https://doi.org/10.2352/ISSN.2169-4451.2018.34.176

Development of a Closed-loop Control System for the Movements of the Extruder and Platform of a FDM 3D Printing System

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Abstract

Most 3D printing systems work with control systems that can be considered open-loop, having little or no feedback to ensure appropriate movements or material output. With open-loop control, 3D printing systems (low-end printers more significantly) are susceptible to factors that cannot be measured or corrected and result in errors during the printing process. Failures in mechanical fittings, jams on the movement system, loss of steps in step motors and external perturbations are some common situations during the printing process and can cause displacement of layers, that ultimately means, producing defective pieces. To achieve closed-loop control in 3D printing systems, the work reported addresses closing the loop on the positioning of the nozzle and building platform. This is performed using an independent microcontroller to read the signals sent from the printer controller board (RAMPS 1.4), which correspond to the desired positions and compares it with the signals coming from three linear optical encoders located in the x, y and z axes of the 3D printer, providing the current relative position of the head and the printing platform. The comparison generates a control action to reduce the error, following the target trajectory. A continuous monitoring of the movements throughout the printing process, ensures a more accurate positioning against possible disturbances, which means a significant saving of time, material and money. This work is applied to an FDM 3D printer but can be extended to other printing techniques or CNC machines improving both the machines and the fabricated pieces.

Introduction

Additive manufacturing, rapid prototyping or 3D printing is a revolutionary technology that has been around for more than 30 years. It began in 1984 with the invention of stereolithography, which allowed creating tangible 3D objects from digital information. The viable commercialization of this technology, the development of higher performance computers and more recently open source developments, have promoted research and growth in this area [1].

The objects created through additive manufacturing are first three-dimensional models designed in a CAD software, then processed and sliced into several two-dimensional layers stacked on top of each other, these layers are then printed in the same manner forming the three-dimensional object [2].

Currently there are several challenges for 3D printing, such as repeatability in manufacturing processes and autonomous abilities understanding it as the independence from human supervision [3].

During the printing process, the relative movements between the nozzle and the building platform allow the material to be deposited forming layers and ultimately the part. Due to low cost, most of the 3D printers use stepper motors to perform the translational movements of the print head or the building platform. The printer relies on these actuators to be reliable and achieve accurate positioning working in open-loop; however, there are some factors that can affect the movements during printing:

- Failures in mechanical fittings (pulleys that do not engage correctly, backlash).
- Jams on the movement system.
- Poorly adjusted voltage and current.
- Wrong motor choice due to insufficient torque.
- Loss of steps in the step motors.
- External perturbations.

With open-loop control the system cannot detect or correct those deviations from the desired trajectories producing displacement of layers, bumps, holes and ultimately defective pieces, loss of money, time and material [4].

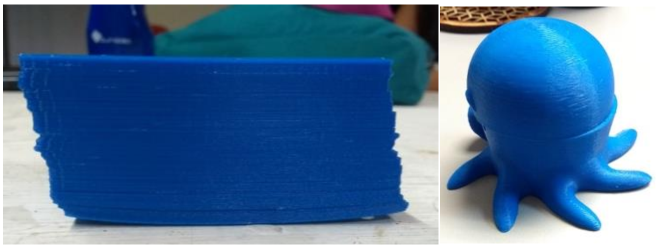

Figure 1 *Displacement of layers in the printing process*

To achieve the closed loop in 3D printing systems, three different approaches have been proposed, which are 1. material output supervision, 2. feedback of the system actuators, and 3. supervision of the printed part throughout the printing process [5].

The first step to close the control loop was developed in Development of a Supervision System: Towards Closing the Control Loop in 3D Printing Systems [6]. This work follows that initiative with the development of the second strategy through the design and implementation of a closed-loop control system for the movements of the nozzle and building platform of a 3D printing system. This work, aims to have continuous monitoring of the movements throughout the printing process, ensuring the accurate positioning of the aforementioned elements against possible disturbances and improving the reliability of the machine and the characteristics of the printed pieces (e.g. surface finish, dimensions, mechanical performance, etc.).

Development of the Control System

The development started by examining the functional decomposition of the printing process, including the position control system (Figure 2), in order to identify the critical sub-functions of the process within the whole system. The project has focused on three sub-functions: detecting current position, the acquiring the desired position, and the control process, which are explained in detail in the following sections.

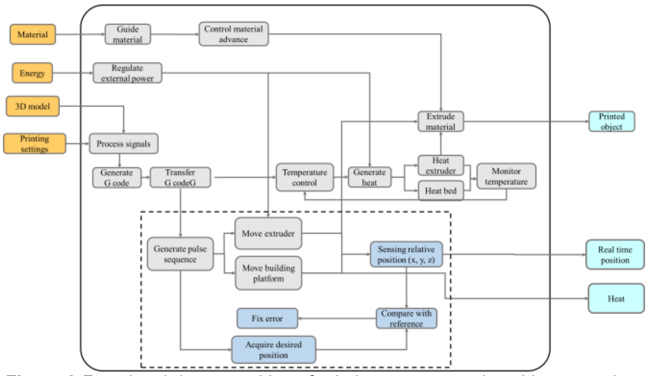

Figure 2 *Functional decomposition of printing process and position control*

Detecting Current position

Sensor selection

Looking to directly capture the position of the extrusion head along the x and y-axes, and the movement of the printing platform along the z-axis, it is decided to use linear sensors because these allow direct measurement of the relative position of the head and the platform despite external disturbances, mechanical failures, loss of steps, etc.

Linear optical encoders were selected, because of its high resolutions and speeds, they are not heated by the friction of the movement, and they are not sensitive to magnetic interference (notable concern when using step motors) [7]. The WTB 500 encoder was selected, it has two quadrature output and a resolution signal of 5um, besides it has an aluminium alloy structure and rubber lips that protect the optical glass and the sensor with its electronics.

Reading of the signals

Incremental or quadrature encoders have two outputs, channels A (blue) and B (yellow), as seen in Figure 3, are 90° out of phase from each other. The output is generated as a sequence of pulses, and by monitoring both the number of pulses and the relative phase of signals A and B, position and direction of the movement can be traced. Encoder resolution improves significantly according to which edges of which channel are counted during movement. [8].

The output sequence is presented with highs and lows that are repeated continuously, and it is represented in Gray code of two bits, which can be translated into a sequence depending on the direction of movement, as seen in the Figure 4. Thereby, this sequence can be encoded to compare the previous state with the current one of the encoder in order to identify if no change is generated, if there is a negative or positive movement sequence, or a change not allowed in the sequence due to an abrupt change in the output.

The reading of this sequence and the coding are done by activating the interruptions of the microcontroller by an upward or downward change in flanks of the pulses of channels A and B, which allows quadruple the amount of registered pulses, obtaining the maximum encoder resolution of 0.005mm.

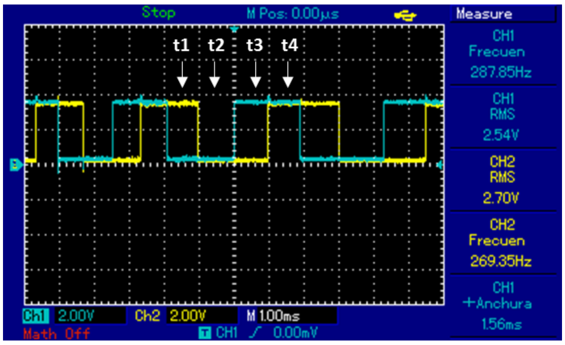

Figure 3 *Encoder output channel A and B 90° out of phase*

	Positive movement				Negative movement		
	A	B	Dec		A	B	Dec
t1	0	1	1	t1	1	0	2
t2	0	0	0	t2	0	0	0
t3	1	0	2	t3	0	1	1
t4	1	1	3	t4	1	1	3

Figure 4 *Channel A and B encoder movement sequence*

Sensors integration to the printer

Linear encoders were located on the x , y and z-axes, in such a way that the body remains in a fixed position, and that the movement of the head and the printing platform are transmitted to the mobile part of each encoder. For this adaptation, the structure and current components of the printer were used (UAO 3DP – an in-house development [9]) as well as the acquired sensors and other designed and printed parts were added to mount the sensors (See Figure 5).

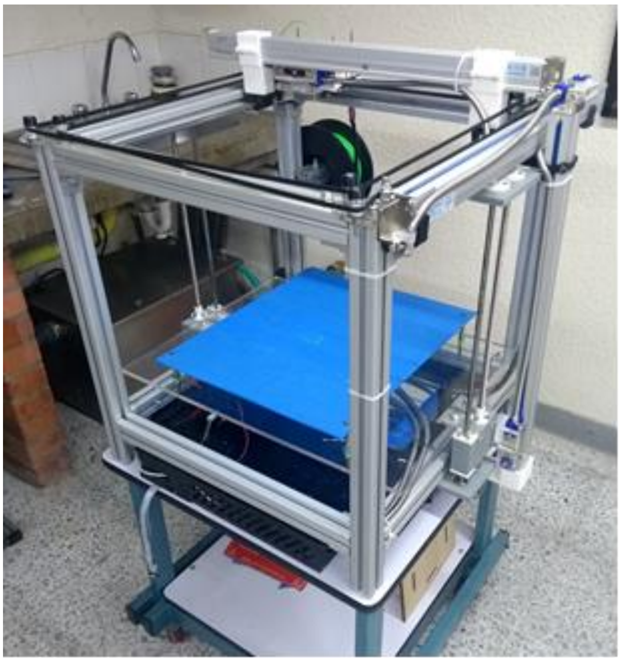

Figure 5 *3D system printer with position sensors*

Acquisition of Desired position

The RAMPS 1.4 is an additional board to the printer controller (Arduino Mega), which translates digital orders into orders sent to the drivers that control the stepper motors. The board allows locating three motors for the movement in the x, y and z axes. In addition, the board configures the drivers with micro steps to increase by a factor of 16 the original resolution of the motors, so instead of rotating 200 steps/revolution (1.8°), can rotate 3200 usteps/revolution (0.1125°). From this analysis, it is obtained that encoder resolution (8000 pulses/rev), is enough to detect the minimum movement that the printer can perform (3200 pulses/rev).

According to the belt pitch, pulley tooth and the power screw of the UAO 3DP, it's firmware is configured with a resolution of 80 steps/mm for the x and y-axes, and 252 steps/mm for the z-axis. This means that drivers send 80 or 252 micro pulses in the corresponding direction to move 1 millimeter in the corresponding axis.

Figure 6 shows pulses sent from the Arduino main controller, each pulse of the STEP signal (yellow) is a micro step for the motor, and DIR (blue) signal indicates the advance direction. Signals were captured generating movements by the Repetier Host manual control at different speeds: 25%, 150% and 300% of the default printer speed (1000 mm/min). The frequency of the pulses is recorded and also calculated taking into account the resolution established from the printer firmware (See Table 1).

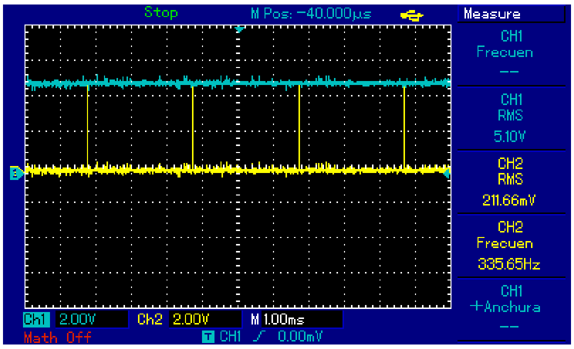

Figure 6 *STEP and DIR signals from RAMPS 1.4*

Table 1 Frequency of sending signals from RAMPS 1.4

Speed (mm/min)	Speed (mm/s)	Calculated frequency (Hz)	Measured frequency (Hz)
250	4.17	333.33	335.65
1500	25	2000	2.01k
3000	50	4000	4.03k

To acquire the current position, an additional board to the RAMPS was made, this circuit acts as a bridge between the main controller and the motor drivers. It connects signals from the RAMPS to the drivers, isolating the control signals STEP and DIR, and the pins that connect to the motor coils of the three drivers [10], in order to avoid sending control signals directly to the motor drivers, but rather are sent first to the Arduino microcontroller, which processes them, correct if necessary, and send the sequence to the motor drivers.

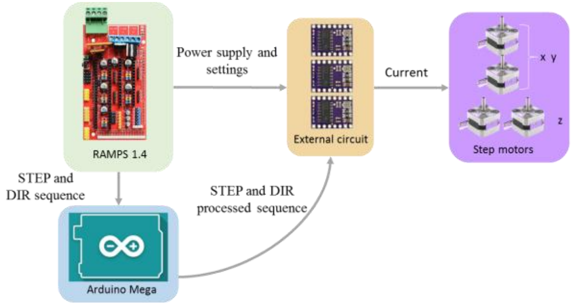

Figure 7 *General scheme for the signals acquisition from main controller board*

Figure 8 *Signal acquisition circuit*

Pulses of each controller coming from main controller are read using interrupts of the Arduino microcontroller activated by the falling edge of the STEP pin, in each routine the number of steps sent and their direction are counted.

Given the CoreXY configuration of the UAO 3DP, it has two motors that allow the movements in the x and y-axes. Looking to validate the functioning of a CoreXY system [11], movement tests on the x y y-axis are performed using Repetier Host manual control in order to send random coordinates (Table 3, columns 1 and 2), from this movements the pulses counted are stored.

The acquired pulse counter (Table 3, columns 3 and 4) increases or decreases according to the different movements, from this counter it is possible to know the number of pulses necessary to perform the movement at each change of coordinates (Table 3, columns 5 and 6). After saving the pulses, the CoreXY functions are modified to identify that que equations that describes the printing system are given by:

$$D1=(\Delta X-\Delta Y)*Fr \quad (1)$$

$$D2=(-\Delta X-\Delta Y)*Fr \quad (2)$$

$$PosX=(D1-D2)/2Fr \quad (3)$$

$$PosY=(-D1-D2)/2Fr \quad (4)$$

$$Fr= (Microstep * Motor (step/rev)) / (Belt pitch *Tooth count)$$

$$Fr= (16*2000)/(5*8) \quad (5)$$

D1: Driver 1 pulses, D2: Driver 2 pulses, Fr: Resolution factor.

With these equations, the expected pulses are calculated (Table 3, columns 7 and 8) using the resolution factor of 80 steps/mm, as established in the Firmware (Repetier). From the acquired pulses, the x and y coordinates are calculated (Table 3, columns 9 and 10) in order to compare them with the position established from the manual control.

It is important to ensure that the acquisition of the pulses is correct because these correspond to the desired input of the position control system. However, there is a difference between the acquired and expected pulses, resulting in differences between the calculated coordinates and those established from the manual control.

For this reason, pulses were analyzed with the oscilloscope to determine actual frequencies and compare it to the calculated (as seen in Table 1). The frequency measured is close but not equal to the calculated one, thereby, the resolution is calculated, and an average value of 80.5 steps/mm is obtained (as seen in Table 2). Despite of the fact that sending the command to move 1mm effectively receives 80 pulses, as larger movements are sent, the pulses accumulate, and slightly larger values are obtained, e.g. when sending a movement of 10mm, 805 pulses were obtained instead of 800 pulses.

Table 2 Resolution of movements verification

Speed (mm/min)	Speed (mm/s)	Calculated frequency (Hz)	Calculated resolution (steps/mm)
250	4.17	335.65	80.556
1500	25	2.01k	80.4
3000	50	4.03k	80.6

By modifying the resolution factor to 80.5 steps/mm (Table 3, columns 11 and 12), the calculated values correspond to those sent from the manual control and the RAMPS controller, which ensures that the input to the control process is actually that established from the g-code.

The movement in the z-axis does not follow the same equations, it depends on the pitch of the power screw used and the rotational movement of the motor; therefore, the desired position is calculated directly with the resolution factor of 252 steps/mm.

PosZ= D3/Frz (6)

Frz= (Microstep * Motor (step/rev)) / Leadscrew (rev/mm) (7)

Control System

The control strategy is shown in Figure 9. Once the pulses from the encoders are received, these are translated into position form in mm, and using the equations 1 and 2, the positions x and y are used to translate the position of the extruder into a number of pulses from drivers 1 and 2.

The desired pulses are compared with the pulses obtained, and an error is calculated. If the error in each driver is within a set range (tolerance), the sending of the pulse sequence is continued to keep the printing process going without any intervention.

Otherwise, if the error is out of bounds, it identifies whether the error is positive or negative to generate a sequence of pulses to move the motor in the opposite direction and correct the error.

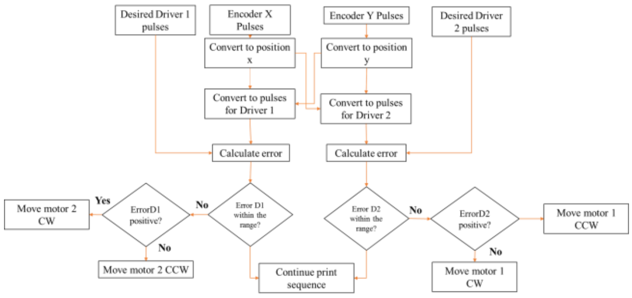

***Figure 9** Flowchart of the error correction sequence*

Table 3 Pulses registered for several movement trials

Manual Position		Pulses Acquisition				Desired Pulses Fr = 80 steps/mm		Calculated Position Fr= 80 steps/mm		Desired Pulses Fr = 80.5 steps/mm		Calculated Position Fr= 80.5 steps/mm	
X	Y	Pulses counter		Pulses by movement				X	Y			X	Y
0	0	D1	D2	D1	D2	D1= Fr(x-y)	D2= Fr(-x-y)	0	0	D1= Fr(x-y)	D2= Fr(-x-y)	0	0
10	0	805	-805	805	-805	800	-800	10,063	0	805	-805	10	0
4	6	-161	-805	-966	0	-960	0	4,025	6,04	-966	0	4	6
4	10	-483	-1127	-322	-322	-320	-320	4,025	10,06	-322	-322	4	10
8	14	-483	-1771	0	-644	0	-640	8,05	14,09	0	-644	8	14

Validation Tests

To validate the control strategy some tests were done printing ten layers of a simple geometry (square, 30mm side) at different speeds in open and closed loop.

Manual Validation

For the test, the external perturbations consisted in a manual push to the extruder head while printing and manual fastening of belts, forcing the system to fail. Tests were performed using different ranges of permissible error, those were: Without error, 5 and 10 pulses error (1 error pulse is equal to 0.0125 mm).

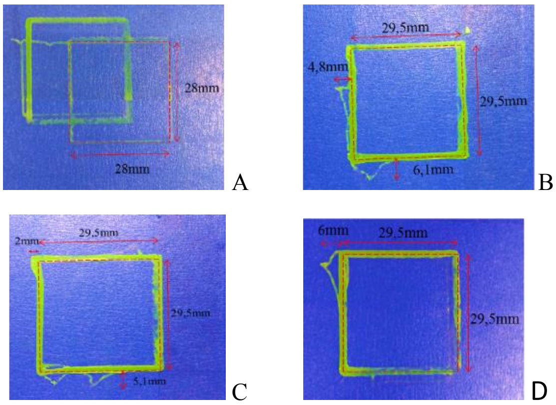

***Figure 10** A: Open-loop printing; B: Closed-loop printing without permissible error; C: Closed-loop printing within permissible 5 pulses range; D: Closed-loop printing within permissible 10 pulses range.*

The disturbances are introduced in the first layers of the printing process to leave the trace of material on the platform and visualize the path travelled during the position correction. As seen in Figure 10-A, when printing is performed with open-loop, the printed geometry dimension differs from the desired geometry by 2mm, in addition, when the disturbance is applied the system continues printing in an incorrect position of the platform, which means that a disturbance can generate a significant defect on the printed part.

Figures 10-B, C, and D show the results of printing when implementing the closed-loop control; the control decreases the difference between the printed and desired measurement to 0.5mm, and also for the three cases, the irregular trajectories deviate from the desired trajectory and then return to it, showing that the system rejected the disturbances.

The lower the error range, the system generates more oscillations. As seen in Figure 10, B and C (without error and error tolerance of ± 0.0625 mm), the control action corrects the position, generating oscillations observed on the left edge of the square. In the last test (Figure 10, D) an greater error of ± 0.125 mm is allowed, in the left edge the oscillations are reduced further, and the trajectory of a straight line is followed more closely. In this last test, the maximum measured deviation was 6.1 mm.

Quantitative Validation

A repeatable standard test is designed to determine a measure of maximum deviation and error of the closed loop printing system. For this, as seen in Figure 11, a disturbance is applied using a spring of constant of 107.11 N/m, which generates a force that increases from 11.546N to 14.802N and is applied opposite to the positive movement of the x-axis of the extruder during the printing of the square geometry.

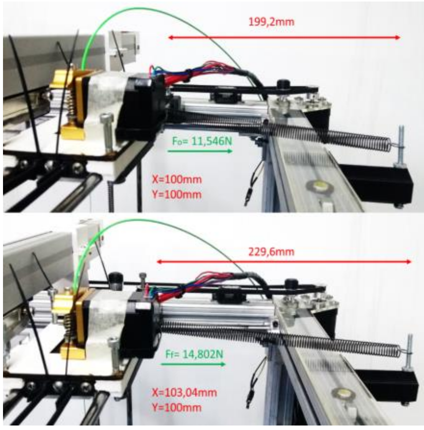

***Figure 11** Validation test design*

The desired position (blue trajectories) from the controller, and the current position (red trajectories) from the motion sensors are stored and compared in open and closed loop, as seen in Figure 12. For each of the tests carried out, the maximum deviation in mm in the trajectory of each of the edges of the printed square is determined, and finally, an average per trajectory is determined, taking into account the magnitude of the deviations (Table 4).

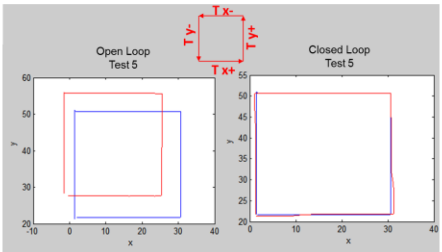

***Figure 12** Desired and measured trajectory comparison in open and closed loop*

Table 4 Maximum deviation by trajectory (T) in open and closed loop validation test

		Tx+	Ty+	T x-	T y-
Open Loop	Test1	2,23	-2,35	1,11	1,03
	Test2	2,93	-2,44	2,11	0,04
	Test3	3,92	-3,29	3,12	-1,56
	Test4	5,05	-4,4	4,07	-2,02
	Test5	5,85	-5,32	4,47	2,98
	Test6	5,44	-4,11	4,07	-2,02
	Average	**3,26**	**3,65**	**3,15**	**1,6**
Closed Loop	Test1	0,1	0,41	0,16	-0,2
	Test2	-0,24	0,64	0,1	-0,13
	Test3	-0,17	0,39	0,1	-0,08
	Test4	-0,11	0,48	0,08	-0,32
	Test5	-0,44	0,61	0,08	-0,32
	Test6	-0,41	0,47	0,12	-0,26
	Average	**0,245**	**0,5**	**0,107**	**0,183**

Due to the Core XY configuration of the printer, the movement on any of the two axes depends on both motors, therefore, in open loop the maximum deviation is 3.65mm and the disturbance affects all the axes. While in closed loop pulses correction is performed independently for each driver, this is why the disturbance mainly affects the positive trajectory of the y-axis with a 0.5mm maximum deviation.

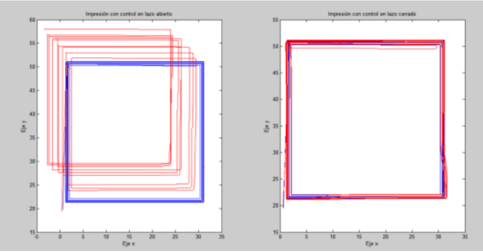

Figure 13 *Full print in open loop and closed loop*

In contrast to the movement of the extruder, movement of the printing platform along z-axis is generated by signals of a single driver that are sent to two stepper motors in parallel. In addition, during printing process the platform only moves in one direction when there is a change in layers, and for its movement power screws were used instead of belts and pulleys. For these reasons, external disturbances are less likely to affect its movement; therefore, the test was performed and the data was captured in open loop and closed loop without applying a disturbance.

Finally, Mean Absolute Error (MAE) was used to determine the average of the magnitude of the error between the values measured by the sensors and those calculated from the main controller of the printer.

$$MAE = \frac{1}{n}\sum_{j=1}^{n}|y_j - \hat{y}_j| \qquad (8)$$

With the coordinate points obtained during the designed test, the independent error is estimated for each axis. Following the logic obtained in the analysis of the maximum deviation per trajectory in a layer, in Table 5 is shown that in the full printing, the error value estimated in open loop is significantly higher than in closed loop in all the axes, mainly in the y-axis.

Table 5 MAE in trajectories of full print

	Open Loop			Closed Loop		
	X	**Y**	**Z**	**X**	**Y**	**Z**
MAE	3,75	5,28	2,17	0,14	0,11	0,04

Conclusions

The work reported illustrates the research and results achieved after the implementation of the closed loop control in a FDM 3D printing system. The system is able to monitor the desired and current relative position of the head and the construction platform during the printing, ensures its correct positioning against possible disturbances and corrects the deviation of the trajectory, which is reflected in the maximum deviation of 0.5mm obtained in the designed test, and in the estimated error.

One of the challenges in the project was incorporating the sensors to the existing 3D printer. Several ways to locate sensors in each axle were tested in order to reduce backlash in mechanical components.

The control system can be applied to other printing techniques (excluding light processing technology - DLP) and CNC machines, which have 3-axis positioning systems.

Moreover, the integration with other techniques to fully close the control loop on the 3D printing process is envisioned to achieve much more reliable systems and 3D printed parts with better performance.

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Manuela F. Cerón Viveros is a mechatronic engineering student and also a student member of the research group in technology for manufacture (GITEM) at Universidad Autónoma de Occidente. She is working in the development of a closed-loop control system for movements of the Extruder and Platform of a FDM 3D Printing System. Throughout her university studies she has developed research projects in her areas of interest related to additive manufacturing, 3D bioprinting, classic and intelligent control, robotics and artificial neural networks.