and the change of error as shown in Table 1, the membership value is determined by centroid defuzzification using min-max inferencing.

Table 1
Example of a rule base table in case of 5 fuzzy sets for both error and change in error, the first row is the membership functions of the error, the first column is the membership functions of the change in error, the rest of the table is the membership functions of the change in output

e/ce	0	1	2	3	4
0	0	1	2	3	4
1	1	2	3	4	5
2	2	3	4	5	6
3	3	4	5	6	7
4	4	5	6	7	8

2.1.2 Equations governing the controller

For error and change in error:

value normalized=(value – value min)*100 / (val max – val min) (1)

br = 100 / (n+1) (2)

b = (current set number*br) + br (3)

a = b – br (4)

c = b + br (5)

If val normalized between a and b:

μ =(val normalized – a) / (b –a) (6)

If val normalized between a and b:

μ =(c – val normalized) / (c – b) (7)

For change in output:

Change in output set = error set + change in error set (8)

3. Hardware Implemented

The fuzzy like PI controller is implemented on an Arduino Nano board with an Atmel ATmega328 microcontroller which runs at 16 MHZ clock speed and with 14 DIO pins -6 of which provide PWM output- and 8 analog input pins, the microcontroller has 32 KB of flash memory and 2 KB of SRAM.

The controller is used to control the temperature of both the extruder heater and the heat bed, the extruder heater is a 12V 40W cartridge heater inserted in the heating block in the extruder assembly shown in Figure 3., while the heat bed is the MK3 aluminum heat bed operating at 19 V shown in Figure 4. Both heaters are controlled by varying the duty cycle of a PWM control signal produced by the microcontroller, the PWM signal is applied to the switching circuit consisted of a 4N35 optocoupler and a IRFP240 MOSFET as shown in Figure 5.

The feedback element in both cases is a NTC 100 Kohm thermistor temperature sensor with B value of 3950, Fig. 6. shows the relation between the thermistor resistance and temperature according to the B parameter equation:

$$1/T = 1/T_0 + 1/B * \ln(R/R_0) \tag{9}$$

where: T is temperature in kelvin, R is current resistance, R0 is the resistance at temperature T0. Figure 7 show the schematic of the interfacing circuit of the sensor with the microcontroller.

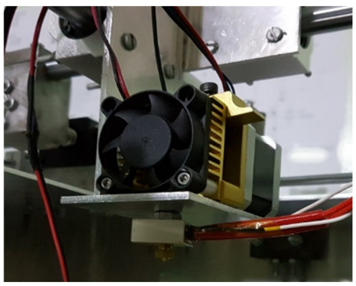

Fig. 3. Extruder assembly

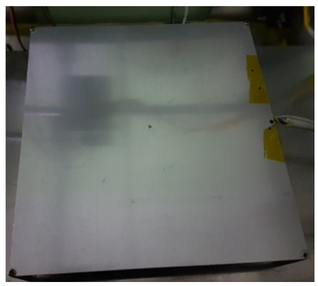

Fig. 4. The Mk3 heat bed

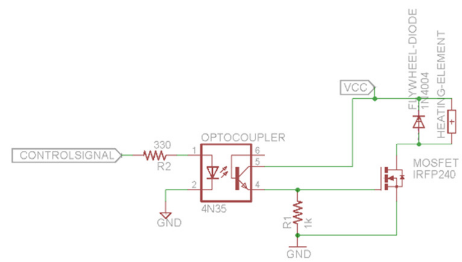

Fig. 5. Heaters' switching circuit

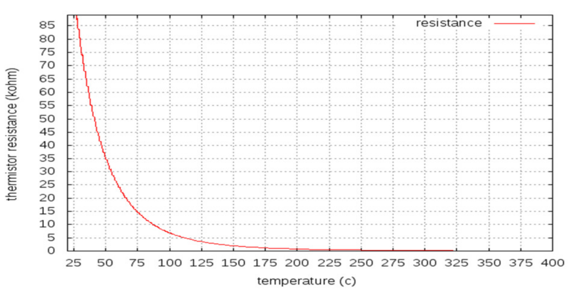

Fig. 6. Thermistors' temperature against resistance graph

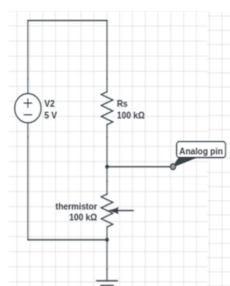

Fig. 7. Thermistors' interfacing circuit schematic

4. Experimental Work

The controller was tested with both the extruder heater and the heat bed, the measured data was sent from the microcontroller to the computer via Arduino serial monitor, then the results were copied to the a .dat file, then the file was processed by the GNUPLOT tool to plot the data.

4.1 Heat Bed Experiment

Experiment parameters: max voltage is 19V achieved by max PWM duty cycle value of 220/255 on a 24V power supply, number of membership functions of both the error and change in error is 9, number of membership functions of change in output is 17, input max is 120 °C, input min is 0 °C, output max is 220/255 duty cycle, output min is 0/255 duty cycle and set point of 105 °C.

4.2 Extruder Heater Experiment

Experiment parameters: max voltage is 12V achieved by max PWM duty cycle value of 255/255 on a 12V power supply, number of membership functions of both the error and change in error is 9, number of membership functions of change in output is 17, input max is 300 °C, input min is 0 °C, output max is 255/255 duty cycle, output min is 0/255 duty cycle and set point of 214 °C.

5. Results and Discussion

5.1 Heat Bed Experiment Results

Max over shoot is 106 °C, steady state value is 104 °C resulting in a steady state error of about 0.95 %, rise time is around 500 seconds and settling time is around 800 seconds, as shown in Figure 8 and Figure 9.

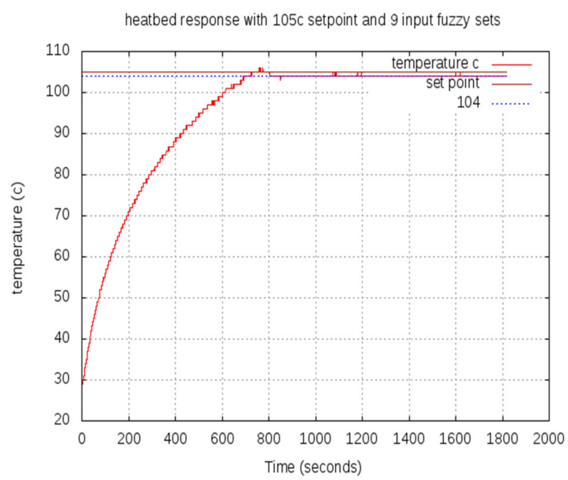

Fig. 8. Heat bed temperature against time

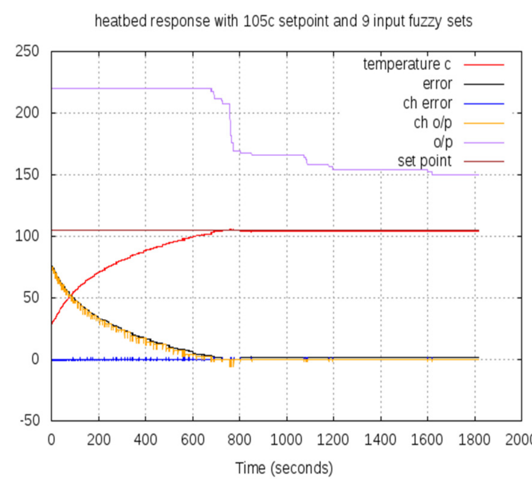

Fig. 9. All data acquired on the heat bed

5.2 Extruder Heater Experiment Results

Max over shoot is 260 °C and max steady state value is 240°C resulting in a steady state error of about 12.15 %, rise time is around 65 seconds and settling time is around 150 seconds, the results shown in Figure 10 and Figure 11 show existence of steady state oscillations due to the decrease in the thermistor's sensitivity in the operation range of the extruder heater as shown in Figure 6, the effect of the decrease in the sensor's sensitivity is apparent in Figure 12 which shows a zoomed graph of the temperature against time around the set point. While testing the heater the oscillations in the temperature didn't introduce any problem while printing. The controller proved to be reliable even when the sensor used was with such low quality.

6. Conclusion

The results prove that the controller has adequate performance while being used to control the heaters of the 3D printer, with a steady state error reached in the heat bed case as low as 0.95% and in the extruder case 12.15% (the value is high due to the lack of sensor sensitivity) with minimal tuning, absence of the system model and without the need to perform system identification. The controller was suitable to be used on small microcontrollers as it occupied 7.5 Kb of Flash memory and 0.3 Kb of RAM, which leaves room to use other complex applications on the microcontroller. Therefore, the use of fuzzy like PI controller is highly justified.

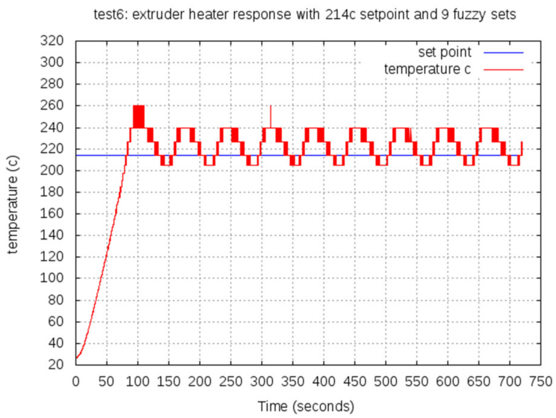

Fig. 10. Extruder heater temperature against time

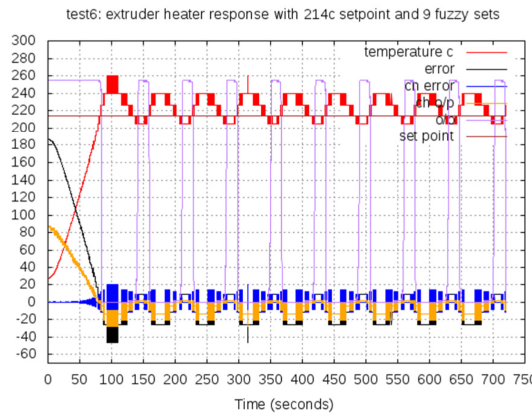

Fig. 11. All data acquired on the extruder against time

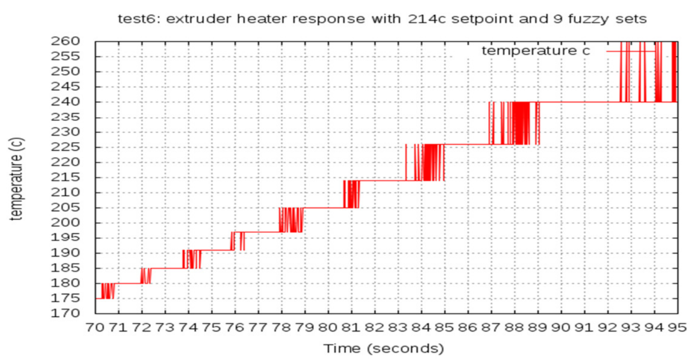

Fig. 12. Zoomed extruder temperature against time

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