Methods of improving rapid FDM prototyping solutions in industrial systems using strategies of Industry 4.0

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Abstract

Modern production relies on technologies introduced by Industry 4.0 (known as Smart Manufacturing in the USA). As one of the nine pillars of this concept, additive manufacturing plays a crucial role, spanning from rapid prototyping to creating custom final products in the shortest and most cost-effective time. Advances in this field have led to the development of various advanced manufacturing technologies such as Fused Deposition Modeling (FDM), Stereolithography (SLA), and Selective Laser Sintering (SLS), enabling the utilization of a wide range of metallic, plastic, and/or composite materials. Klipper is open-source software designed for 3D printers, providing capabilities for faster and more precise printing. The technique employed involves offloading computationally intensive processes to a separate microcontroller from that of the printer, resulting in performance, versatility, and customization benefits, significantly reducing the time of the prototyping process. The purpose of this article is to analyze the weaknesses of common/affordable printers with average performance using the software tools integrated into Klipper. Additionally, the study focuses on enhancing the performance of the printer Tevo Black Widow. As an additional outcome, it also focuses on improving the quality of printed parts (surface quality and dimensional accuracy). The study is comparative, analyzing the standard performance of a Tevo Black Widow printer with those offered by the same system while using the Klipper firmware.

1. Introduction

Various additive manufacturing techniques have been devised to fulfill the need for producing intricate structures with low waste **(Hui et al., 2018).** The advancement of these technologies has been primarily motivated by the desire for rapid prototyping, mitigating printing imperfections, and enhancing the mechanical characteristics of printed objects. Among these methods, fused deposition modeling (FDM) stands out as the most prevalent form of 3D printing, particularly employing polymer filaments. In the FDM process, a continuous thermoplastic polymer filament is utilized to build up material layers three-dimensionally. FDM offers several advantages, including cost-effectiveness, rapid processing, and operational simplicity. Conversely, challenges such as suboptimal mechanical properties, visible layering, surface imperfections, and a limited range of compatible thermoplastic materials are the main drawbacks of this technology **(Hui et al., 2018)**.

Klipper is an open-source 3d printer firmware that integrates processors from single-board computers and 3D printer mainboards into a unified system, enhancing the computational capacity of 3D printers **(Nguyen, 2022)**. Traditionally, other 3D printer firmware relied on a single microcontroller to manage file processing and computations to operate the printer's components. As 3D printer firmware evolves with new features, microcontrollers struggle to cope with the increasing processing demands. Klipper addresses this challenge by distributing processing power across different processors and microprocessors **(Nguyen, 2022).**

In conjunction with Klipper, we employed the Mainsail web interface **(https://docs.mainsail.xyz/)**. It's a user-friendly web-based interface that allows monitoring and control of 3D printers, users can adjust printer settings, initiate prints, and monitor progress from any device with a web browser, thereby enhancing accessibility and convenience in 3D printing workflows.

In this paper, we aim to enhance the overall quality of our specific 3D printer through a process of observation and experimentation, leveraging the built-in tools within the Klipper firmware. Our approach focuses on two goals simultaneously: improving print surface quality and enhancing printing speeds without compromising the quality of our parts. We will try to demonstrate the impact of utilizing the tools provided by Klipper on various aspects of 3D printing, including surface quality and print reliability, and quantify the expected improvements in real-life scenarios. By analyzing the outcomes of our experiments, we seek to provide tangible evidence of how the functionalities embedded within Klipper influence both the surface finish and the decrease in print times.

Our methodology begins with a test print of a calibration cube, to identify potential issues within our 3D printer. Upon identifying a specific problem, we address it using the tools provided by the Klipper firmware and reprint the cube to evaluate the effectiveness of the solution. However, this iterative process often reveals additional challenges that were previously unnoticed.

It is important to note that for the **Quality improvements** section and **Performance improvements** section of this paper, filaments from different manufacturers were used, although both PLA, due to the available resources at the time of this research.

Once all discernible part quality issues have been addressed through our iterative problem-solving process, we experiment with increasing the print speeds to assess their impact on real print times, combined with overall higher acceleration values.

Hardware-software setup ASTA E CAPITOL NOU??

1.1 General data about Tevo Black Widow

Tevo Black Widow is a DIY 3d printer kit with a build volume of 370 x 250 x 300 mm **(3DPrintersBay, 2024).** The kit contains a direct drive extruder built out of metal with a 5:1 gear ratio to improve the available torque, and the system is built to be compatible with 1.75 mm filaments. The kit also includes a 400 x 250 heated bed, an MKS MOSFET heating controller, anodized CNC milled plates to help the rigidity of the printer and an ANTCLABS BLTouch bed probe. All this is controlled through an MKS gen v1.4 board running Marlin software **(3DPrintersBay, 2024).**

1.2 The setup of our particular printer

Reassembled the printer, putting it back together and making sure everything was square, tightened, and applied grease to the two screws of the Z-axis.

Cooling shroud, we have printed and installed a shroud to better direct and focus the airflow through the fins of the hotend, to cool that area more efficiently and remove the risk of heat creep that could aid in printing errors.

Part cooling, the kit doesn't contain any type of part cooling so we installed a blower-style fan and a simple air duct to better cool our printed parts, as that was a huge bottleneck in printing speeds and quality even from the start.

Belt tensioning mechanism, we printed and installed a screw-based tensioner for the Y-axis belt so we could more easily tighten it.

Glass bed, after finding out our heated bed had a concave shape, we opted for a glass surface, that's flatter and easier to clean, and for the fact that parts come off easier off the build plate as it cools down.

Klipper firmware, we opted for this open-source firmware because of its features, such as easy and convenient printer tunning and configuration, wifi connectivity, and remote connection to the printer, bringing modern software capabilities to our prints, and offloading the computationally intensive processes to a Raspberry pi.

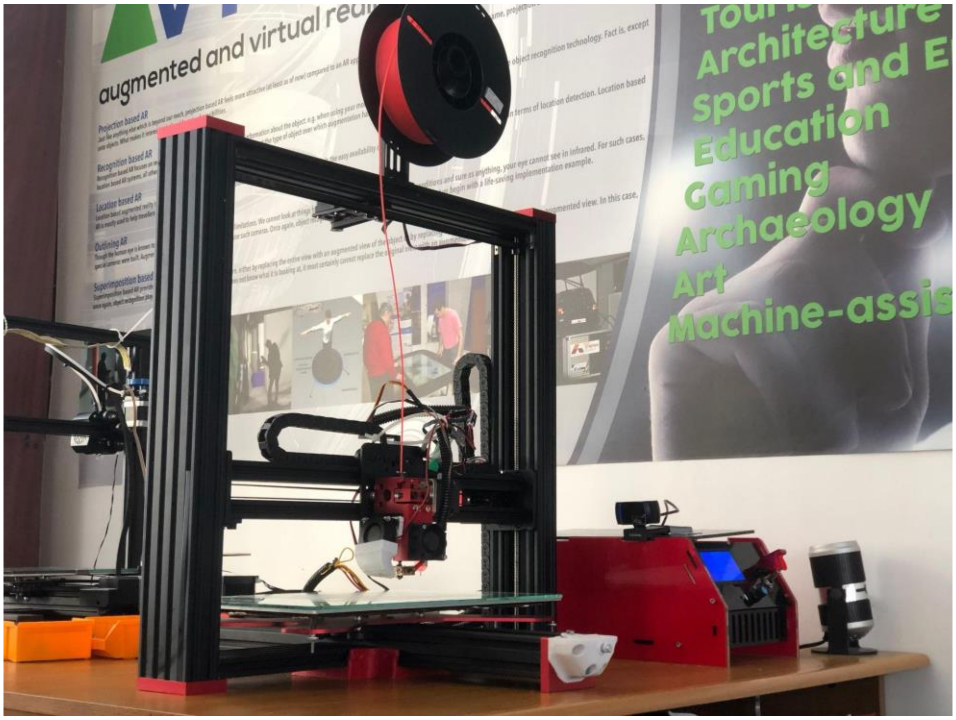

Fig.1 Photo of our Tevo Black Widow printer in its current setup ASA CUM AM MAI SPUS, LA ORICE FIGURA TREBUIE SA AVEM DESCRIERE SI TRIMITERE IN TEXT CU (v.fig.n)

2. Improvements

2.1. Quality improvements

2.1.1 Measuring and visualizing the flatness of the bed **PESTE TOT LA FEL CU NUMEROTAREA CAPITOLELOR**

Using the “Heightmap” feature we can take multiple probes on the surface, and visualize it as a mesh **(Klipper 3D Printer Firmware, n.d., a)**. Klipper also stores the highest and lowest points and gives us an approximate difference between the peaks that the bed probe reads. The mesh was created by a 6 x 6 grid of points equally spaced on the print bed. **(Klipper 3D Printer Firmware, n.d., a).**

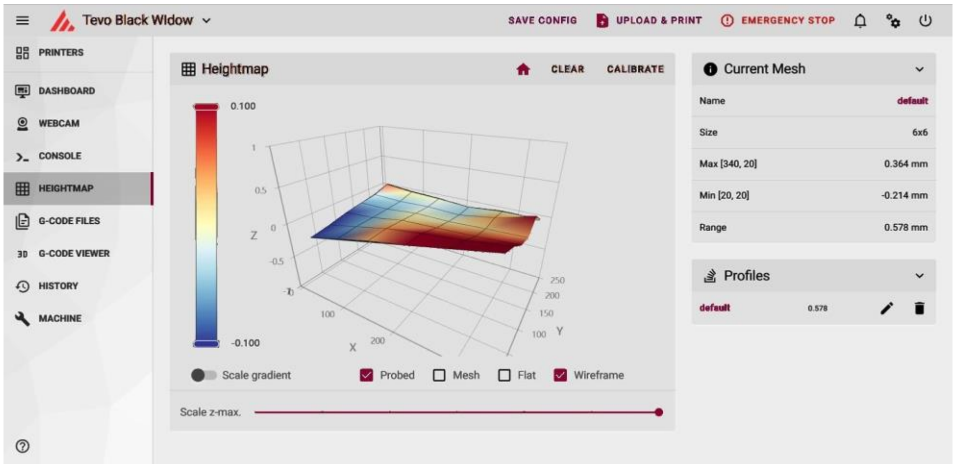

Fig. 2 Bed mesh of our initial print bed

The stock heated bed can be seen in **Fig. 2 as being concave, with the highest point at 0.364 mm, the lowest point at -0.214 mm a delta of 0.578 mm.**

In **Fig. 3**, we can see the mesh of the glass surface, which is way flatter, which is also confirmed by the software, where we can see it has the highest point at 0.179 mm, the lowest point at -0.129 mm, and a lower than before delta of 0.308 mm and a generally flatter mesh.

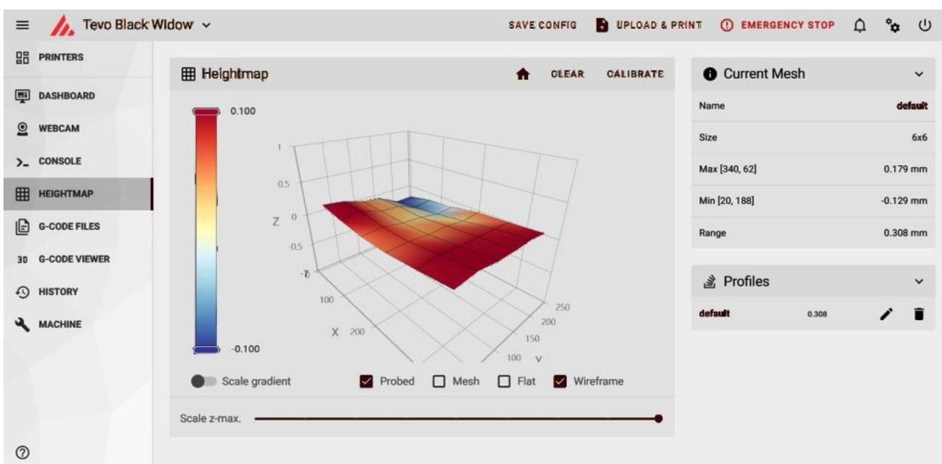

Fig. 3 Bed mesh of glass bed

2.2 What is PID tuning and how it works

First, we printed a calibration cube, and we identified that there appeared to be inconsistent layer heights, and after verifying the Z screws were moving freely and without a problem, we the first weakness of our printer, the fluctuating temperatures, so we used the **PID tuning** feature of Klipper **(see Pranav, 2022)** to solve this issue.

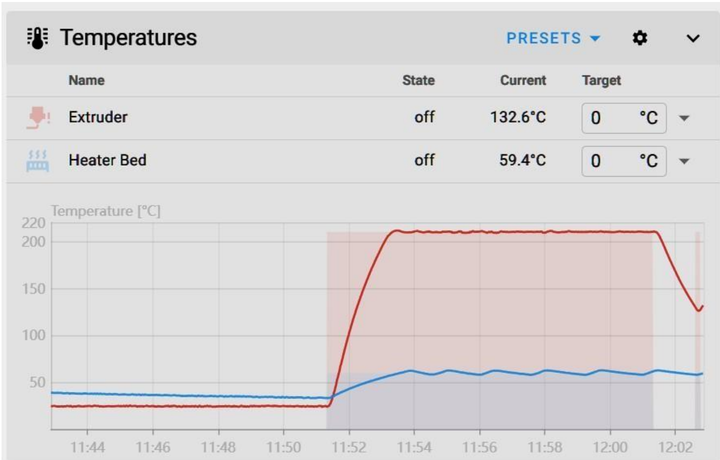

Fig. 4

Bed temperature fluctuations (blue)

PID controller stands for **Proportional Integral Derivative Controller** and in our case, it's a digital temperature controller application, and its job is to take and maintain a steady state for a particular function **(Microcontrollerslab, n.d.)**. It's a closed-loop feedback system that continuously measures the error in your system and tries to correct it **(Microcontrollerslab, n.d.)**. An error like the one seen in Fig. 4, where the temperatures fluctuate above and below the target.

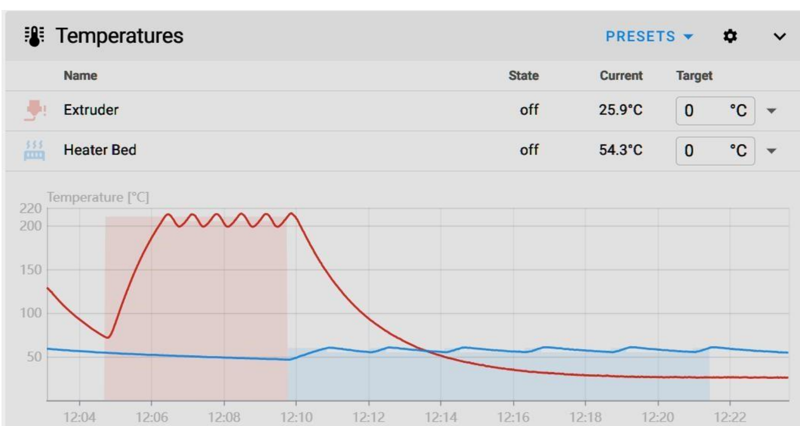

Fig. 5 Klipper PID tuning routine

After running the **PID_CALIBRATE**

HEATER=heater_bed TARGET=60 and

SET_HEATER_TEMPERATURE HEATER=extruder TARGET=210 commands in the console, as **210°C for the extruder** and **60°C for the bed** are the temperatures we're usually printing at, the software runs a heat cycle routine (seen in Fig. 5) for the heated bed and the extruder that will generate the PID values and correct the fluctuations seen before while trying to hold a steady temperature (Klipper 3D Printer Firmware, n.d., b).

After saving the generated values by the commands in the configuration of the printer, we tested to see if it held a steady temperature, and it did. As that wasn't enough proof we printed another calibration cube after the changes to see if there is any visible quality improvement.

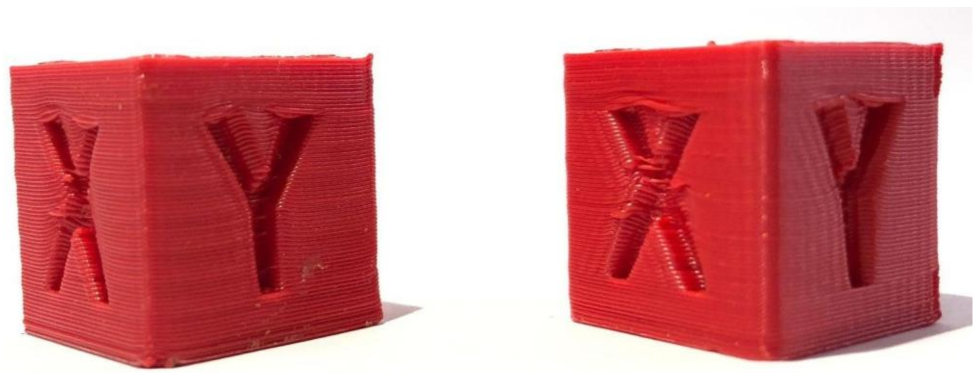

Fig. 6 Cube before PID (left) next to cube after PID tuning (right)

The tuning has completely removed the horizontal rings that appeared on the cube on the left, as shown in Fig. 6, but this enabled another printing error to be more visible. The repeated horizontal patterns and lines are known as ringing or ghosting. That 3D printing quality issue results from vibration in layers, too high of a printing speed, high acceleration, or a displacement in the printing area (Klipper 3D Printer Firmware, n.d., e).

2.3 Input Shaper

Input shaper is a feature supported by Klipper. It's an open-loop control technique that creates a commanding signal that cancels the printer's vibrations (Klipper 3D Printer Firmware, n.d., e). One of the most accurate ways to tune the values for your device is by measuring the resonance using an accelerometer (Klipper 3D Printer Firmware, n.d., e).

We connected an **MPU6050** gyroscope and accelerometer to our Raspberry Pi and ran two tests in Klipper using the command **TEST_RESONANCES** (Klipper 3D Printer Firmware, n.d., e). Once for the X-axis, and once for the Y-axis, which returned 2 CSV files that we plotted onto graphs, using a stand-alone script on the Raspberry Pi (Klipper 3D Printer Firmware, n.d., e).

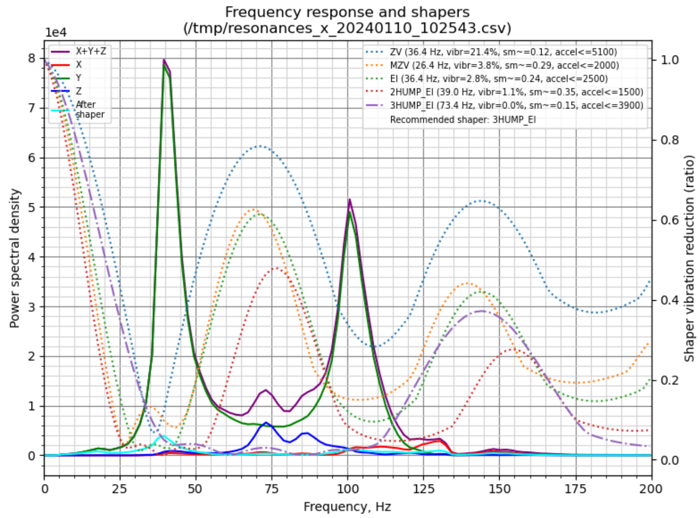

Fig. 7
Graph generated by the stand-alone
Scrip for the X-axis

These graphs contain a lot of information, of which the most important would be the **recommended shaper** that will reduce vibrations the most, "**sm"** or **smooth time,** and "**accel**" or **acceleration** which is the maximum recommended acceleration for that axis. After looking at both graphs, we chose a middle-ground option.

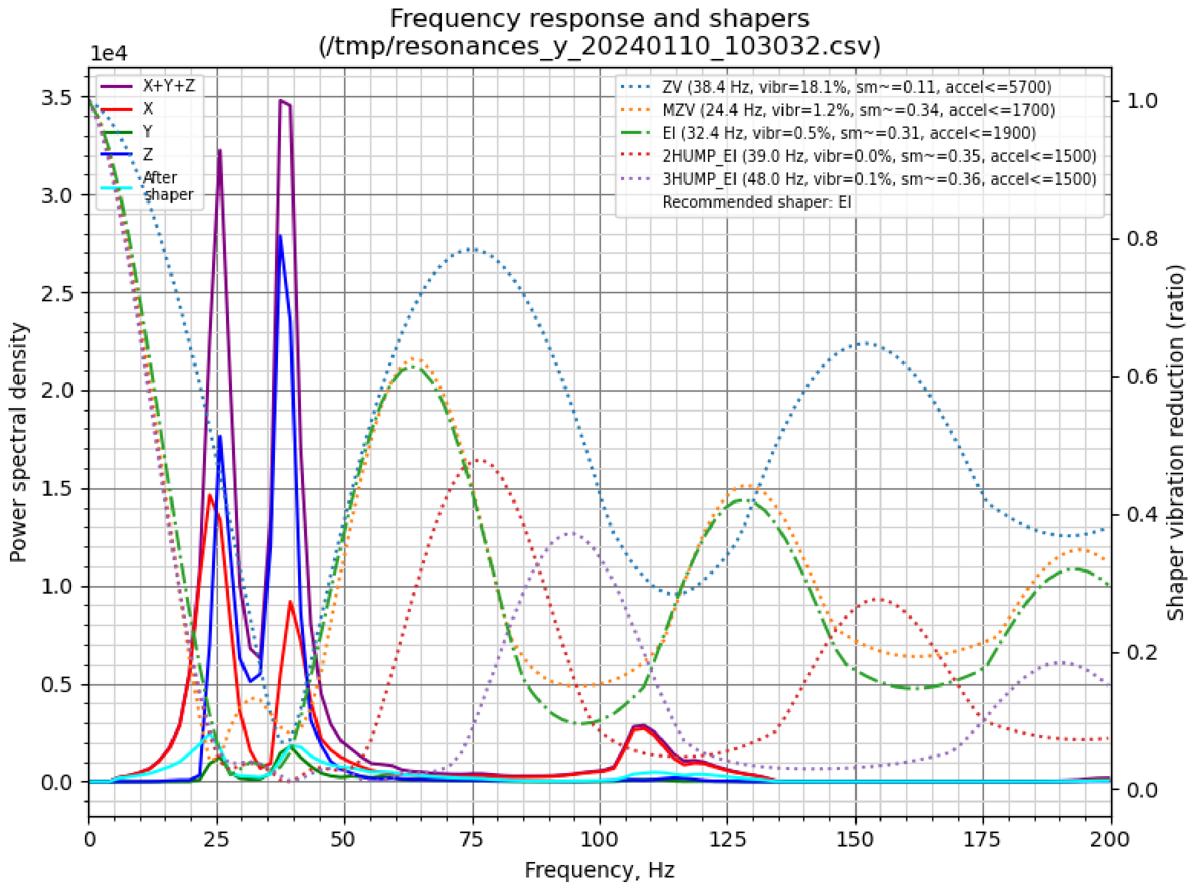

Fig. 8
Graph generated by the stand-alone
Scrip for the X-axis

and quality so we upped the acceleration to 2500.

This acceleration of 2500 mm/s^2 is considerably higher than the stock 1000mm/s^2, but acceleration alone doesn't make a big difference in print times. **Input Shaper**, through the way it works, allows us to use higher print speeds in our slicer without accentuating the ghosting effect.

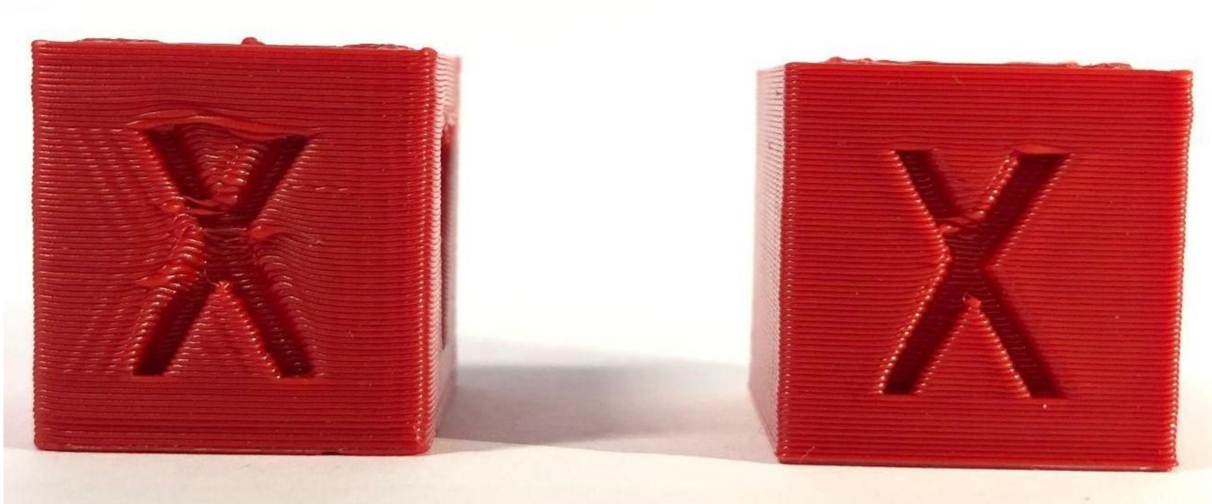

Fig. 9 Cube without Input Shaper (left), cube with Input Shaper (right)

The pressure advance feature can help reduce ooze. In the ideal case, as an extrusion move progresses, the same volume of filament should be deposited at each point along the move. It's common while following basic extrusion formulas to cause too little material to exit the extruder at the start of an extrusion move, and too much material to exit after the extrusion ends. **(Klipper 3D Printer Firmware, n.d., d)**

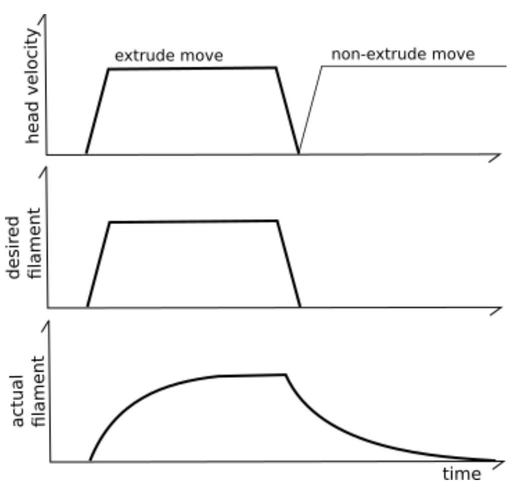

Fig. 10

Extruder moves as explained on the Klipper3d website

The "pressure advance" system attempts to account for this by using a different model for the extruder. Instead of assuming that the volume of plastic fed into the extruder will immediately exit it, Klipper uses a model based on pressure. The key idea is that the relationship between filament, pressure, and flow rate can be modeled using a linear coefficient:

pa_position = nominal_position + pressure_advance_coefficient * nominal_velocity

The basic pressure advance formula can cause the extruder motor to make sudden velocity changes. Klipper implements "smoothing" of the extruder movement to avoid this. **(Klipper 3D Printer Firmware, n.d., c)**

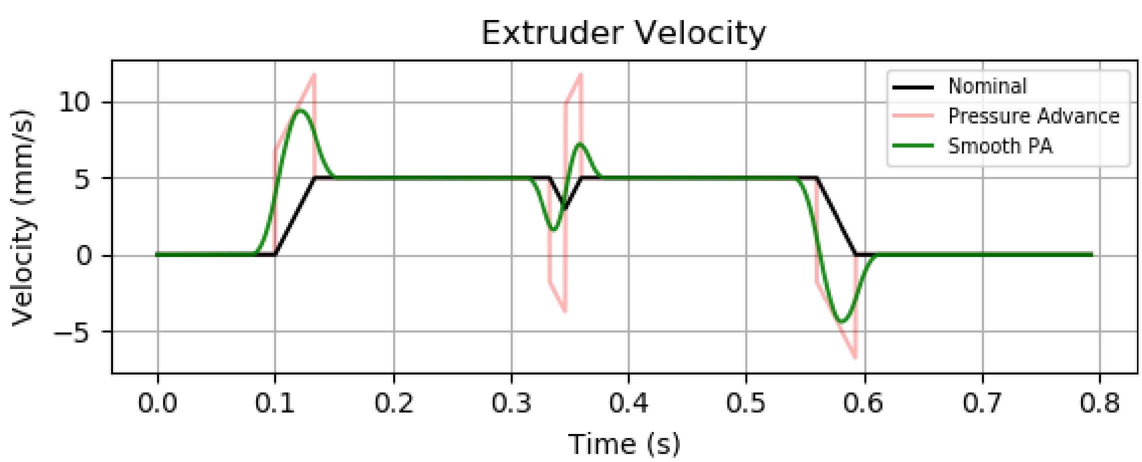

Fig. 11
Extruder velocity over time PA graph from Klipper3d website

The pressure advance system causes additional filament to be pushed into the extruder during acceleration. The higher the desired flow rate, the more filament will be pushed in during acceleration to account for pressure. During the deceleration, the extra filament is retracted (the extruder will have a negative velocity). **(Klipper 3D Printer Firmware, n.d., c)**

To calibrate pressure advance, the printer must be configured and operational as the tuning test involves printing and inspecting a test object. We used a slicer to generate the g-code for a large hollow square, with zero infill, a layer height of 75% of the nozzle diameter (nozzle of 0.4 mm), and a print speed of 100mm/s. Then we used the **SET_VELOCITY_LIMIT SQUARE_CORNER_VELOCITY=1 ACCEL=500** and **TUNING_TOWER COMMAND=SET_PRESSURE_ADVANCE PARAMETER=ADVANCE START=0 FACTOR=.005** commands and started the print.

The **"TUNING_TOWER"** command instructs Klipper to alter the pressure_advance setting on each layer of the print. Higher layers in the print will have a larger pressure advance value set, and "**SET_VELOCITY_LIMIT"** makes the nozzle travel slower through corners to emphasize the effects of extruder pressure. **(Klipper 3D Printer Firmware, n.d., d)**

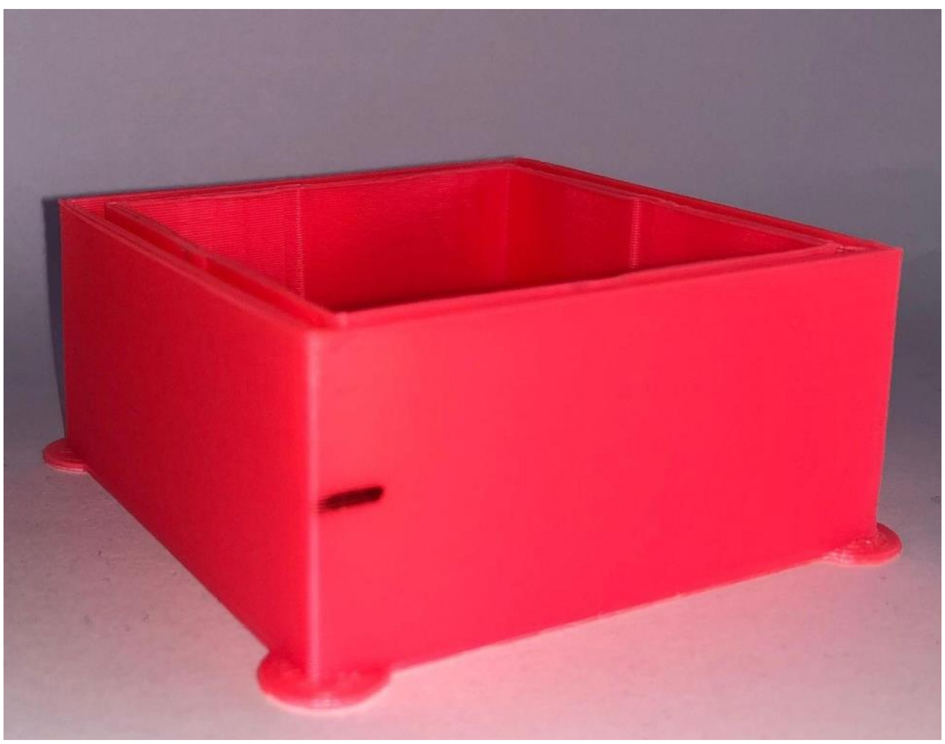

Fig. 12
Pressure Advance Tower with a marking at the height with the sharpest corners

` After about half an hour we observed on the tower that the area with the sharpest corner already passed, and on the higher layer there were signs of under-extrusion, so we stopped the print. We measured the height of the best corner at about 13.50 mm distance from the base and marked it, and using the given formula of **pressure_advance = <start> + <measured_height> * <factor>**, we got a value of 0+13.50*0.005= 0.0675, which we saved into the printer config file.

Performance improvements

2.5 Theoretical limits

If we're talking about our maximum print speed, we're limited by two big factors: how much filament can we push through the nozzle and how fast can we cool it afterward? As our cooling fan is working at 100% capacity during our prints, we can't gain any benefits without finding a better cooling solution like a bigger fan, a larger quantity of fans, or a more efficient cooling duct.

After doing some extrusions of 20mm of filament at different feed rates, we observed our hotend is capable of a volumetric flow of 12 mm^3/s at an extrusion feed rate of 5mm/s on the 0.4mm nozzle we have installed. We know that volumetric **flow = speed * line width * layer height (Ellis, n.d.).** With this formula, we can determine that our theoretical maximum print speed is **150 mm/s** with a 0.4 nozzle and a 0.2 layer height.

2.6 Real-world performance improvements

For our testing, we printed 3 models, with all the quality improvements and higher printing speed, and compared them to how they used to be printed before all the changes and calibrations. We chose a **calibration cube (iDig3Dprinting, 2016),** because it's small, and doesn't have many features, making it easier to inspect the surface quality, and a **speaker ring (zerpie2, 2019),** because it's round and combines both the X and Y-axis in its moves at the same time. Furthermore, for our third model, we chose an **articulated dragon (kimseungwoo11, 2022),** because it's a more complex and organic shape, that should benefit from both higher accelerations and faster printing speed settings in the slicer, while also showcasing printing errors.

For our slicing, we used Ultimaker Cura 5.5.0 slicer (**https://ultimaker.com/software/ultimaker-cura/**) since it's a commonly used slicer. For our settings, we added the Tevo Black Widow printer as a profile, and for our default prints, we used the **Draft 0.3 mm** layer height, or **Normal 0.2** mm layer height profiles without any changes.

For this section of real-world improvements and testing, we used **CR-PLA Fluo-Red** filament from Creality, with a nozzle temperature of 210°C and a bed temperature of 60°C.

In the following section, we will describe the details of the printing process and the time improvements achieved. Any changes that we made to the slicer settings or particularity will be mentioned for each model.

2.6.1 Calibration cube

For our “fast” print

Settings: Normal 0.2 mm profile - 0.4 mm nozzle

- Print speed: 100 mm/s
- Generate support: no
- Build plate adhesion: brim
- Ironing: enabled

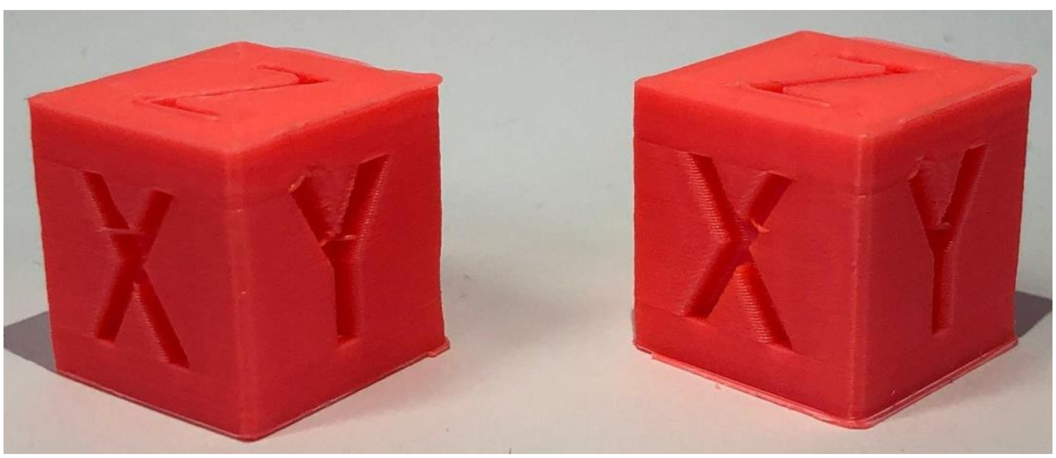

Fig. 13
Calibration Cube 50mm/s (left) next to Calibration Cube 100mm/s (right)

For our “slow” print we used the same settings, only with the print speed being 50mm/s. The “fast” print finished in **23m 2s** with an average of **13.9s** per layer, compared to the “slow” **30m 38s** with an average of **18.5s** per layer, giving us an approximate **33% improvement**.

2.6.2 Speaker Ring

For our “fast” print

Settings: Normal 0.2 mm profile - 0.4 mm nozzle

- Print speed: 100mm/s
- Generate support: yes
- Buidplate adhesion: brim
- Infill: gyroid
- Ironing: enabled

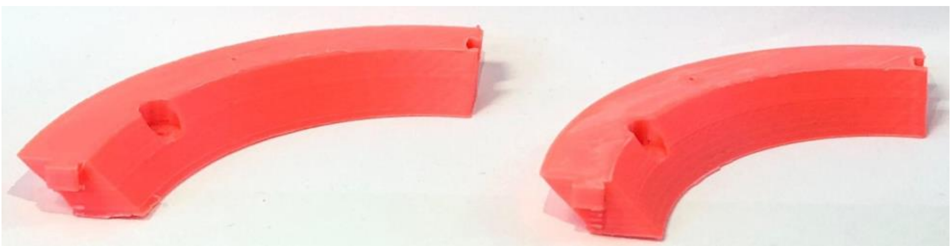

Fig. 14
Speaker Ring 50mm/s (left) next to Speaker ring 100mm/s (right)

The “slow” profile was the same, only with the print speed being 50mm/s. Our print time went from **3h 17m 57s** to **1h 49m 33s**, or from an average of **3m 15s** per layer to an average of **1m 46s** per layer, with an approximate improvement of **55%**.

2.6.3 Articulated dragon

For our “fast” print

Settings: Normal 0.2 mm profile - 0.4 mm nozzle

- Print speed: 100 mm/s
- Generate support: yes
- Build plate adhesion: brim

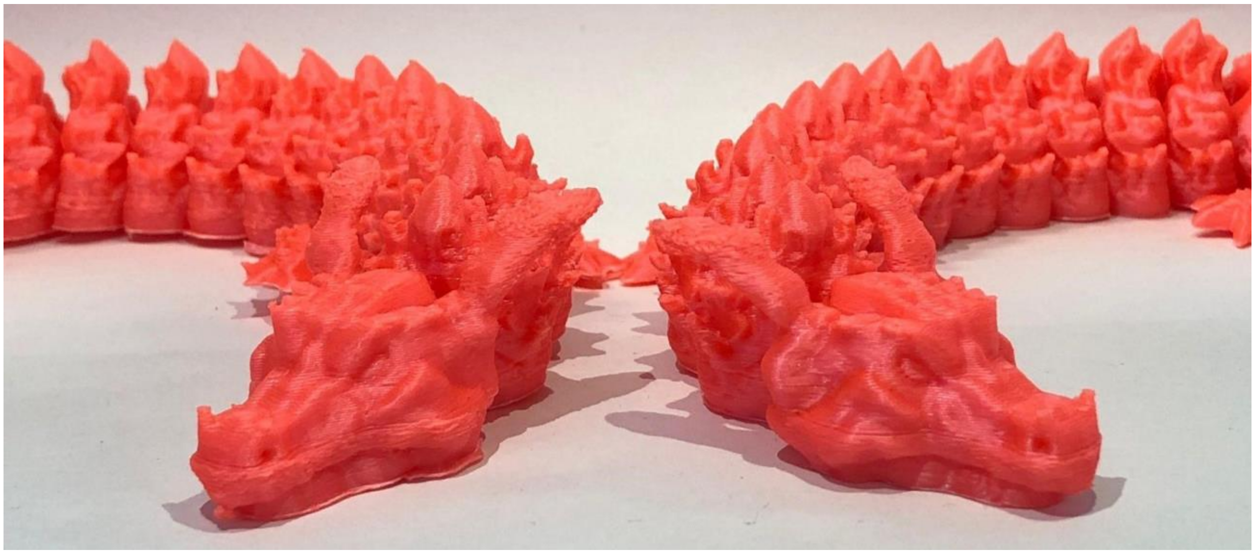

Fig. 15
Articulated dragon 50mm/s (left) next to articulated dragon 100mm/s (right)

The “slow” profile was the same, only with the print speed being 50mm/s. Our print time went from **12h 15m 2s** to **7h 54m 13s**, or from an average of **5m 52s** per layer to an average of **3m 47s** per layer, with an approximate improvement of **55%** in print time.

Conclusions

Overall, we improved the surface finish while also improving the printing time by an average of **47.6%**. We have improved the quality of our prints going from parts with a lot of surface quality issues to prints with barely any major defects while also reducing the print times to around half on average, this being best shown in Fig. 15, overall achieving our set goal of improving one without sacrificing the other, thanks to Klipper and it’s tools.

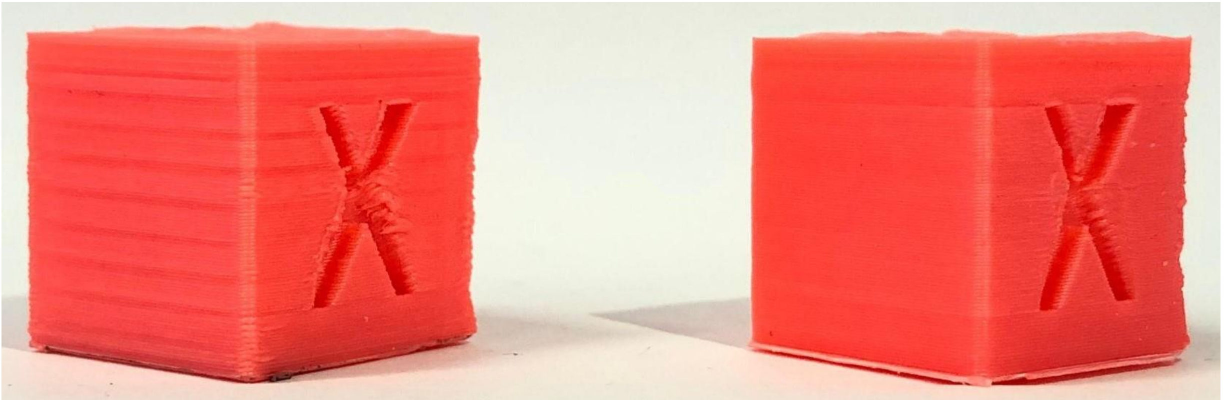

Fig. 16
Calibration cube printed 50mm/s before all improvements (left) next to calibration cube printed at 100mm/s after all improvements are applied

2.7 Limitations

In our research we didn't:

- Try more nozzle sizes and types, we stuck with only 0.4 mm nozzles
- Try more materials besides PLA and see if the performance is any different with other common materials like PETG or ABS
- Try PLA from a multitude of manufacturers, as it could have an impact on maximum print speed or printing times
- Try multiple printer configurations like Core XY or Delta printers, we only tested on a bed slinger type of printer
- Try different slicer options or settings to print faster or better quality parts
- Try different extruder hotends that could melt plastic better or worse than ours

All of these factors could and most probably make a difference in the quality of parts as well as in how fast you can print, the results of the "Quality improvements" steps like **Input Shaper** or **Pressure Advance** would be different from our own, based on the specific setup of the printer or material used.

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