Systematic Evaluation of Classical and Adaptive Control Strategies for Gantry Positioning Reliability in FDM Additive Manufacturing

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Abstract

This study presents a comparative analysis of four control strategies—open-loop, bang-bang, PID, and adaptive model-reference control—for improving XY gantry positioning in Fused Deposition Modeling (FDM). A lumped-parameter model of a belt-driven Cartesian gantry was developed using vendor data, capturing motor limits, belt compliance, and dry friction. Each controller was implemented in MATLAB/Simulink and evaluated under identical conditions to assess rise time, damping, steady-state error, and robustness to ±10% model uncertainty. Results reveal open-loop systems with the highest tracking accuracy, while bang-bang control introduces limit cycles. PID control, when tuned, eliminates steady-state error with moderate robustness. Adaptive control delivers consistent performance under uncertainty, albeit with slower response due to real-time adaptation. This work offers simulation-based insights to guide upgrades of consumer-grade FDM platforms, highlighting the reliability benefits of closed-loop and adaptive control. Future work will transition to hardware validation to quantify impacts on print quality and dimensional accuracy.

Keywords: Additive Manufacturing, 3D printing, Fused Deposition Modeling, Motion control, Gantry

1. Introduction

Control Theory, adapted from Applied Mathematics, uses feedback elements to influence the outcome of a system. In Control Engineering, there are two types of control systems: open-loop and closed-loop control systems. Open loop control systems have input and output signals, but there is no provision for feedback. Systems with highly predictable outputs and little disturbance can be run in an open loop with minimal error. On the other hand, a feedback element, such as a sensor, is incorporated into a closed-loop control system to detect errors in the expected output and minimize them to near zero. The desired behavior is known as the reference signal. Control problems that the reference changes with time are called tracking problems [1, 2].

In commercial Fused Deposition Modeling (FDM) 3D printing systems, especially the filament-based type (Fused Filament Fabrication, or FFF), stepper motors are used to control the positioning of the printhead and the extrusion rate because of their high open-loop control accuracy. though highly accurate at low speeds, the actual values deviate as speeds increase because of extruder slippage, skips in motor steps, and tension in the drive system of the motors at the axes [3-6]. Temperature control in commercial printers is achieved by PID closed loop control due to high instability and slow response time. The actual temperature at the nozzle exit is lower than the set temperature due to the distance of the nozzle from the heater and temperature sensor. This is because part of the heat generated at the liquefier is dissipated before it is conducted to the tip of the nozzle [7].

The literature is replete with works aimed at improving the deposition process by optimizing process parameters such as nozzle and bed temperature, printing speed and layer thickness to maximize the quality of 3D prints [4, 5, 8-12]. Very few research works have considered the application of controls in FDM and its role in improvement of FDM printing performance. A review on control strategies implemented in FDM by Martini, et al. [6] was qualitative, and focused on strategies for extrusion control without analytical backing. A few other articles, such as Moretti and Rossi [3], Guidetti, et al. [13], Ralchev, et al. [14] and a few others [15-18] have implemented closed loop control on specific process variables, such as feed rate and extrusion temperature, with an interest in PID or adaptive controls. To the authors' knowledge, no research has been done to compare different control strategies on subsystems in the FDM machine.

This work aims to demonstrate the effect of choice of control strategies in an FDM gantry system. This was achieved by comparing the accuracy and response times of different control strategies on the X-Y positioning subsystem. This will inform the implementation of effective feedback controllers for the process parameters. A mathematical model of the FDM gantry system was developed, and different control strategies were implemented on the model (open loop, on/off control, PID, Adaptive control). The performance of each model was evaluated in terms of their impulse and step response times, accuracy, and overshoot.

2. Methodology

An understanding of the behavior of the various subsystems in an FFF machine is particularly important and therefore should be accounted for during system design and process control. This will enable efficient control of the various variables to ensure optimal quality and high throughput. Due to this, a simulation-based study on the control of the belt drive used in positioning systems for FFF 3D printers was carried out. A belt drive model was developed based on the SOVOL SV01 printer's XY drive system, and four control strategies were implemented to enable precise tracking of the XY position.

2.1 Belt Drive Model

Because belt drives are commonly used for XY positioning of the FFF machine, a lumped parameter model of the belt drive was developed using Simscape (MathWorks Inc). A system diagram of the belt drive is shown in Figure 1 where:

θ_1 is the angular position of the motor pulley.

θ_2 is the angular position of the second pulley.

x is the linear position of the load (build plate or printhead, depending on the axis).

l is the center distance of the two pulleys; and

all states (x, θ_1 and θ_2) are all shown in the figure in their zero positions.

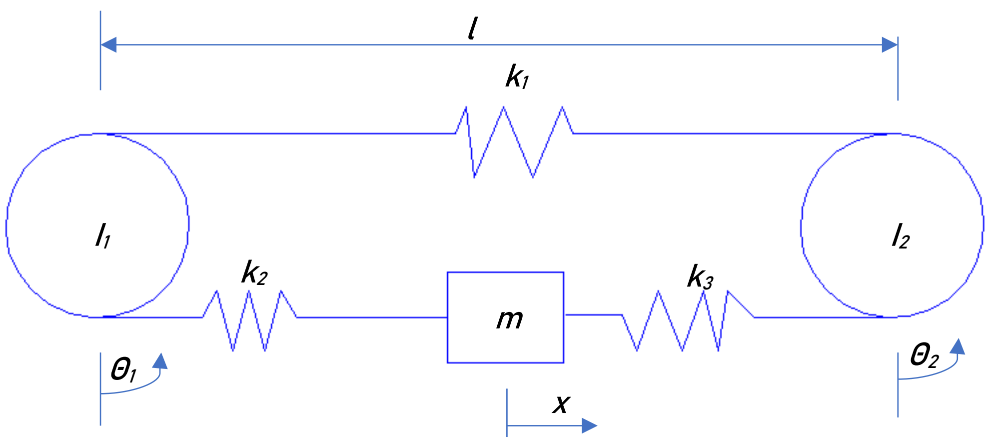

Figure 1. System Diagram for belt drive commonly used in 3D printers.

The model is based on the following assumptions:

1. The belt does not slip.
2. The masses of the springs are negligible.
3. The belts have the same stiffness in tension and compression.
4. Friction on the pulleys is negligible, but rolling friction on the printhead is not.

The total Potential energy in the three springs is:

$$PE = \frac{1}{2}\{k_1 r^2(\theta_1 - \theta_2)^2 + k_2(r\theta_1 - x)^2 + k_3(r\theta_2 - x)^2\}$$

The total Kinetic energy in the inertial elements is:

$$KE = \frac{1}{2}\{m\dot{x}^2 + I_1\dot{\theta}_1^2 + I_2\dot{\theta}_2^2\}$$

The nonconservative force in the system is due to Coulomb Damping in the mass:

$$F_{friction} = \mu mg.sign(\dot{x})$$

Based on Lagrangian Dynamics, the Lagrangian is calculated using the equation:

$$L = KE - PE$$

And taking x, θ_1 and θ_2 to be the states of the system, then for each state,

$$\frac{d}{dt}.\frac{\partial L}{\partial \dot{x}_i} - \frac{\partial L}{\partial x_i} = F_{x_i}$$

Where x_i is the ith state, and F_{xi} is the nonconservative force (or torque) in the ith direction.

Taking θ_1 to be the input (x_{in}/r), the Lagrangian can be computed for the three state variables to yield the matrix equation:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & m \end{bmatrix} \begin{pmatrix} 0 \\ \ddot{\theta}_2 \\ \ddot{x} \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ \mu mg.sign(\dot{x}) \end{pmatrix} + \begin{bmatrix} 0 & -k_1r^2 & -k_2r \\ 0 & (k_1+k_3)r^2 & -k_3r \\ 0 & -k_3r & k_2+k_3 \end{bmatrix} \begin{pmatrix} 0 \\ \theta_2 \\ x \end{pmatrix} = \begin{pmatrix} -I_1 \\ 0 \\ 0 \end{pmatrix} \ddot{\theta}_1 + \begin{pmatrix} -(k_1+k_2)r^2 \\ k_1r^2 \\ k_2r \end{pmatrix} \theta_1$$

The Simscape model for the belt drive is shown in Figure 2. The belt is modeled as three springs connected to two pulleys. The load could be the build plate or hot end, depending on whether the belt drive is for the X or Y axis.

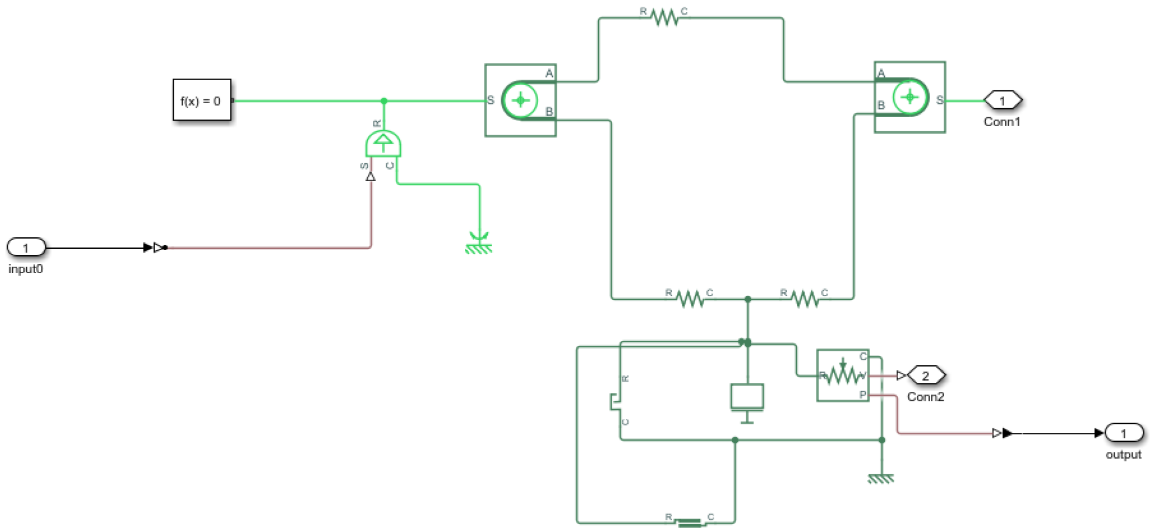

Figure 2. A Simscape Model of the belt drive system.

In a real system, the belt has nonlinearities whose differences need to be considered:

1. Due to the slenderness of the belt, it is strong in tension and weak in compression. Which means that the stiffness of any section of the belt can be taken as zero when that section is in compression:

$$k_i = \begin{cases} 0, in\ compression \\ \frac{AE}{l_i}, in\ tension \end{cases} \quad for\ the\ ith\ section\ of\ the\ belt$$

2. The stiffness of a bar is inversely proportional to its length. This means that for springs k_2 and k_3, their stiffness will change depending on the x-position:

$$l_i = \begin{cases} l, for\ k_1 \\ \frac{l}{2} + x, for\ k_2 \\ \frac{l}{2} - x, for\ k_3 \end{cases}$$

To determine whether these nonlinearities are significant, the state space model for the system was linearized at x=0, and its response to a positive going ramp was computed. Also, the values of k in the model were modified to account for nonlinearities, and the response was recomputed for comparison.

The material properties and geometrical dimensions used in the analysis is shown in Table 1. The measured values are based on the SOVOL SV-01 FFF printer.

Table 1. Material properties and Geometrical Dimensions used in the Belt Drive Analysis

Parameter	Value	Source
Pulley Diameter, *2r*	18 mm	Measured
Center Distance	45 mm	Measured
Elastic modulus (for polyester-reinforced timing belts)	13.7895 GPa	[19]
Load mass, *m*	1 kg	Assumed
Belt cross-sectional area	5.5×7 mm^2	Measured
Coefficient of static rolling friction, μ	0.001	Assumed
Coefficient of Dynamic rolling friction	0.003	Assumed
Inertia for the two pulleys, I_1 and I_2	0.001 m^4	Assumed

2.2 Control implementation

Four control strategies were implemented using a reference position of 100 mm with 66.7mm/s ($\frac{200}{3}\ mm/s$):

1. Open-loop control: Taking the input position to be directly proportional to the motor angle (with a gain of 1/r), the position was set by setting the motor angle.
2. On/off control: Two reference signals (+ 0.5 m/s and -0.5 m/s) were used in correcting the position, depending on whether the input was greater or less than the output speed, respectively.
3. PID control: the PID tuner application in MATLAB was used to linearize the system at x=0 and tune the PID parameters. These parameters were then used to set the actuating signal. The PID gains set by the tuner were:
   P = 19.307, I = 1.297, D = 15.403.
4. Model Reference Adaptive Control (MRAC): Using the reference model below,
   $$\dot{x}(t) = -x(t) + x_{in}(t)$$
   A direct MRAC model was developed to control the position, using the state as the disturbance model.

The system response to these control strategies were computed using Simscape in Simulink (MathWorks Inc.), and the following information was computed for each control strategy:

1. Percentage overshoot
2. Steady state error
3. Rise time
4. Settling time

3. Results

3.1 Significance of Nonlinearities

The response of the system and its linear approximation is shown in Figure 3, which shows that they both follow the reference signal and have the same response time. Since the difference in the steady state responses are negligible (hence the overlap in the graphs), the Simscape model can be taken to be a good approximation of the nonlinear model for the purpose of control system analysis.

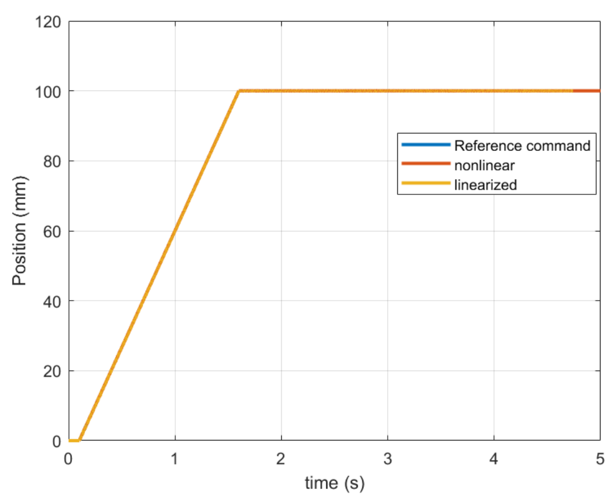

Figure 3. The system model and its linearized approximation (the lines in the legend overlap, showing good error tracking).

3.2 System Response

From the system response graph shown in Figure 4, The open-loop control has the best transient response, with the lowest rise time and overshoot. The PID response has a less fast response time, but high overshoot. The on/off control strategy has a slow response time and oscillates at steady state around the reference value. The amplitude of oscillations increases when the threshold actuating signals increase.

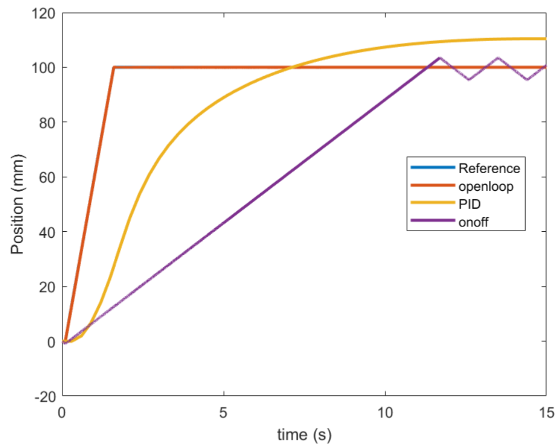

Figure 4. System Response to different control strategies.

Based on Figure 4, The open loop strategy reaches steady state in the shortest amount of time and therefore coincides with the reference signal (hence the overlap in the graph). This is followed by the on/off control, then the adaptive control. All control strategies have a steady state error of near zero (PID reaches steady state at 40 s, which is not visible in the figure), though the on/off signals show the largest oscillations at steady state value.

Figure 5 shows the system response for the Model Reference Adaptive control. This shows a slow response time and high overshoot for MRAC when compared to the other types of control. The response could be improved with better initial estimates of the controller parameters to ensure faster adaptation of the model [1].

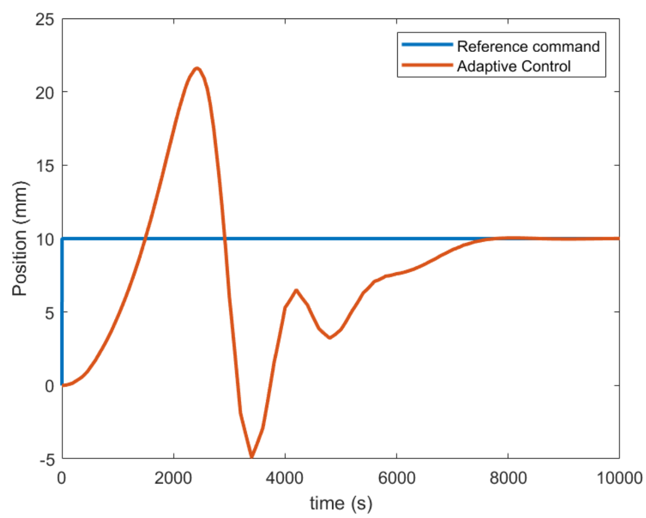

Figure 5. System response for adaptive linear control.

4. Discussion

The implementation of controls in Additive manufacturing is important, and proper analysis needs to be done before implementation to determine the best control strategy. The results show that the open-loop control strategy is ideal for gantry positioning, provided the stiffness of the belt is large enough to minimize compliance of the mechanism. This explains the justification for implementing open loop control in modern positioning systems for FDM printers at low to moderate speeds. At higher speeds, issues such as stepper motor dynamics and inherent damping due to viscoelasticity in the belt can increase the error, which gives rise to considering closed loop control as a better alternative.

Control systems are also important in the regulation of temperature in FDM system. Given that Temperature has a characteristic lag, many commercial printers employ PID feedback control in the regulation of temperature to ensure maximum accuracy. The large wait times and large deviations in the temperature setting warrants the need for a control system analysis to select the best control strategy for temperature regulation in AM.

Extrusion mechanisms in FDM process also require efficient control strategies. Large deviations occur in the extrusion rates due to slippage, skips in motor steps and nonlinear melt dynamics. Improving the quality of 3D printed parts require implementation of control strategies, which will minimize deviations in set parameters and product defects, thus improving the quality of the printed parts.

5. Conclusion

This paper presents the impact of four classical control strategies (open-loop/feedforward, on-off (bang-bang), PID, and MRAC) in position control accuracy. A lumped parameter model of the belt drive used in FDM printer XY positioning was developed from first principles, and these strategies were employed in a simulated environment to assess the system response. The findings revealed that in terms of response times, the open-loop response coincided with the natural dynamics of the positioning system since there was no feedback controllers implemented. A change in the system dynamics was also observed in the other control strategies, such longer response times overshoot and zero steady state error. But the system is expected to have lower steady-state errors due to the error-correcting capacity of feedback controllers. Implementing the right control strategy for FDM printing parameters results in parts with fewer defects and higher quality, thus enhancing the system performance.

Future work includes implementing the MRAC and PID strategies using an embedded motion controller and validating their performance on a commercial FDM printer, measuring dimensional accuracy, surface roughness, and throughput during high-speed printing. Additional studies will introduce sensor-noise models and non-linear belt and motor dynamics to assess robustness under real-world disturbances, extend the framework to simultaneous multi-axis coordination, and investigate hybrid feed-forward and adaptive schemes that preserve rapid rise times while enhancing disturbance rejection. Finally, coupling the motion-control loop with extrusion-pressure and thermal-regulation controllers will provide a complete view of how integrated control architectures can further improve print fidelity and process stability across a broader range of materials and geometries.

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References

[1] R. H. Bishop, *The mechatronics handbook*, 2nd ed. (Electrical engineering handbook series). CRC Press, 2008.

[2] K. Ogata, *Modern control engineering*, 5th ed. (Instrumentation and control series). Prentice-Hall, 2010.

[3] M. Moretti and A. Rossi, "Closed-Loop Filament Feed Control in Fused Filament Fabrication," *3D PRINTING AND ADDITIVE MANUFACTURING,* vol. 10, no. 3, pp. 500-513, JUN 1 2023, doi: 10.1089/3dp.2021.0236.

[4] J. Go, S. N. Schiffres, A. G. Stevens, and A. J. Hart, "Rate limits of Additive Manufacturing by Fused Filament Fabrication and Guidelines for High-throughput System Design.," *Additive Manufacturing,* vol. 16, pp. 1-11, 2017.

[5] J. Kattinger, T. Ebinger, R. Kurz, and C. Bonten, "Numerical simulation of the complex flow during material extrusion in fused filament fabrication," *Additive Manufacturing,* vol. 49, p. 102476, 2022/01/01/ 2022, doi: https://doi.org/10.1016/j.addma.2021.102476.

[6] M. Martini, M. Scaccia, G. Marchello, H. Abidi, M. D'imperio, and F. Cannella, "An Outline of Fused Deposition Modeling: System models and Control Strategies," *Applied Sciences,* vol. 12, p. 5400, 2022, doi: 10.3390/app12115400.

[7] I. Gibson, *Additive manufacturing technologies*, Third edition / Ian Gibson, David Rosen, Brent Stucker, Mahyar Khorasani. ed. Springer, 2021.

[8] M. P. Serdeczny, R. Comminal, D. B. Pedersen, and J. Spangenberg, "Experimental and analytical study of the polymer melt flow through the hot-end in material extrusion additive manufacturing," *Additive Manufacturing,* vol. 32, 03/01/March 2020 2020, doi: 10.1016/j.addma.2019.100997.

[9] C. Okenwa Ufodike, G. Chukwuka Nzebuka, and A. Mazedur Rahman, "Combine effect of feeding rate and modeling parameter on the extrusion pressure in material extrusion additive manufacturing," *Manufacturing Letters,* vol. 35, no. Supplement, pp. 485-492, 08/01/August 2023 2023, doi: 10.1016/j.mfglet.2023.07.007.

[10] G. C. Nzebuka, C. O. Ufodike, A. M. Rahman, M. B. Minus, and C. P. Egole, "Thermal-fluid Modeling and simulation of Ti-6Al-4V alloy filaments during shaping in the hot-

end of Material Extrusion Additive Manufacturing," *Journal of Manufacturing Processes,* vol. 131, pp. 866-878, 2024, doi: https://doi.org/10.1016/j.jmapro.2024.09.040.

[11] G. C. Nzebuka, C. O. Ufodike, A. Rahman, C. M. Gwynn, and M. F. Ahmed, "Numerical modeling of the effect of nozzle diameter and heat flux on the polymer flow in fused filament fabrication," (in English), *JOURNAL OF MANUFACTURING PROCESSES,* vol. 82, pp. 585-600, OCT 2022, doi: 10.1016/j.jmapro.2022.08.029.

[12] G. C. Nzebuka and C. O. Ufodike, "Numerical Transient Thermal Development of Melting a Solid Filament in A Hot-End of a

Material Extrusion System," in *Solid Freeform Fabrication 2022*, Austin, TX, 2022, 2022, pp. 2019-2032.

[13] X. Guidetti *et al.*, "Force controlled printing for material extrusion additive manufacturing," (in English), *ADDITIVE MANUFACTURING,* vol. 89, JUN 5 2024, Art no. 104297, doi: 10.1016/j.addma.2024.104297.

[14] M. Ralchev, V. Mateev, I. Marinova, and Ieee, "Thermal Control of Filament Supply in FFF/FDM 3D Printing Technology," presented at the 2021 XXXI INTERNATIONAL SCIENTIFIC SYMPOSIUM METROLOGY AND METROLOGY ASSURANCE (MMA 2021), 2021.

[15] B. Weiss, D. Storti, and M. Ganter, "Low-cost closed-loop control of a 3D printer gantry," *RAPID PROTOTYPING JOURNAL,* vol. 21, no. 5, pp. 482-490, 2015, doi: 10.1108/RPJ-09-2014-0108.

[16] P. Y. Wu, C. Qian, and C. E. Okwudire, "Modeling and feedforward control of filament advancement and retraction in material extrusion additive manufacturing," (in English), *ADDITIVE MANUFACTURING,* vol. 78, SEP 25 2023, Art no. 103850, doi: 10.1016/j.addma.2023.103850.

[17] P. Y. Wu, C. Qian, and C. E. Okwudire, "Design, modeling and feedforward control of a hybrid extruder for material extrusion additive manufacturing," (in English), *ADDITIVE MANUFACTURING,* vol. 92, JUL 25 2024, Art no. 104378, doi: 10.1016/j.addma.2024.104378.

[18] P. Y. Wu, K. S. Ramani, and C. E. Okwudire, "Accurate linear and nonlinear model-based feedforward deposition control for material extrusion additive manufacturing," (in English), *ADDITIVE MANUFACTURING,* vol. 48, DEC 2021, Art no. 102389, doi: 10.1016/j.addma.2021.102389.

[19] "Different Belt Configurations," Stock Drive Products / Sterling Instrument. [Online]. Available: https://www.sdp-si.com/D265/PDF/D265T010.pdf