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The Algorithm Development and Implementation for 3D Printers based on Adaptive PID Controller

Araştırma Makalesi / Research Article

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ABSTRACT

The 3D printers widely used in the world are produced in different mechanical and electronic designs. The 3D printers which have various mechanical structures such as cartesian, delta and core (xy , xz) already are used open source code software such as Sprinter, Marlin, Cura 3D and Teacup. The control of the 3D printers is usually done by the classical Proportional-Integral-Derivative (PID) control algorithm. In this study, we have developed for the designed 3D printer a new software by using adaptive PID control algorithm instead of classical PID. Five step motors of the designed 3D printer are controlled by the adaptive PID. In addition, there are both heating and cooling processes in the extruder system and these processes are controlled by the adaptive PID. The mechanical design uses a belt and pulley drive system which is suitable for accelerated movements. In the system software, 3D Printing Software Pipeline (input model, orientation and positioning, support structures, slicing, path planning, machine instructions) is applied. The control algorithms for extruder and step motors are prepared as separate function files in software implemented in C. It has been observed that the designed software is particularly successful in eliminating errors on the surface of the products.

Anahtar Kelimeler: Adaptive PID, 3D printer, step motor, algorithm.

3 Boyutlu Yazıcılar için Uyarlamalı PID Kontrol Tabanlı Algoritma Geliştirilmesi ve Gerçeklenmesi

ÖZ

Dünyada yaygın olarak kullanılan 3B yazıcılar farklı mekanik ve elektronik tasarımlarda üretilmektedirler. Kartezyen, delta ve core (xy , xz) gibi çeşitli mekanik yapılara sahip olan 3B yazıcılarda hâlihazırda Sprinter, Marlin, Cura 3D ve Teacup gibi açık kaynak kodlu farklı yazılımlar kullanılmaktadır. 3B yazıcıların denetimi genellikle klasik PID denetim algoritması ile yapılmaktadır. Bu çalışmada, klasik PID yerine uyarlamalı PID kontrol algoritması kullanılarak yeni bir yazılım ile 3B yazıcı tasarlanmakta ve geliştirilmektedir. Tasarlanan 3B yazıcıda beş adet adım motoru kullanılmakta, her bir motorun denetimi uyarlamalı PID ile yapılmaktadır. Ayrıca, ekstruder sisteminde hem ısıtma hem de soğutma yapıları bulunmakta olup bu süreçler uyarlamalı PID ile kontrol edilmektedir. Mekanik tasarımında ivmeli hareketler için elverişli olan kayış ve kasnak sürücü sistemi kullanılmaktadır. Sistemin yazılımında, 3B yazıcı yazılım aşamaları (giriş modeli, yönlendirme ve konumlandırma, destek yapıları, dilimleme, yol planlama, makine komutları) uygulanmaktadır. C ortamında gerçekleştirilen yazılımda ekstruder ve step motorlar için kontrol algoritmaları ayrı fonksiyon dosyaları şeklinde hazırlanmaktadır. Tasarlanan yazılımın özellikle ürünlerin yüzeyindeki hataların giderilmesinde başarılı olduğu gözlemlenmektedir.

Keywords: Uyarlamalı PID, 3 boyutlu yazıcı, adım motor, algoritma

1. INTRODUCTION

The 3D printer is called a device that produces models that are designed on a computer or scanned in 3D using different materials without the need for any pattern. 3D solid objects are produced by 3D printers with the aid of 3D file prepared in digital environment. The models that have been designed in the digital environment come into being as tangible objects in a short time thanks to 3D printers. The different methods such as Fused Deposition Modelling (FDM), Laminated Object Manufacturing (LOM), Polyjet Photopolymer, Selective Laser Sintering (SLS), Stereolithography (SLA) and Syringe Extrusion are used to perform the 3D printing process [1]. The most widely known and used of these methods is FDM. In the

FDM method, extruded thermoplastic or wax from a heated extrusion head is used to track the solid areas of the physical models. The thermoplastic such as Polylactic Acid (PLA) and Acrylonitrile Butadiene Styrene (ABS) materials that can take shape with heat are used in this method [2]. In this study, FDM type 3D printer has been used.

The technological development of additive manufacturing and 3D printing provides a significant contribution to the rapid prototyping of commercial products and designed products [3-5]. The minimum error production of prototypes of commercially produced or designed products is very important. The 3D printing process needs to be controlled so that these prototypes can be produced with minimal error. The extruder position control of the 3D printers is usually done by the classical PID control algorithm [6-8]. Even though the

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control algorithms such as PID are used in 3D printers, it is possible some errors especially on the surface of the produced objects [9, 10]. These errors are seen more common, especially during the production of objects with complex geometries. In order to correct these errors, additional error correction processes have to be applied and this situation leads to an increase in production cost.

The 3D printers widely used in the world are produced in different mechanical and electronic designs. The 3D printers which have various mechanical structures such as cartesian, delta and core (xy , xz) already are used open source code software such as Sprinter, Marlin, Cura 3D and Teacup [11-13]. In these 3D printers, the control of the motors and the heating and cooling processes in the extruder system are controlled by classical control methods.

In this study, we have developed for the designed 3D printer a new software by using adaptive PID control algorithm instead of classical PID. Five step motors are used in the designed 3D printer. The heating-cooling processes in the extruder system and each motor of the designed 3D printer are controlled with the adaptive PID instead of classical PID. The control algorithms for extruder and step motors are prepared as separate function files in software implemented in C. It has been observed that the designed software is particularly successful in eliminating errors on the surface of the products.

This article is organized as follows: mechanical design of 3D printer in Section II. The adaptive PID of 3D printer is expressed in Section III. Experimental studies and discussions are presented in Section IV, and conclusions are finally given Section V.

2. MECHANICAL DESIGN OF 3D PRINTER

The 3D printers are manufactured in different designs such as cartesian, delta and core xy . Cartesian-designed 3D printers usually consist of a thermoplastic sprayer attached to the xyz cartesian platform. In the cartesian 3D printer, the x and y axis movements are provided by the eccentric trigger strap. The movement in the z axis is controlled by two step motors using a screw-on mile. A typical cartesian 3D printer [14] is shown in Figure 1.

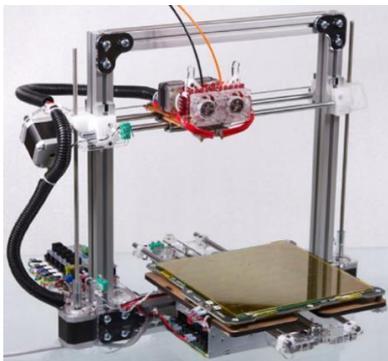


Figure 1. A typical cartesian 3D printer (a Deezmaker Bukobot Duo)

The main difference that distinguishes delta printers from other printers is that they are driven from three points by a three step motor to ensure vertical z axis movement. This difference is due to the triangular shapes of the delta printers. A deltabot 3D printer [14] is shown in Figure 2.



Figure 2. A deltabot 3D printer (the seeMeCNC Orion)

In core xy designed 3D printers, x and y axis movement is provided by strap pulleys. In this design, the head where the smelting process is performed is connected to the xy coordinate system. The movement of the heating table is in the z axis direction. The heating plate is controlled by step motors via screw shaft. The configuration of core xy designed 3D printer [13] is shown in Figure 3.

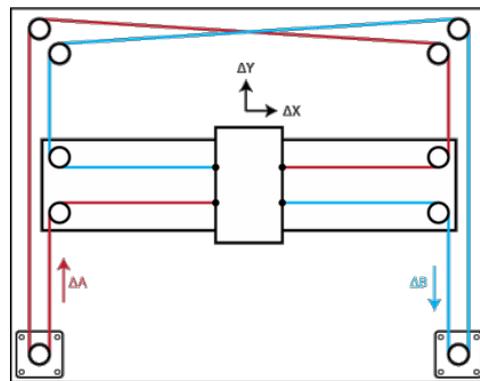


Figure 3. Core xy configuration [15]

In this section of our study, the mechanical design and prototype of the 3D printer are realized. The 3D printer, which is designed as a cartesian type, is used five step motors. The dimensions of the designed and produced prototype are $320 \times 390 \times 350$ mm. Also, in designed 3D printer is used a heated table with dimensions of $210 \times 210 \times 210$ mm, a nozzle with a size of 0.4 mm and xy belt mechanism for driving. The 3D printer, which is

designed and prototyped, is presented in Figure 4 and Figure 5.



Figure 4. Front view of the designed 3D printer

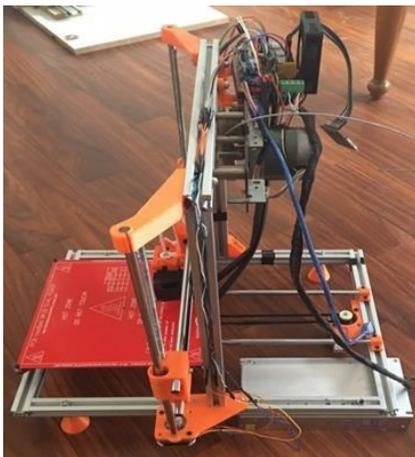


Figure 5. Side view of the designed 3D printer

The system is designed to take place in the open housing. With the prototype 3D printer the goal is to minimize errors on the surface of the produced objects. The surface deformation, which is a major problem especially in the production of objects with complex geometries, is greatly reduced by the 3D printer being designed. In this study, a body built from sigma profiles is designed because it can be easily mounted on the prototype produced and easy attachment can be made. Axes are mounted on the body formed by the sigma profiles and fasteners. The extruder, which is the part where the filament is pushed into the nozzle tip, is located on the y axis. To facilitate the movement of the extruder, toothed belts and ball-bearings are used. Also, a fan is used to cool the nozzle against overheating. The front view of the extruder in the designed 3D printer is shown in Figure 6. In the designed 3D printer, the fixing of the heating table is carried out as in the Prusa model construction and the fixing mechanism is presented in Figure 7. The heating plate moves in the z direction. As shown in Figure 7, the heating plate is fixed to the bearings by means of bolts in

accordance with the design specifications of the plate fastener. The heat value of the heating plate is controlled by the electronic processor card. In addition, the designed system also has a card holder for the mounting of electronic cards.



Figure 6. Front view of the extruder in the designed 3D printer



Figure 7. The view of heating table and heater table fixing

3. ADAPTIVE PID ALGORITHM FOR 3D PRINTER

It is very important to control the speeds of the x , y and extruder axes as well as the speed of the printer so that an object can be produced in good shape with the 3D printer. The MakerBot-endorsed open-source firmware for the Replicator I, Cupcake, and Thing-O-Matic printers includes default acceleration and speed change settings. The Marlin firmware, which is used on a variety of printer designs, also specifies defaults. Acceleration specified by Sailfish is 1000 mm/sec^2 , while Marlin uses a much higher 3000 mm/sec^2 . Sailfish's speed change default is 15 mm/sec and Marlin's is about the same at 20 mm/sec . Generally, these parameters are tuned by manufacturers or users to minimize print time and avoid skipped steps while maintaining smooth extrusion and finished part surface quality. Because the motors are run open-loop, any steps skipped are undetectable and

therefore unrecoverable, resulting in the entire print shifting in the x or y direction from that layer onwards [16].

Many industrial process are controlled using PID controllers. PID controller is used to solve a wide range of problems such as process control, motor drives, magnetic and optical memory, automotive, flight control and instrumentation. The controller consist of many different forms, as standard single-loop controllers, as a software component in programmable logic controllers and distributed control systems, as a built in controller in robots and CD players [17]. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity which allows engineers to operate them in a simple and straightforward manner. To implement such a controller, three parameters must be determined for the given process: proportional gain, integral gain, and derivative gain [18]. The PID controller provides a proportional term, an integration term and a derivative term. The continuous form of a PID controller, with input $e(\cdot)$ and output $u(\cdot)$ is generally given as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{d}{dt} e(t) \quad (1)$$

where K_p is the proportional gain, K_i is the integral gain, and K_d is the derivative gain.

The adaptive and learning control technique is one of promising control methods to overcome the difficulties in such an unknown or uncertain operating condition [19]. Nowadays 3D printers are usually controlled by the classical PID or open loop control method. The adaptive PID learning controller proposed in this study consists of PID feedback input component and feedforward learning input component control inputs. Unlike other studies, the 5 step motors used in the 3D printer designed in this study are controlled by the adaptive PID algorithm in software. In addition, the nozzle and heater plate temperatures are controlled by the same algorithm.

The learning rule for adaptive PID applied to the designed 3D printer

$$K(t) = pr [K(t-T)] + \Lambda_1 xy(t) \quad (2)$$

$$v_i(t) = pr [v_i(t-T)] + \Lambda_2 y(t) \quad (3)$$

where $pr[\cdot]$ is a projection into a bounded set, Λ_1 and Λ_2 are the learning gains of positive diagonal matrix and positive constant.

The control objective of designed 3D printer is to find the suitable control variables so that the system tracks desired load angular position and velocity with accepted errors while keeping the states and control variables bounded too. There are many internal and external uncertainties that may affect the performance of the controlled system. These uncertainties are the stiffness of

the flexible shaft, the inertia of the rotor [20]. The adaptive control is used to tune the parameters of the PID controller online. This is achieved by scheduling the gains of the PID control based on system performance indices as shown in Figure 8. In Figure 8, \square_{\square} and \square_{\square} denote the controller's output signal, \square_{\square} and \square_{\square} are the reference angular speed and angular displacement, respectively. The control closed loop outputs are the actual angular displacement and speed (\square, \square). In this study, two motors used for z axis control, two motors used for x and y axes control and one motor used for driving the filament are controlled by adaptive PID algorithm. In the system software, 3D Printing Software Pipeline is applied as shown Figure 9. The control algorithms for extruder and step motors are prepared as separate function files in software implemented in C.

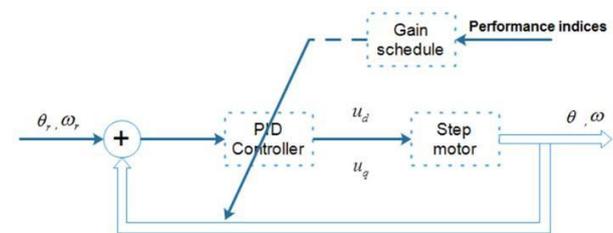


Figure 8. Block diagram of adaptive PID controller

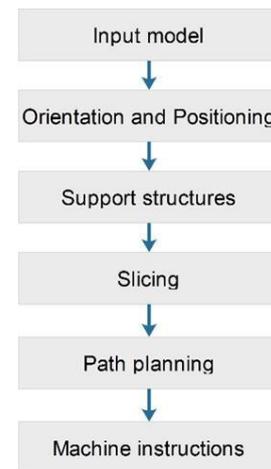


Figure 9. 3D printing software pipeline

4. EXPERIMENTAL STUDIES AND DISCUSSION

The coordinate information obtained from the G code of the object drawn in the CAD environment is prepared to be applied to the adaptive PID controller for driving the motors as binary values. Also, in the designed 3D printer, the table temperature is one of the factors affecting the print quality and the adhesion to the table. In this study, the temperature of the 3D printer table is set at 70 °C. Its control is also provided by the adaptive PID controller. The objects printed with classical PID and adaptive PID at 100 mm/sec are presented in Figure 10 and Figure 11, respectively.

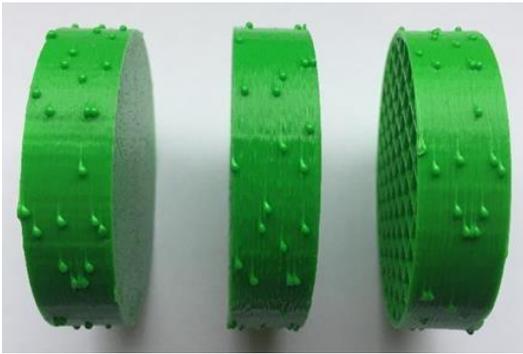


Figure 10. The objects printed with PID control at 100 mm/sec



Figure 11. The objects printed with adaptive PID control at 100 mm/sec

The designed 3D printer is operated at 100 mm/sec and the surface areas of the objects printed with classical PID and adaptive PID are compared. It has been observed that the surface area of objects printed with the adaptive PID control have a marked improvement compared to the surface area of the objects printed with the classical PID control. The printing of the objects was completed in 14 minutes with a nozzle of 0.4mm and a filling of 60%. Note that classical PID object has been prepared as same time as adaptive PID. The PID coefficients for the designed 3D printer were given in Table 1.

The Pearson Correlation method is used to determine the amount of surface deformation of objects printed with conventional PID and Adaptive PID. The *R* provides a measure of level of the linear relationship between the desired and the measured values. The *R* value is an indication of the relationship between the outputs and targets. If *R* = 1, this indicates that there is an exact linear relationship between outputs and targets. If *R* is close to zero, then there is no linear relationship between outputs and targets. The *R* is obtained by [21]:

$$R = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (4)$$

where \bar{x} and \bar{y} are the averaged desired values and measured values, respectively.

It is obtained that the surface deformation of objects printed with the adaptive PID is 1.501% while the surface deformation of the objects printed with the classical PID is 28.013%. The circular selection of the geometry of the object to be printed in this study is rapid change in the surface coordinates relative to the linear geometric shape.

Table 1. PID coefficients of designed 3D printer

	<i>Kp</i>	<i>Ki</i>	<i>Kd</i>
Case 1	4	5	0.14
Case 2	10	0.293	1
Case 3	3	0.521	0.821

5. CONCLUSION

The designed for cartesian construction the 3D printer was controlled with classical PID and adaptive PID. The position of the 5 step motors used in the 3D printer, the temperature of heating table and nozzle were controlled by the both classical PID and adaptive PID. The circular geometric shapes were printed with both controller methods and surface defects of shapes were investigated. It was obtained that the surface deformation of objects printed with the adaptive PID was 1.5% while the surface deformation of the objects printed with the classical PID was 28%. In the system software, 3D Printing Software Pipeline (input model, orientation and positioning, support structures, slicing, path planning, machine instructions) was applied. The control algorithms for extruder and step motors were prepared as separate function files in software implemented in C. It has been observed that the designed software is particularly successful in eliminating errors on the surface of the products.

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