HDPE plastic extruder design and control for 3D printing with plastic pellet feeding method

B Setiawan1*, D C Permatasari1, A D W Sumari1,2, T Winarno1, V U Audiana1 and A M Damayanti1

1 Department of Electrical Engineering, State Polytechnic of Malang, Jl. Soekarno-Hatta No. 9, Malang 65141, East Java, Indonesia
2 Faculty of Defense Technology, Indonesia Defense University, IPSC, Sentul, Bogor, West Java, Indonesia

*budhy.setiawan@polinema.ac.id

Abstract. 3-Dimensional (3D) Printing Technology (3D printer) has become a Standard Acceleration Tool for Industry 4.0. Until now, 3D Printing system material melting technology has been using Fused Deposition Modelling (FDM) method. FDM is the melting of plastic materials through melting temperature and the formation of 3D objects in layer by layer manner. Meanwhile, the feeding for melting material is in the form of rolling filament. Currently, in this research FDM uses plastic pellet feeding method. Its extrusion is called extruder, that is, plastic pellet processed through heater zone and pushed out by screw to the nozzle where the nozzle is a Computer Numerical Control (CNC) drives 3-Degree-of-Freedom (3DOF) applying cartesian axes. In this research, the printing uses high density polyethylene plastic pellet (HDPE). Temperature control in melting heater using proportional-integral-derivative (PID) method is controlled by microcontroller and programmed through marlin firmware. The design and implementation result showed that the extruder system is capable to melt HDPE pellet at 200°C with heater power 300Watt and the screw can rotate to push out melted plastic at 2mm of nozzle.

1. Introduction

3-Dimensional (3D) printer is the most popular issue in recent years. Actually, 3D printing and rapid prototyping can be traces back to 1980. 3D printing brings mass production of customized products to life. Furthermore, not only it can produce models that traditional manufacture technology cannot produce, but also it can save much time in developing and making new products. On the comparison of traditional model manufacturing, this new technology can print out delicate components, and the cycle and producing process are short and simple. Furthermore, it has diverse choices of raw materials and can generate models which are complicated. These advantages make 3D printing stands out markedly and becomes a trend nowadays [1].

More recent contributions considered is screw extrusion as a useful technology for 3D printing application allowing to manufacture a wider variety of materials than FDM, while using polymer granules as raw material [2]. The polymer is fed into the hooper and passed through the temperature zones where it is heated and melted. The melted polymer material is pushed forward by a powerful screw and passed through the extruder mechanism to form the die by nozzle [3]. In order to produce a good quality of filament plastic, the temperature in melting zone must be appropriately set and precisely
controlled [3]. To print a 3D object, this research uses plastic pellet polymer that is directly formed from the nozzle of extruder. The plastic pellet is used in this research are high-density polyethylene (HDPE).

2. Literature review

2.1. 3D printing

3D printing is a new manufacturing technology, related to materials, computing mathematics, and other disciplines. 3D printing has shown a huge advantage for the automotive, aerospace manufacturing industry and brought a lot of conveniences. With the development of 3D printing technology, variety materials printing methods have been developed, such as the most commonly used fused deposition modelling (FDM) technology. FDM is printing technology that uses computer aided design of layer by layer manufacturing print and has the advantages of low cost, easy maintenance, and so on [4]. Meanwhile, the technology of FDM for melting material use filament. But in this research FDM uses plastic pellet feeding method. The process of plastic melted become an object is extruder.

2.2. Screw Extruder and heater extruder

Extruder is a part of 3d printing and process used for manufacturing objects with fixed shapes and specific properties. A screw extruder is divided into one or several conveying zones (transport zones), melting zones (for material fusion), and mixing zones in which the extruded melt is submitted to high pressure, before its evicton through the nozzle. The pumping effect of the rotating screw moves the material from the feeding zone to the nozzle which influences the transport phenomena by having a restrictive effect, namely, the melt is accumulated behind the nozzle and fills completely the available volume in this region. The net flow rate at the nozzle exit is mainly influenced by the material flow in the longitudinal direction if one neglects the clearance between the screw and the extruder barrel [5]. Heater extruder is an extruder heating block consist of an aluminum mounting block and a 40W heating element where is rated at 12V. The power dissipated by this heating element is controlled by varying the duty cycle of the PWM applied by the microcontroller.

2.3. Stepper motor

Stepper motor is an electromechanical actuator which converts the input pulse train into a precisely defined increment in the shaft position. Each pulse moves the shaft through a fixed angle, called step angle. Stepper motors have emerged as cost-effective alternatives for direct-current (DC) servo motors in high-speed, motion control applications, where the high torque is not required, with the improvements in permanent magnets and the incorporation of solid-state circuitry and logic devices in their drive systems [6].

2.4. Marlin firmware

Marlin firmware is structured to utilize a repetitive loop method that periodically checks for serial input. To determine the command process flow, a manual code review was performed tracing the path of incoming G-code commands from reception to execution. It was found that while the firmware uses sequential numbering and check sums to validate incoming commands from the desktop application before processing, it is possible to bypass this functionality by directly updating private variables with desired hardware parameters values [7].

3. The proposed method extruder

In this research, extruder uses plastic pellet feeding method. Plastic pellet processed through melting zone and pushed out by screw to the nozzle. The advantages of extruder uses plastic pellet are low cost because plastic pellet is cheaper than rolling of filament and do not require a lot of time to print an object with diameter of nozzle that is used 2mm. On figure 1 is the mechanical design of the extruder for 3D Printing. Parts of extruder such as inlet as the pipe hole to insert HDPE plastic pellet, a stepper motor to rotate a screw, a screw rotates to push HDPE plastic pellet through melted process by heater and a nozzle with diameter of 2mm are used to form the HDPE filament.
Figure 1. The mechanic design of the extruder.

3.1. Design of heater power
Design of heater to determine heater power. Heater is used to melt HDPE plastic pellet with melting temperature at 200°C where discharge speed of the filament is 100mm/s with nozzle diameter of 2 mm. To calculate the maximum discharge of the filament or debit of filament, use (1)

\[ Q = A \times V = \left(314 \times 1 \times 1\right) \times 100 \]

\[ Q = 314 \]  

\[ A = \text{Area of nozzle with diameter 2mm (mm}^2\)\n\[ V = \text{discharge speed of filament (mm/s)}\n\[ Q = \text{debit of filament (mm}^3/\text{s)}\n
From the above result, the weight of HDPE filament can be calculated by using (2)

\[ W = \rho \times Q = 0.96 \times 0.314 \]

\[ W = 0.301 \]

\[ \rho = \text{density (g/cm}^3\)\n\[ Q = \text{debit of filament (cm}^3/\text{s)}\n\[ W = \text{Weight or mass of filament (g/s)}\n
The next step is to calculate the energy of HDPE to produce filament with speed 100 mm/s by using (3)

\[ E = m \times c_{\text{hdpe}} \times (t_2 - t_1) = 0.000301 \times 2.25 \times 447.15 \]

\[ E = 0.302 \]

\[ m = \text{mass of filament (kg/s)}\n\[ c = \text{specific heat of HDPE (kJ/kg}^\circ\text{K)}\n\[ t_2 - t_1 = \text{(final temperature 200°C - initial temperature 26°C) then convert celcius to kelvin (+273.15)}}\n\[ E = \text{Energy (kJ)}\]
Then convert the energy to power in watt-hour using (4)

\[ P = E \times Wh = 0.302 \times 0.278 \]

\[ P = 0.084 \]

\( E \) = Energy (kJ)
\( Wh \) = Watthour
\( P \) = Power (Wattour)

From the above result, then convert the heater power from watthour to wattsecond by using (5)

\[ P = 0.084 \times Ws = 0.084 \times 3600 \]

\[ P = 302.4 \]

\( Ws \) = Wattsecond
\( P \) = Power (Wattsecond)

So heater power needed to melt HDPE pellet with the speed of filament 100mm/s is 302.4 Wattsecond.

3.2. Torque design of screw

The calculation design of screw torque to determine the stepper motor specification is used for this system. The angle of screw (\( \Theta \)) is 34.3\(^\circ\), the slide angle of screw (\( \alpha \)) is 55.7, and the friction force of screw (\( f \)) is 45.75 Newton. Before calculating the torque, the thrust force of screw has to be calculated by using (6).

\[ F = \eta + f \cos \alpha + \frac{f \sin \alpha}{\sin \alpha} = 75 + 45.75 \cos 55.7 + \frac{45.75 \sin 55.7}{\sin 55.7} \]

\[ F = 146.53 \]

\( f \) = friction force (N)
\( \alpha \) = slide angle (\(^\circ\))
\( \eta \) = viscosity of HDPE (N)
\( F \) = thrust force (N)

Then calculate the torque using (7)

\[ T = \frac{F \times de}{2} \left( \frac{1 + \pi \times de}{\pi \times de - \mu \times l} \right) = \frac{146.531 \times 4.44}{2} \left( \frac{1 + 3.14 \times 4.44}{3.14 \times 4.44 - 0.61 \times 15} \right) \]

\[ T = 1.3 \]

\( l \) = pitch screw (mm)
\( de \) = effective diameter of screw (mm)
\( \mu \) = friction coefficient of bearing (N)
\( F \) = thrust force (N)
\( T \) = Torque (Nm)

So the torque of screw for this system is 1.3 Nm

3.3 Speed design of stepper motor

In this system, speed design filament with 2mm diameter is 100mm/s and extruder system use stepper motor to rotate the screw. The speed of stepper motor can calculated by using (8)
\[ n = \frac{v \times 60}{s} = \frac{0.1 \times 60}{0.015} \]
\[ n = 400 \]  

\( n \) = speed of stepper motor (RPM)

\( v \) = speed of filament (mm/s)

\( s \) = screw pitch (m)

So the speed design for the stepper motor for the speed of filament for 100 mm/s is 400 RPM.

4. Methods

Figure 2 shows how the system works. The extruder divides the system into two parts, namely, the temperature control for melting temperature of HDPE pellet and the speed of the stepper motor for rotating the screw. The process of temperature control is carried out by microcontroller with proportional-integral-derivative (PID) method. Temperature controller uses heater to melt HDPE pellet and temperature sensor is used for sensing the temperature setpoint of the melted HDPE. This system uses a stepper motor with Nema 23 type for rotating the screw and pushing out the melted pellet to the nozzle. The output of 2mm nozzle is discharge of plastic melted.

![Block diagram of the extruder system](image)

**Figure 2.** Block diagram of the extruder system.

5. Results and discussion

The results for extruder system consists of temperature testing and stepper motor testing.

5.1. Temperature testing

Temperature testing was conducted to know if the temperature control system worked well or not. Temperature control used heater to melt plastic pellet. Based on design heater power in equation (5), heater power needed to melt HDPE pellet is 300Watt. In this case, the temperature control system is used to stabilize the temperature on the melting process. The temperature set point is entered on system with melting temperature of HDPE pellet at 200°C. The result of the temperature response toward the time on heating process is displayed in Figure 3.
Figure 3. Melting temperature control response.

Figure 3 shows the temperature test with PID control method. The result of melting temperature control for HDPE pellet reached stability at 200°C.

5.2. Step Motor testing

Table 1 is the data of testing result for speed of step motor toward length of the filament. The step motor was set on 200 pulse then changed the values of the step motor speed to rotate the screw in marlin firmware to know the length of HDPE filament that was come out. The result shown in Table 1, the speed of the step motor of 100mm/min produced 81 mm filament length, the speed of the step motor 90 mm/min produced 83 mm filament length, the speed of the step motor 80 mm/min produced 80 mm filament length, and the speed of the step motor 70 mm/min produced 84 mm filament length. The lower the speed of the step motor, the lower of HDPE filament discharged from the nozzle and also the lower the frequency of step motor is.

| Speed of the step motor (mm/min) | Time (s) | Length of Filament (mm) | Frequency (Hz) |
|---------------------------------|----------|-------------------------|---------------|
| Marlin                           |          |                         |               |
| 100                              | 71       | 81                      | 331.1         |
| 90                               | 82       | 83                      | 297.6         |
| 80                               | 92       | 80                      | 265.2         |
| 70                               | 99       | 84                      | 232           |

6. Conclusion

The design and testing result showed that the extruder system is capable to melt HDPE pellet at 200°C with heater power 300Watt. Temperature control of heater by using a PID method can reached stability at 200°C and speed of step motor to rotate the screw can produced melted plastic at 2mm of nozzle.

References

[1] Lin K-H, Shen C-Y, Du J-L, Wang G-Y, Chen H-M and Tseng J-D 2016 A design of constant temperature control system in 3D printer 2016 IEEE International Conference on Consumer Electronics-Taiwan (ICCE-TW) (IEEE) pp 1–2

[2] Koga S, Straub D, Diagne M and Krstic M 2018 Thermodynamic Modeling and Control of Screw Extruder for 3D Printing 2018 Annual American Control Conference (ACC) pp 2551–6
[3] Ravi S and Balakrishnan P A 2010 Modelling and control of an anfis temperature controller for plastic extrusion process *2010 International Conference On Communication Control And Computing Technologies* (IEEE) pp 314–20

[4] Xiaoyong S, Liangcheng C, Honglin M, Peng G, Zhanwei B and Cheng L 2017 Experimental analysis of high temperature PEEK materials on 3D printing test *2017 9th International conference on measuring technology and mechatronics automation (ICMTMA)* (IEEE) pp 13–16

[5] Diagne M and Krstic M 2015 State-dependent input delay-compensated bang-bang control: Application to 3d printing based on screw-extruder *2015 American Control Conference (ACC)* (IEEE) pp 5653–8

[6] Morar A 2015 The modelling and simulation of bipolar hybrid stepping motor by Matlab/Simulink *Procedia Technol. 19* 576–83

[7] Moore S B, Glisson W B and Yampolskiy M 2017 Implications of malicious 3D printer firmware