Automatic Pressure Advance Calibration Using Laser Triangulation

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***Abstract*—Modern 3D printers have numerous parameters that can be optimized to improve print quality. However, many of these parameters, including pressure advance, require a mostly manual tuning process. This research paper presents a novel approach for automatically calibrating pressure advance on a 3D printer using laser triangulation with a low-cost line laser and a USB camera. The method involves printing a calibration pattern of straight lines while varying speeds, which introduces deformities at the speed transitions. The line laser and USB camera are then used to generate a height map of each printed line, which is analyzed to determine the magnitude of deformities. The settings from the line with the least deviation can then be applied to future prints. The calibration process was tested across different build plate materials and lighting conditions to determine the optimal environment for accurate calibration. This paper provides detailed information about the development of this method, the Python scripts used, and experimental results and analysis. The automatic calibration process is a significant advancement in open-source 3D printing technology, as it eliminates the need for manual tuning.**

I. Introduction

A. Background and Motivation

Over the past decade, the performance of consumer 3D printers has improved significantly due to advancements in both mechanical design and firmware development. While mechanical improvements have led to decreased moving mass and improved availability of precision components at affordable prices, firmware developments have introduced new features such as pressure advance (PA) to improve print quality.

To take full advantage of these firmware improvements, these features must be tuned for each printer. While there is one 3D printer that implements a system to automatically calibrate pressure advance [1], no open-source solution has been published at the time of writing. For open-source 3D printers, PA calibration is a manual process that requires domain-specific knowledge and can be time-consuming. This paper presents a novel approach for automatically calibrating PA using laser triangulation with a low-cost line laser and a USB camera. This method provides a more efficient and accurate way to calibrate PA, which can lead to improved print quality and reduced printing time.

Thank you to Fabreeko and 3DO for providing the build surfaces and USB camera, respectively.

B. Pressure Advance Parameter

Despite having a tightly constrained filament path, a 3D printer's extruder experiences a certain degree of elasticity as it pushes filament through the hotend. This results in a lag in the release of filament when the extrusion rate changes, such as when starting or stopping motion. This phenomenon is commonly visible in printed parts as imperfections on the corners. The printer tends to over-extrude filament when coming to a stop, and under-extrude when speeding up.

Pressure advance [2] resolves this issue by pre-emptively applying and removing pressure to the hotend as the print-head's motion changes. Increasing the value selected for the pressure advance increases the degree to which the printer compensates, and values that are too high can even induce the opposite effect, causing under-extrusion while coming to a stop, and over-extrusion while speeding up. Additionally, different print settings, such as temperature or using different filament, may necessitate different PA values. Therefore, it is crucial to select the optimal coefficient, as choosing poorly can introduce more issues.

There are several popular methods for manually calibrating pressure advance on 3D printers. Ellis [3] showcases three popular techniques in their printer calibration guide. Each of these methods involves printing a calibration pattern with a range of PA values and then inspecting the printed pattern to determine which one looks the best. However, this inspection process is subjective and can be error-prone, making it a less-than-ideal method for selecting the optimal pressure advance parameter. Furthermore, the manual nature of this process can be time-consuming, resulting in fewer calibrations than what would be considered optimal.

II. Related Work

This paper builds on the work previously performed by Tronvoll et al. [4] by using a similar calibration pattern. Their work validates the mathematical model used for PA, but it still relies on manual inspection of the printed pattern. Their paper also notes that the appropriate PA value is dependent on a variety of factors, such as filament material and temperature, highlighting the benefit of an automatic calibration solution. This paper proposes a method to automatically detect the print defects illustrated in [4, Fig. 2], thus allowing for a more objective analysis of the calibration pattern.

III. Tools

A. Hardware Setup

All tests were performed on a 350mm Voron 2.4r2 running Klipper. The toolhead used a Mellow Fly SB2040 controller communicating with the motherboard via CAN Bus. The USB camera used was a 1080p USB nozzle camera from 3DO. It should be noted that the version of the camera used is no longer available for purchase; however, 3DO offers a 4k version that will likely work with minor adjustments to the code provided. The camera and laser were mounted to the front of the toolhead with a 3D printed fixture to ensure rigidity. The camera was pointed directly at the bed, with the laser mounted at a 45° angle relative to the toolhead. The line laser was a generic 5mw 650nm 5v line laser with adjustable focus. Fig. 1 shows the system attached to the printer toolhead. The laser was mounted and focused such that the line was most in focus at the same Z height as the camera. Macros were implemented in Klipper for turning the laser on and off at the beginning and end of the scanning process. Print settings used throughout testing are provided in Table I.

The calibration process was tested on 3 different build surfaces: smooth translucent polyetherimide (PEI), Fabreeko HoneyBadger Black Textured PEI, and Fabreeko HoneyBadger P-Series Smooth Black PEI.

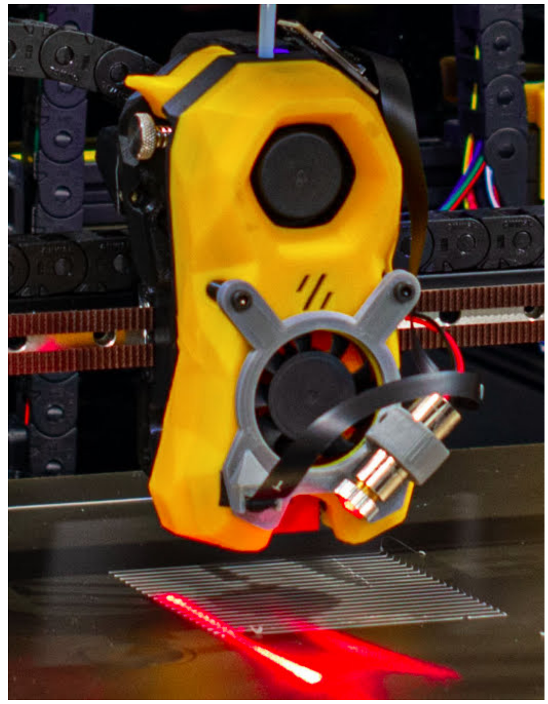

Fig. 1. The calibration system installed onto the printer's toolhead.

TABLE I
PRINTING PARAMETERS

Parameter	Value
Layer Height	0.2 mm
Nozzle Size	0.4 mm
Filament Material	ABS
Build Plate Temperature	110°C
Nozzle Temperature	255°C
Acceleration	3000 mm/s^2

B. Software

All software was implemented in Python. Videos were recorded using FFmpeg, and OpenCV was used for processing each frame. The printer was controlled using the Moonraker API [5]. Numpy was used for analyzing line deviation.

IV. Methodology

A. Printing the Calibration Pattern

The calibration process relies on a pattern of printed lines. The pattern is designed to aggravate the conditions that necessitate PA. It does so by printing lines that each have a period of rapid acceleration and deceleration. When PA is not used, the transitions in velocity result in gaps in the extruded material during periods of acceleration, and excess material during periods of deceleration. As each new line in the pattern is printed, the PA value used is incremented by a fixed amount. Assuming an appropriate range of PA values are tested, the lines in the pattern will range from under-compensating to over-compensating, with the appropriate PA value somewhere in the middle. Fig. 2 shows a pattern printed earlier in development. An ideal PA value would result in a line with uniform thickness and height across the length of the pattern. Inspecting the pattern shown in Fig. 2, the lines appear most uniform roughly 1/3 of the way up. During the project's development, a Python library was created to automatically generate the G-code for printing calibration patterns. A printed border was added to the calibration pattern to aid with removal from the build plate. This library accepts the following parameters for generating the pattern:

- X and Y location
- The range of PA values to print with
- How many lines to print
- The distance between the printed lines
- The length of the printed lines

This configurability allowed testing with a variety of settings. Experimentation showed that the size of the pattern could be reduced significantly without negatively impacting the calibration process. The pattern width was reduced to 30mm, down from the original 100mm pattern used by Tronvoll et al. [4, Fig. 10]. Further reduction in size is likely possible with sufficient experimentation. Minimizing the pattern size not only reduces wasted material, but also maximizes the useable build plate area in the event that the calibration is performed immediately preceding a print. The pattern used for the data presented in the paper was printed with the parameters shown in Table II.

B. Theory of Operation

Lines in the pattern with incorrect PA values have defects. These defects result in a varying cross-section throughout

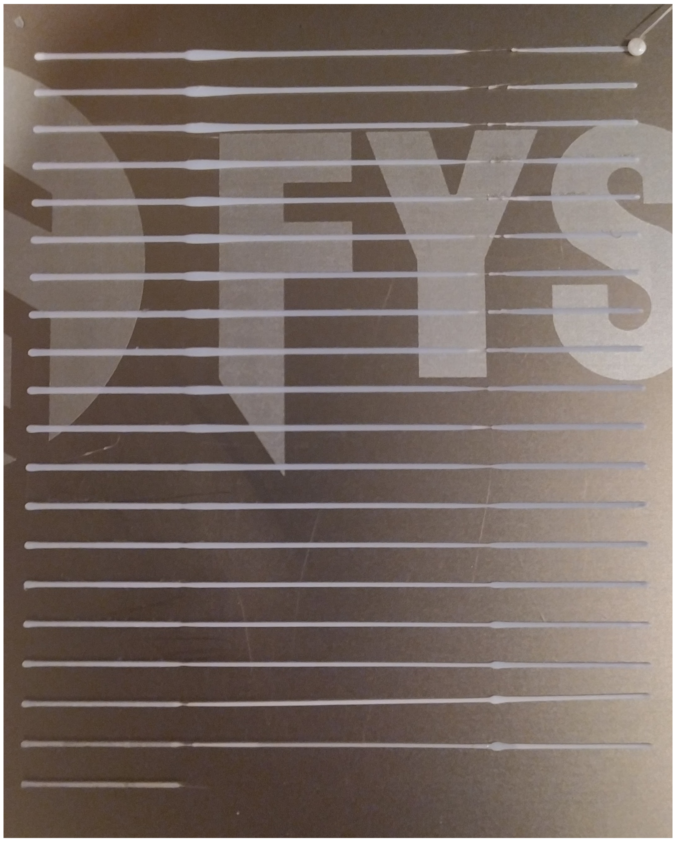

Fig. 2. The original, hand-crafted PA test pattern.

TABLE II
CALIBRATION PATTERN PARAMETERS

Parameter	Value
Number of lines	10
Line Length	30mm
Spacing	4mm
PA Value Range	0-0.06

the printed line. The USB camera and line laser can be used to generate a 3D model of the printed line using laser triangulation. As outlined by Bradshaw [6], the line laser's shape as seen by the camera represents curvature of the surface being scanned. Fig. 3 demonstrates this principle. The pattern on the left shows an area where the filament is over-extruded, resulting in a larger cross-sectional area. Due to this increased cross-sectional area, the line exhibits a different curve than the pattern displayed on the right. The x position of the laser at each point in the image can be translated to the height of the filament at that location. By recording the shape of the laser as the camera moves across the pattern, the software can reconstruct a 3D representation of the printed line. This information can be analyzed to select the line with the least deviation.

C. Recording and Post Processing

An additional Python library was developed to aid with the process of scanning the calibration patterns. Information

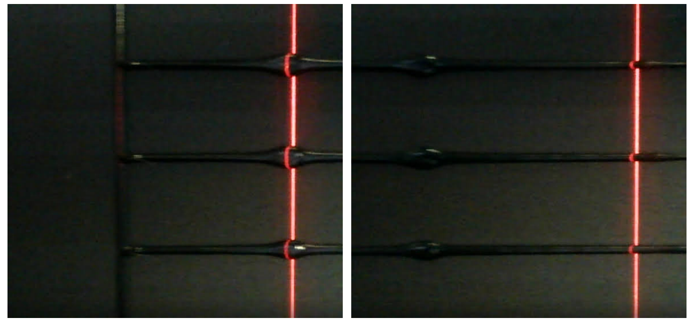

Fig. 3. The line laser's shape on two different areas of a calibration pattern.

specific to the hardware implementation of the camera and laser can be easily configured. Values such as the camera's X and Y offset from the nozzle, the Z height where the camera and laser are in focus, and the area of interest on the camera are all adjustable. This customization should facilitate the use of different cameras and lasers, as long as the appropriate constants are calculated. The scanning library is coupled with the printing library such that the same information used to print the pattern can be used to scan the pattern. Before the the scan takes place, the software activates the line laser and turns off the build chamber lights. Patterns are scanned by sweeping the camera over the printed lines at a fixed speed while recording. A small section of the beginning and end of each printed line is skipped in order to ensure that the filament has had time to begin extruding correctly. Once all video segments have been recorded, the line laser is turned off, and the build chamber lights are turned back on.

The raw video data is too noisy to analyze, so additional post processing is performed. First, each frame is cropped so that only the line being scanned is visible. The cropping process also removes any areas of the frame that are unlikely to contain the laser during normal operation. Second, a range mask removes all pixels with a red value below a certain threshold. This filters out most of the pixels that are not illuminated by the laser, further reducing noise. The frame is also converted to grayscale at this point, as color information is no longer needed. Finally, a gaussian blur is performed to further reduce hot spots in the image. This helps with finding the center of the line. Fig. 4 shows the frame data after each step.

The post processed frame is then analyzed to estimate the laser's X location for each frame. The brightness values in the frame range from 0-255, so they are first normalized by dividing by 255. The normalized values are then raised to an exponent to increase the relative intensity of the brighter pixels. Finally, a weighted average is computed, with the weights for each pixel corresponding to the brightness at that location.

The resulting cross-section from the frame shown in Fig. 4 can be see in Fig. 5. Even with an input resolution of only 45x60 pixels, the post processing techniques allow a relatively accurate cross-section to be calculated. It is hypothesized that

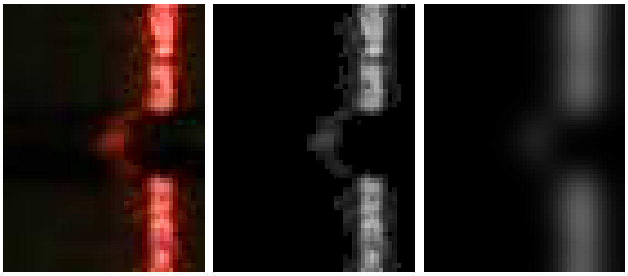

Fig. 4. Frame data after cropping, masking, and blurring.

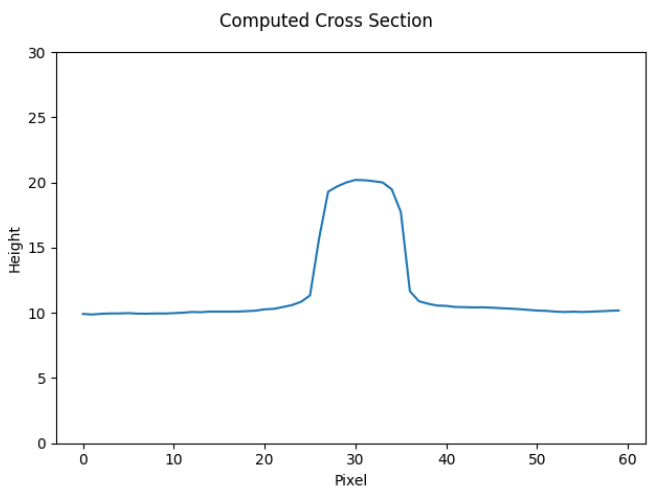

Fig. 5. Fully processed height data for frame from Fig. 4

with additional research into laser line finding algorithms, the strength of the gaussian blur used could be decreased without negatively impacting the results. This could yield additional detail in the final heightmap, though it may not be beneficial for the task at hand. To give a scale to the heightmaps, all lines used for testing were printed with a height of 0.2mm.

Due to the small physical scale of the line, and the fact that all measurements for computing the deviation are relative, the calculated X value for the laser is used directly as the height value. While this means that the height map is less accurate, testing has shown that the current approach appears to be sufficient. Furthermore, the reduced computational complexity of the height map generation allows for faster image processing. Both a 2D and 3D visualization of a heightmap are shown in Fig. 6 and 7.

D. Analysis

Each heightmap is analyzed to determine the deviation from an ideal line. The heightmaps are stored in memory as a 2D array of floats, where the X axis represents the video frame index, and the Y axis represents the Y axis of each frame. Scores are generated by computing the standard deviation for each row of the heightmap, and then summing those values. Lines with a lower score have less deviation, such that the line with the lowest score has the least deviation. Any changes in the printed line's width or height will be reflected by an increased score. The deviation is visible in the generated height maps, as shown in Fig. 7, 8, and 9. Fig. 8 shows a line where the PA value is set too low. Fig. 9 shows a line where the PA value is set too high. Although there still is some deformation present in Fig. 7, each row has fairly consistent height values all the way across. Because of this, the score for Fig. 7 is the lowest out of all three.

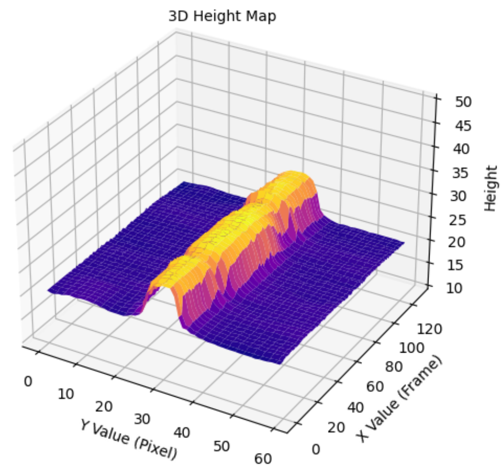

Fig. 6. A 3D visualizatio of the heightmap shown in Fig.7.

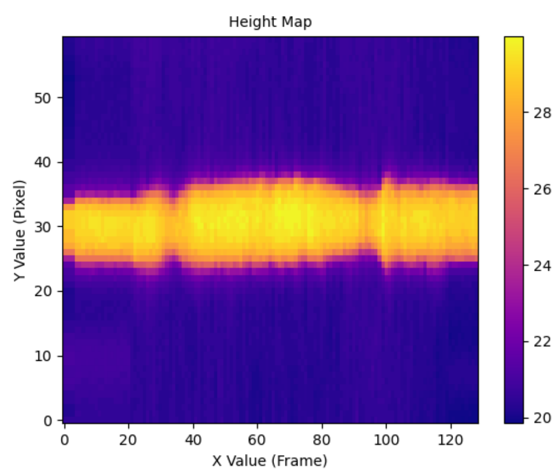

Fig. 7. A line printed with a PA value of 0.033. Score: 25.05

E. Process Improvements

Several improvements were made through experimentation throughout the research process. The first iteration of hardware utilized a cheap USB Endoscope and a fixed focus line laser. The endoscope had a focus distance of 7.5cm and was only 480p, as compared to the nozzle camera's focus distance of 3.45cm and 1080p resolution. The video data recorded with the endoscope proved that the theory behind the calibration

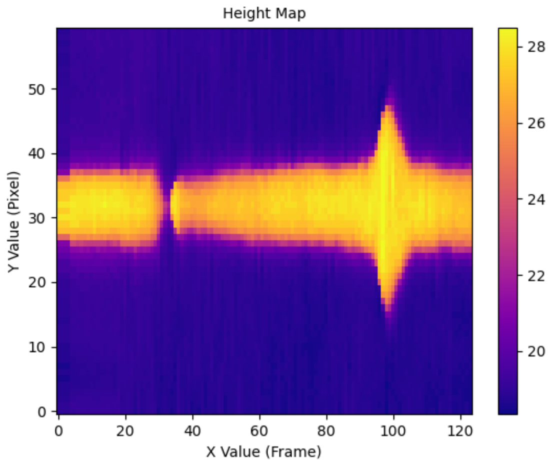

Fig. 8. A line printed with a PA value of 0.013. Score: 55.04

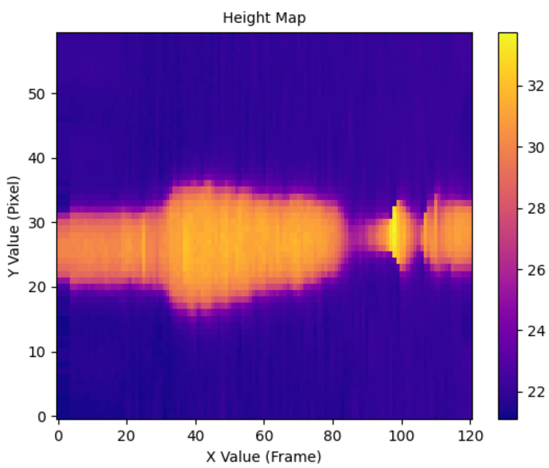

Fig. 9. A line printed with a PA value of 0.06. Score: 55.28

process was sound, but noise in the images and the limited resolution led to some variability in the results. The video from the camera provided by 3DO was much clearer, and all further tests were performed with it instead of the endoscope. In theory, the lenses on either camera could be adjusted to decrease the focus distance, increasing the number of pixels available for analysis. However, as the results with the 3DO camera were sufficient out of the box, no focus adjustments were made.

Like the endoscope, the original line laser was found to be insufficient. The beam was not sufficently focused at the close distances required by the camera. A 3D printed slit mask was placed in front of the laser to decrease the thickness of the beam, but the resulting decrease in brightness was detrimental to the camera's ability to detect the laser. In response to these issues, a laser with adjustable focus was acquired. Fig. 10 shows the two line lasers side by side, with the newer one on the left. The new laser yielded an improved signal to noise ratio (SNR), and improved the consistency of the calibration process.

Fig. 10. Side by side comparison of the adjustable focus laser (left) and the fixed focus laser (right).

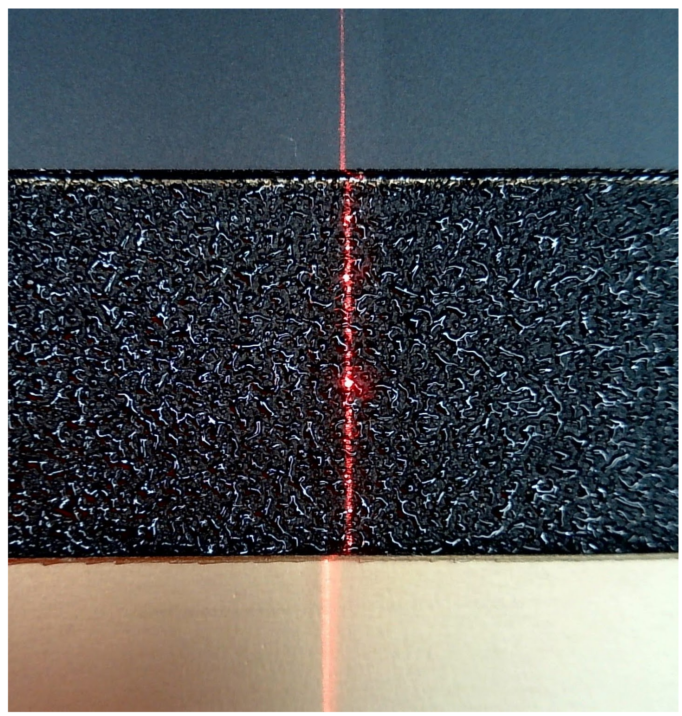

Fig. 11. Laser visibility on the matte, textured, and translucent PEI build plates.

During early tests, it was noted that the laser line diffused through PEI build surface. It was hypothesized that a more opaque build plate would result in a crisper line, possibly improving consistency. To test this theory, two build plates were acquired from Fabreeko. One with a matte black surface, and another with a textured black surface. Fig. 11 shows the laser on each of the build plates. Note the decreased beam thickness on the matte black plate.

F. Repeatability Testing

In order to validate the calibration process and find factors that could impact the accuracy of the results, the calibration process was performed repeatedly under a variety of circumstances. The calibration pattern was printed 27 times, as shown in Fig. 12, for each set of conditions. This test was performed for each combination of the following parameters:

- Black and White Filament
- Textured, Matte, and Translucent Build Plates
- With the printer in total darkness, and with lights in the room turned on.

For testing different lighting conditions, the pattern was not printed a second time, just scanned again. The results for all 324 patterns are discussed below.

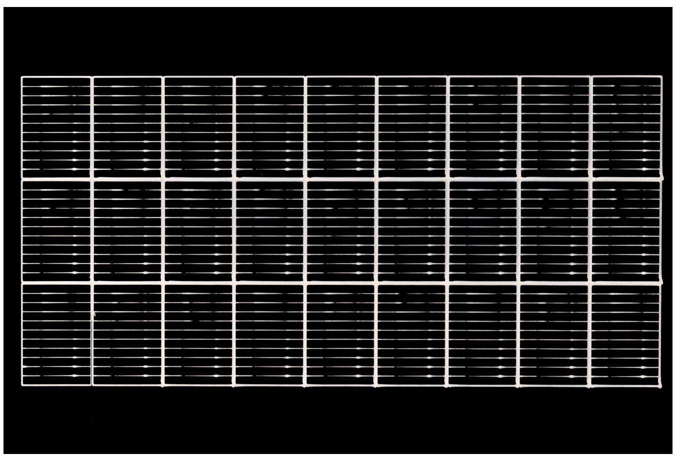

Fig. 12. The 27 pattern test printed on the matte black PEI sheet.

V. Results And Discussion

A. Consistency

The full results from all scans are shown in Fig. 16 and 17. Fig. 17 shows the computed deviation for each line in each pattern, with a trendline and R^2 provided for each set of conditions. Fig. 16 shows how often a given PA value was selected for each set of conditions. Overall, the system performed quite consistently. Under every set of conditions, the selected PA values are centered around the same value.

The most significant contributor to consistent results was using an opaque build plate. The matte black build surface was the most consistent across all tests, followed by the black textured plate, with the translucent PEI performing worst. The matte black build surface was also affected the least by ambient light. R^2 values for ambient light tests were within 0.01 of their counterparts. In 46/48 patterns scanned on the black build plate, recommended PA values were within ± 1 discrete value from the average. The only time this was not the case was with black filament and ambient light, both of which can negatively impact the calibration process. This indicates an extremely high degree of repeatability, and as such a matte black build surface is recommended for the system. The Bambu Lab X1, which also utilizes a laser as part of its calibration process, uses a matte black build plate [1]. It is possible that this is done for similar reasons.

On average, white filament's calibrated value is higher than that of black filament. It's not unusual for different materials to have different ideal PA values, so this is expected. The average R^2 for white filament is slightly higher, with slightly improved grouping for selected values. This suggests that the calibration process is more consistent with white filament, perhaps because more light from the laser is reflected by the filament.

Ambient light negatively impacted the consistency of the results in all tests, likely due to decreased contrast between the laser and the build plate. It is hypothesized that a brighter or more focused laser could offset this effect. Alternatively, using opaque or tinted side panels for the printer's enclosure would help to decrease the ambient light. In support of this hypothesis, the Bambu Lab X1 has a tinted front panel and opaque walls [1], possibly to help improve the SNR during their calibration process.

B. Measured Improvement

In addition to the tests to confirm repeatability, a test was also performed to show the impact of the calibration process. The calibration was performed, and then two additional patterns were printed. One with pressure advance turned off, and another with all lines printed using the calibrated value. Fig. 13 shows printed patterns, with the pattern used for calibration on the left, followed by the control, and calibrated patterns. The average deviation in the calibrated pattern was 80.4% lower than the control. In addition, the calibrated pattern is visibly improved. The control has visible gaps on each printed line, but each line in the calibrated pattern is continuous, with very little deviation.

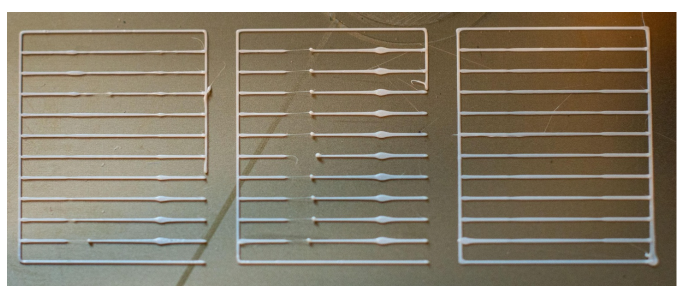

Fig. 13. Calibration, control, and calibrated patterns.

C. Precision

As implemented, the system is capable of detecting extremely small features. Fig. 15 shows a line that was printed during testing where a small string of filament failed to adhere to the build surface. Despite being less than 0.1mm across, the defect was clearly visible in the height map. Fig. 14 shows a top down view of the line side by side with the height map.

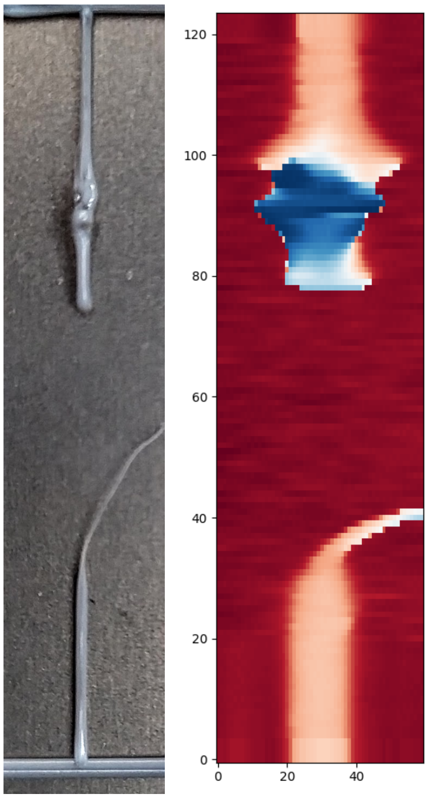

Fig. 14. A line from the calibration pattern compared with the computed height map.

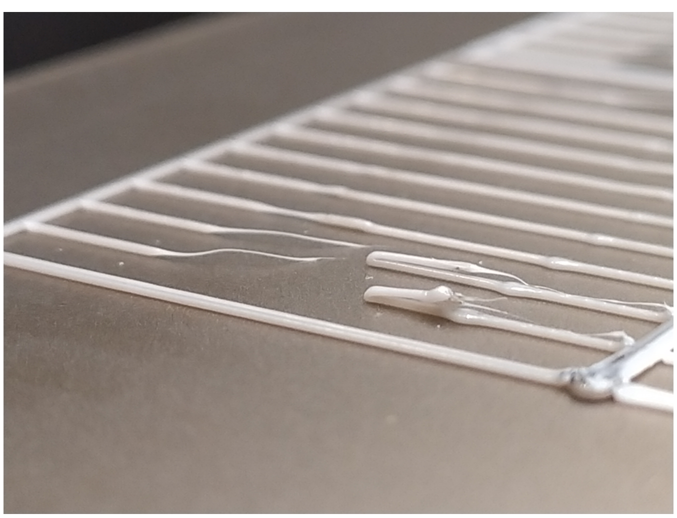

Fig. 15. The printed line from Fig. 14 shown from the side.

VI. Future Work

Moving forward, there are several areas of future research that should be explored to improve the system's effectiveness. For instance, a camera with a higher resolution and a closer focus distance could be utilized to improve the quality of the scan data. An optical bandpass filter was acquired for the system, but it was never utilized as part of the research. Placing a bandpass filter in front of the camera could minimize the impact of ambient light on the system by blocking out light from sources other than the laser. Furthermore, tuning the calibration across a wider variety of filaments, including different colors and materials, could lead to more accurate results. Printing the pattern multiple times and averaging the results could help improve consistency in suboptimal conditions. With sufficient accuracy in the calibration process, the data obtained could be interpolated to select a PA value from a continuous range rather than the discrete values tested. Finally, additional research into laser line finding algorithms should be performed.

VII. Summary

In conclusion, this research demonstrates the feasability of using a laser triangulation system for 3D printer calibration. The results indicate that the system can provide consistent and precise calibration values, with the use of an opaque build plate being the most significant contributor to consistent results. Additionally, this paper shows that the calibration process improves print quality and reduces deviations. As presented, the system provides an effective and automatic means for calibrating pressure advance. This system represents the first open-source solution for doing so, and manages to do so using off-the-shelf hardware.

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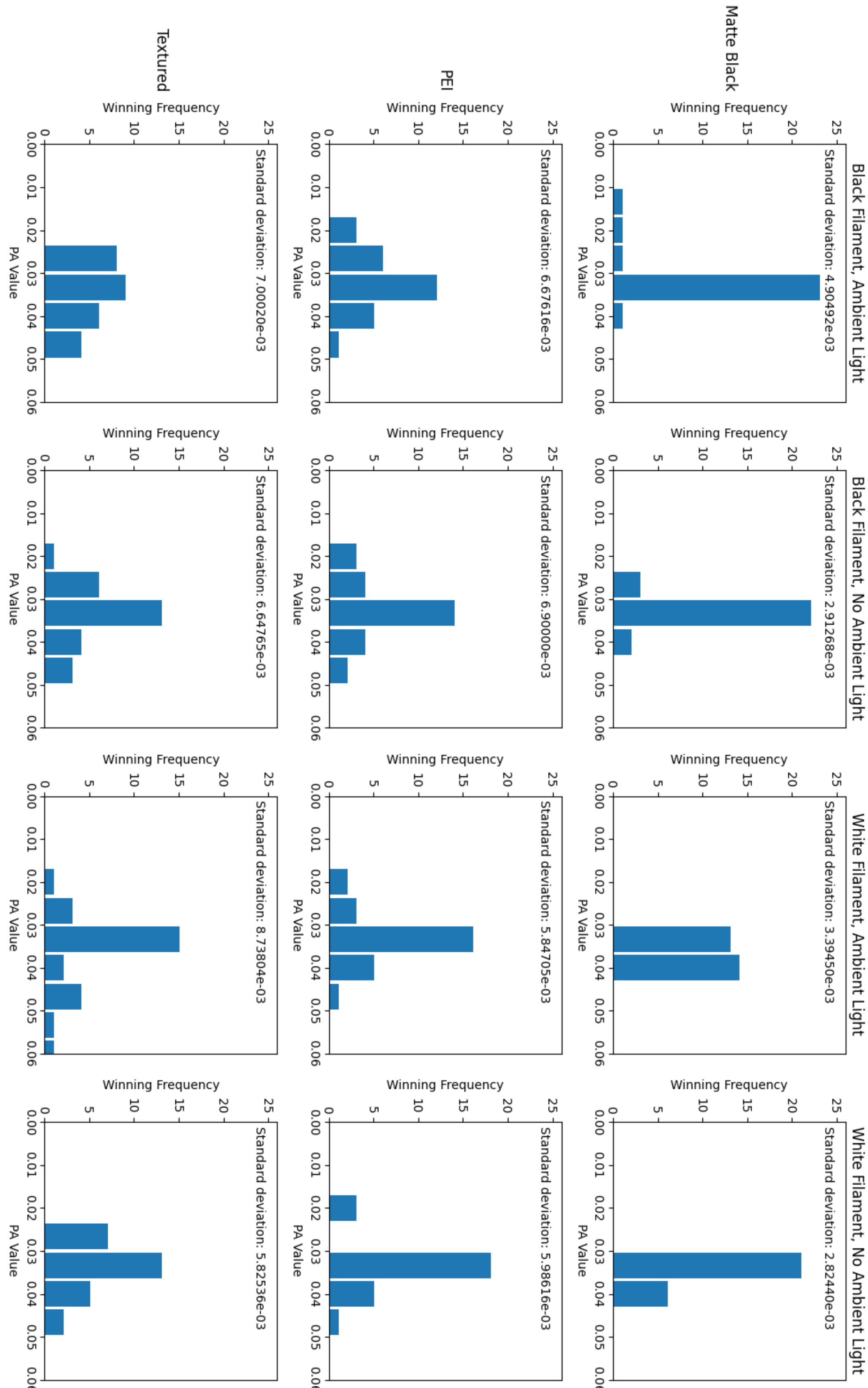

Fig. 16. Selected PA values from performing the calibration process 27 times for each set of conditions.

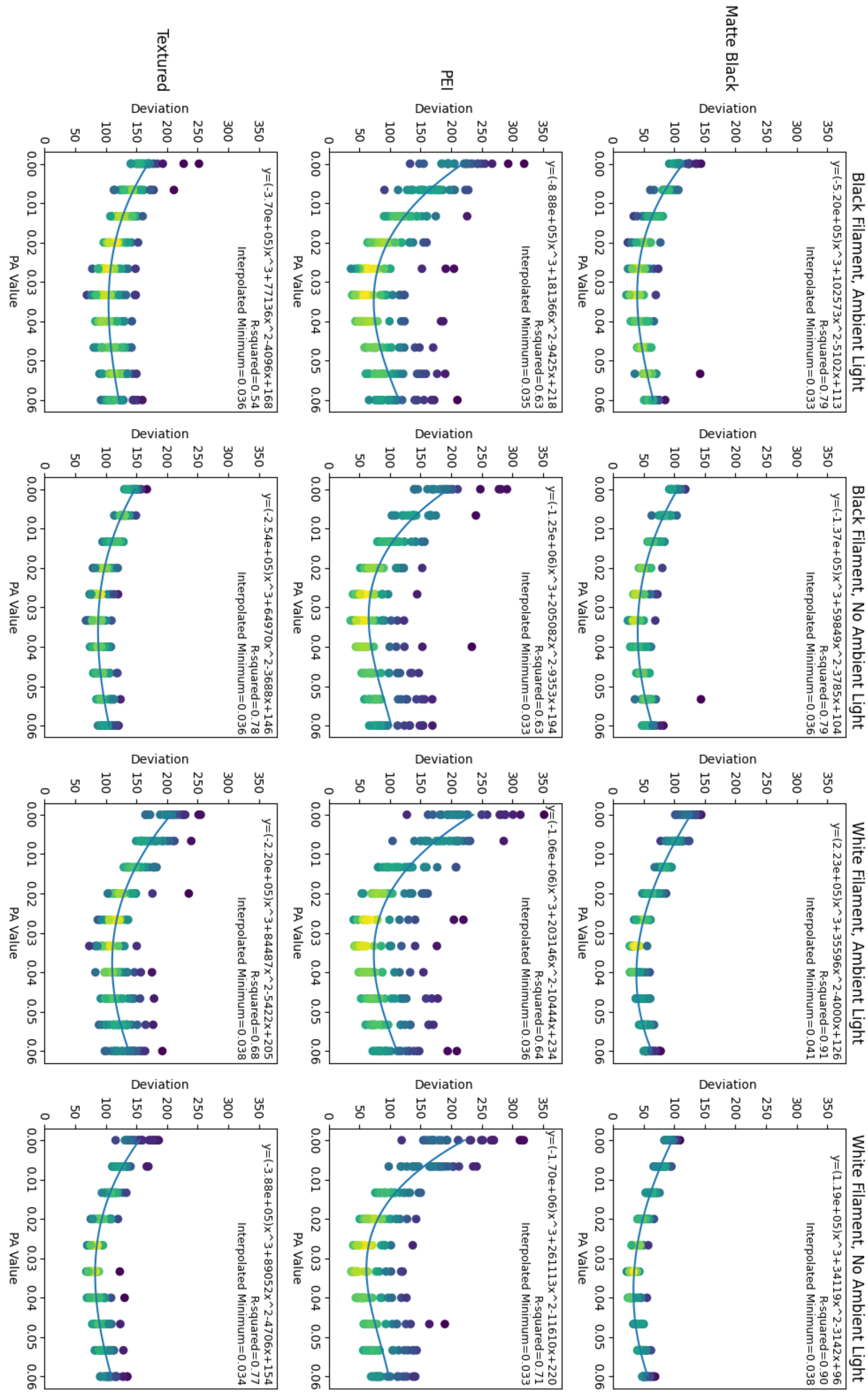

Fig. 17. Aggregated results from performing the calibration process 27 times for each set of conditions.

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