Printing at 300 mm/s is something quite impressive. You’ve probably seen it at least once on a few printer specs or on a video. Are they really printing at this speed? Maybe, but it is very hard to verify. Printing at this speed is possible but under certain conditions.

This blog will explore all the requirements to verify, understand and configure a printer so it can reach 300 mm/s or as close as possible. It might also be very useful if you are building your printer.

This first part explores the components involved in both speed and acceleration performance. It also compares the two most commons 3D printer types.

Motion basics

Before heading to hardware limits, let’s make sure we understand the basics. There are some very specific details used in 3D printing that are pretty unique, and misleading to what is seen in the industry standard, see “Jerk” below.

Speed

Speed is the easiest parameter to get, we see it in many aspects of our lives: driving (km/h), downloading (kB/s), etc. A 3D printer moving at 100 mm/s require 1 second to move 100 mm away. However, the speed does not change instantaneously, it slowly gets faster until it reaches it’s target speed. This transition is called acceleration.

Acceleration

Acceleration is a little bit harder to get. It is the change of speed in time. For example, a car start at 0 km/h and want to reach 100 km/h. It starts moving slowly and then reach 100 km/s in 10 seconds. It means that each second, the speed increased by 10 km/s, so the acceleration is 10 km/h/s. This unit can be confusing, but it is basically a length / time^2, this is the reason why you see acceleration values in mm/s^2 in 3D printers. Since the components are light and small, acceleration can be very high compared to a moving car.

Based on Marlin firmware, the standard acceleration is 3000 mm/s^2, which is a good value for a rigid setup. A 3D printer would only require 0.033 seconds to reach 100 mm/s. Some manufacturers reduce acceleration below 1000 mm/s^3 to reduce corner ringing and other imperfections.

Jerk

As mentioned above, jerk is misleading in 3D printing. In industrial motion application, jerk is the variation of acceleration, so the same logic can be applied between jerk and acceleration than we applied between acceleration and speed. Its unit can be mm/s^3.

Jerk is not used in trapezoidal acceleration profile, which is the motion profile used in 3D printers. This means the acceleration changes abruptly.

The jerk we see in 3D printing has units of mm/s. As you probably remember, these are speed units. Actually, in 3D printing, jerk is used as a threshold for minimum speed requiring acceleration. For example, a standard jerk value of 20 mm/s will make any move below 20 mm/s without acceleration. This happens often when an infill line is very short and the 3D printer will vibrate extremely quickly.

Motion profile

Motion profile is controlled by the firmware. The most common profile is trapezoidal because the logic is very easy to program. The acceleration is constant, either positive (accelerating) or negative (decelerating). Being easy to program has few disadvantages. Compared to other known motion profiles types, it reaches the lowest acceleration for the same motor power. Also, the movements can be very rough, because the jerk is considered infinite.

Advances motion profile can get smoother motion, higher acceleration, and higher velocity than trapezoidal profile, such as cycloidal and polynomial. You may want to read this great article about jerk, acceleration and motion profiles.

Hardware

Your hardware is the first limit for a high-speed printing. Specifications will help you determine the best configuration to reach 300 mm/s. You will need to make a few calculations, these will be explained in the next part.

Construction strength

Make sure to get the most reliable solution for your budget. Higher print speed requires more output torque, a geared extruder is a better choice for optimal performance.

For long lasting reliability, all-metal construction extruder should be preferred. Heated bed, hotend, and enclosed chamber will heat the air around the extruder and greatly reduce the mechanical properties of any plastic components.

Dual pitch system reduces the risk of grinding the filament. At high speed, the high force needed to push the filament will increase the chances of slipping and grinding.

The DyzeXtruder GT is a high-performance solution for this kind of application. It has a no-compromise construction for amazing print quality, even at very high speed. Check the shop page for more information.

Optimal spring tension

There is less adjustment required with the extruder than with a hotend. If you have an adjustable spring tension, find the sweet spot where your filament does not grind and where you do not reduce your maximum motor torque due to over-tightened springs.

Maximum speed

Geared extruder greatly benefit from higher torque, but the maximum speed is decreased. For a Nema17 motor, make sure to use a motor with a ratio lower than 12:1. Higher ratios won't be able to extrude fast enough.

NEMA17 Stepper motor

Motors

The X and Y motor will be working very hard at this speed. Some high torque motors won't be able to reach high rotation speed, some high inertia won't be able to reach high acceleration. We will check how to determine the maximum performance of a motor and what can be improved.

Motors specification

Your stepper motors is built to get a good compromise between torque and speed. You can have two completely different motors with the exact same physical size if you change the windings. A higher inductance stepper will lead to a higher torque, but a lower maximum speed. Since a higher inductance magnet takes longer to get activated, the maximum speed is reduced.

There are very common standards between motors manufacturers, but any variation can be customized.

A bigger motor will have more torque, but higher inertia. Inertia is linked to acceleration. The higher the inertia, the higher is the torque required for a given acceleration.

Printer

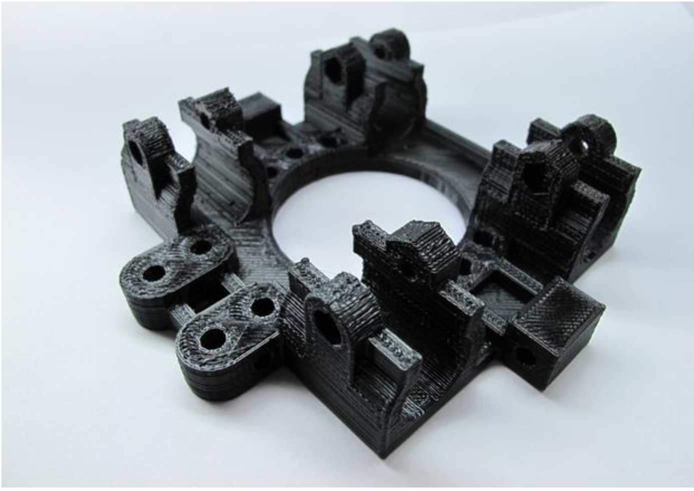
The printer is considered as the 3 axis movement system. Cartesian and delta are the two most common used in 3d printers. Their construction will greatly impact the speed and acceleration. They both have their own advantages. The major point to focus is the weight because the speed will be determined by the motors.

Cartesian vs Delta

Cartesian printers are very common, and deltas are gaining in popularity. It can be very hard to compare both motion system because there are many variations with their own advantages.

	Cartesian	**Delta**
Pros	Easy to debug Easy to calibrate Carriage can be heavy, direct drive possible Low CPU requirement	Fast prints High speed on each axis High acceleration Low maintenance
Cons	Print quality highly depends on printer robustness Low Z axis speed Low acceleration	Carriage must be light, direct drive not possible High CPU requirement Arm vibration

Carriage

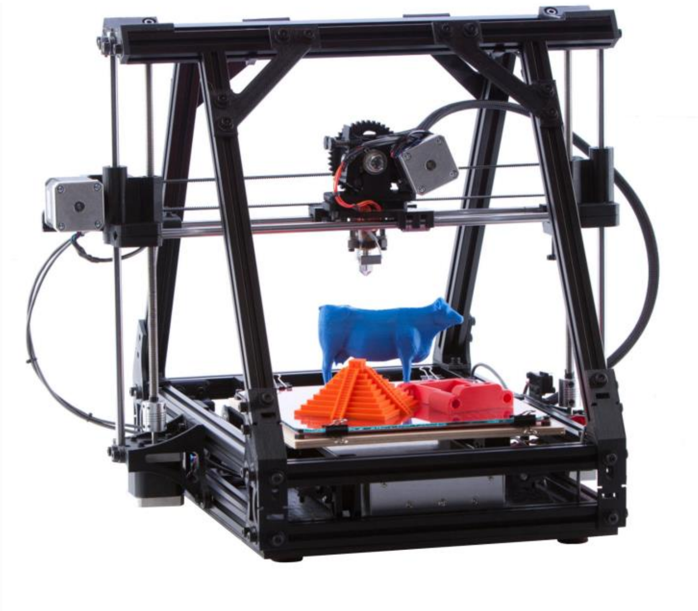


Reinforced Prusa X Carriage by jonaskuehling

The carriage moves the hotend and sometimes the extruder. The lighter it is, the higher the accelerations can be. The bearing should be well integrated to avoid the added mass of a bearing housing. Light material such as aluminum should be preferred with as many material removals as possible. Many great designs exist made from plastics such as the one from jonaskuehling.

Delta printers have another name for a carriage: effector. It is very rare to see an extruder mounted on it due to the high mass. The long arms aren’t made to move heavy stuff, they are better at moving light objects very quickly. It is commonly used as a picking robot.

Robustness

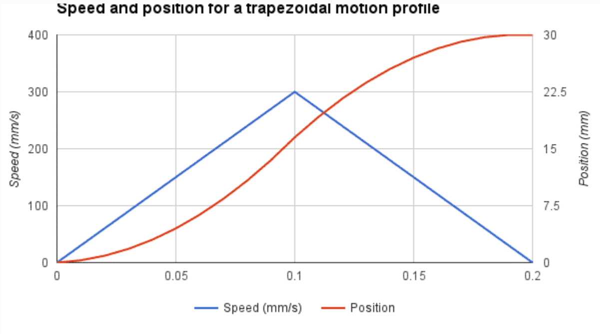


Mendel Max seen at 3D hub

High acceleration means high dynamic forces. The printer must be robust enough to keep good printed part tolerances. Some printers are made to be economic and aren’t designed to handle such forces. Cubic and prism frame shape should be preferred over open frame design.

The Mendel Max is a great example of a good frame design. The number of frame parts is minimized and still, the frame is very sturdy.

Motion



Speed and position graph

As we have previously seen the relation between speed, acceleration, and jerk, we will now explore these parameters in our goal to achieve 300 mm/s. Let's consider our printer have an acceleration setting at 3000 mm/s^2. Remember that most printers have lower settings.

$$TimeToAccelerate = \frac{Speed}{acceleration} = \frac{300mm/s}{3000mm/s^2} = 0.1s$$

Knowing that our printer takes 0.1 second to reach its full speed isn't very useful. However, we can find the minimum distance for maximum speed easily.

$$MinimumDistance = \frac{1}{2} * Acceleration * Time^2$$

$$= \frac{1}{2} * 3000 * 0.1^2 = 15mm$$

15mm is quite long for a single edge. Remember that this distance is for **accelerating only**. The worst case, like a square edge, will require decelerating too, so the same length will be required. In short, we need to print a **30mm square** if we want to reach 300 mm/s during a fraction of a second. In this case, the average speed will be about half of the max speed, so 150mm/s .

Hotend

As you've seen in part 1, we have determined that the maximum output flow using a 0.40mm nozzle is about 15 mm^3/s at 250°C. The optimal line width is between 1.1 and 1.5 times the nozzle diameter, so between 0.44mm and 0.60mm. Let's consider a line width of 0.50mm for this example. We can now determine the maximum layer height:

$$LayerHeight = \frac{Flow}{LineWidth * Speed} = \frac{15mm^3/s}{0.50mm * 300mm/s} = 0.10mm$$

0.1mm layer is a good setting for printing great quality prints. We will see later if we can obtain a quality print with these settings!

Extruder

Based on the hotend maximum flow, you can determine the filament speed and your motor rotation speed.

$$FilamentSpeed = \frac{4 * Flow}{\pi * FilamentDiameter^2}$$

$$= \frac{4 * 15mm^3/s}{\pi * (1.75mm^2)^2} = 6.23mm/s$$

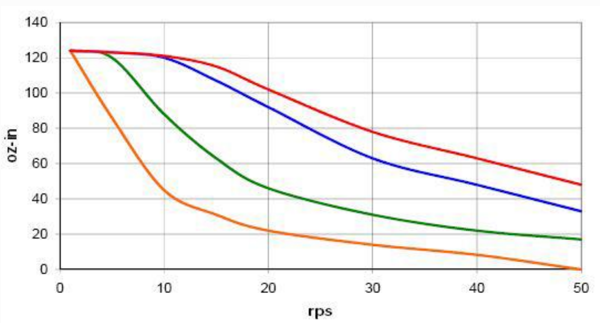
To measure the rotation speed, it is better to use the firmware steps/mm than measuring the outer diameter of the driving wheel. The teeth penetration in the filament is important to consider. We will consider the values for the DyzeXtruder GT, and we will compare the result with the motor specs later.

$$RPM = \frac{FilamentSpeed * MotorSteps * GearRatio}{steps/mm * \mu stepping} * 60$$

$$\frac{6.23mm/s * 200steps/turn * 5.65}{742steps/mm * 16} * 60 = 35.6RPM$$

Stepper motors are rated from 800 up to 5000 RPM, depending on the motor, voltage, and driver. 35 RPM is nothing to worry about.

Motors



Stepper curve from Applied Motion

Steppers have a unique torque-RPM curve due to the way they work. They start with a high torque which slowly decreases with speed. Depending on the parameters, some motors will be able to maintain their maximum torque for a wide range of speeds.

If we take the 0.9° stepper motor from the previous example, we can easily find the maximum RPM for maximum torque using the following formula:

$$MaxRPM = \frac{Voltage}{Inductance*2*Current*Steps} * 60$$

$$= \frac{12V}{0.004H*2*1.68A*400steps/rev} * 60 = 133.9RPM$$

133.9 RPM may sound low, but remember that it is the maximum speed at maximum torque. The maximum speed with lower torque is determined by experimentation and torque curves should be consulted.The torque is lower because the voltage applied is reduced by the back electromotive force (back EMF), thus each coil can’t reach the full magnetic force. Back EMF increases with motor rotation speed.

Extruder Motor

As you can see, the previous motor has no problem driving a 5.65:1 geared extruder for a 300 mm/s print. The actual motor inside the DyzeXtruder GT is much smaller and requires a lower current thus increasing the maximum RPM at maximum torque to 310 RPM. The specs are 1A, 200 steps and 0.0058mH. This motor can still run faster while maintaining its output torque.

Axis motor

Accelerating at 3000 mm/s^2 requires strong axis steppers. Depending on the driving mechanism, higher speed or higher torque will be required. The methodology is very simple:

- Calculate the total mass
- Find the equivalent in moment of inertia
- Determine the required torque
- Compare with motor

Belt

A general note regarding the belt is the pulley pitch diameter. It is the effective diameter where linear and angular motion are linked. We will often use the pitch radius for torque and speed calculation. For a 20 teeth GT2 2mm pitch pulley:

$$PulleyRadius = \frac{Teeth*Pitch}{2*\pi}$$

$$= \frac{20*2mm}{2*\pi} = 6.36mm$$

The length moved by a full pulley turn can be determined by the following formula:

$$PulleyTurn = Teeth * Pitch = 20 * 2mm = 40mm$$

X Axis

Belt drive is very common and very well suited for 3D printers. The belt mass is pretty negligible and the cost is low. However, the belt requires tensioning and can act as a spring and vibrate, or “ring”, especially at corners. The most common pulley size is 2mm pitch GT2 with 20 teeth.

$$MaxRPM = \frac{Speed}{PulleyTurn} * 60$$

$$= \frac{300mm/s}{40mm} * 60 = 450RPM$$

As we previously checked with two different motors, the maximum speed is currently higher than the results we had. It means simply that we cannot consider the maximum torque when the printer is running at 300 mm/s. The torque requirement will depend on acceleration and carriage mass. The extruder is often the heaviest mass to move on the X axis due to the big motor driving it. Most NEMA17 used in extruders can weight between 350 grams and 450 grams alone. The extruder with all its components can weight as much as 500 grams, which is a lot. The DyzeXtruder GT uses a custom geared reduction to lower the motor mass while maintaining a high torque output. The extruder weight only **275 grams**, less than most extruder on the market.
To calculate the torque, we will first need to find the moment of inertia of our carriage. It depends on its mass and the pulley diameter. It also depends on the motor rotor inertia. Other components such as the belt, pulley and bearing have a negligible role in inertia.

$$MomentOfInertia = CarriageMass * PulleyRadius^2 + RotorInertia$$

If you have a DyzeXtruder GT with a DyzEnd and a printed carriage, the mass will be around 350 grams.

For a generic extruder with a powerful motor, a generic hotend and a printed carriage, the mass will be about 650 grams.

A genera NEMA17 stepper motor will have a rotor inertia of about 6.8 kg.mm^2 (68 g.cm^2)

$$MomentOfInertia = 0.35kg*(6.36mm)^2+6.8kg.mm^2 = 20.98kg.mm^2$$

We also need to convert our linear acceleration to angular acceleration:

$$AngularAcceleration = \frac{LinearAcceleration}{PulleyRadius}$$

$$\frac{3000mm/s^2}{6.36mm} = 471rads/s^2$$

Now we can calculate the acceleration torque:

$$AccelerationTorque = MomentOfInertia*AngularAcceleration = 20.98kg.mm^2*471rads/s^2 = 9889kg.mm^2/s^2 = 9.889mN.m$$

As you can see on Laser 2000 NEMA17 motor, this stepper should be able to offer the required torque for our acceleration and carriage without trouble. However, with a heavier carriage as explained earlier, this motor might not be able to accelerate the carriage and would skip steps. The acceleration should be reduced, or a lighter extruder should be chosen.

Y Axis

The same methodology applies to the Y axis. for a 200mm x 200mm print bed, here are the components weight:

- Glass: 350 grams
- PCB heated bed: 125 grams
- Y axis Frame: 215 grams
- Hardware: 25 grams
- Printed part: 300 grams

For a total of 1015 grams. As you can see, this is a lot more than the X carriage total mass. You need to include a big printed part mass because you don’t want your printer to start skipping at the end.

With the same pulley and motor, we end up with an inertia of:

$$MomentOfInertia = 412.8kg.mm^2 + 6.8kg.mm^2 = 47.94kg.mm^2$$

The required torque would then be:

$$AccelerationTorque = 47.94kg.mm^2 * 75rads/s^2 = 22589kg.mm^2/s^2 = 22.589mN.m$$

The Y axis motor has a bigger load than the X axis for a moving bed. It can result in more pronounced flaws on a printed part on this axis.

Ball Screw

Ball screws are less common in 3D printers but more common in CNC. It has a higher mass, thus a higher inertia, and might be bottlenecking a 3D printer. Let's see what would happen on a Y axis.

Most economic ball screws are 12mm in diameter and have a pitch of 4mm.

Since these kind of screw are very efficient, the torque required to move a mass of 1015 grams can be quite low.

$$LoadTorque = \frac{Pitch*Friction*Mass*Gravity}{2*\pi}$$

$$= \frac{4mm*0.10*1.015kg*9807m/s^2}{2*\pi} = 633kg.mm^2/s^2 = 0.633mN.m$$

The rolling balls generate very little friction and the lead pitch act as a reduction ratio compared to a belt system. For a full turn, the ball screw will rotate 4mm, compared to 40mm with a 20 teeth pulley.

The most important factor with ball screw is the inertia. This reduction ratio will require the motor to accelerate about 10 times faster than a belt system. Added the inertia of the long screw, it can generate quite a lot of torque. To accelerate to 3000 mm/s^2 as required, we can determine the rotation acceleration with the following formula:

$$AngularAcceleration = \frac{LinearAcceleration}{Pitch} = 750revs/s^2 = 4712rads/s^2$$

The moment of inertia will be slightly different than before because the inertia of the screw is important compared to an aluminum pulley, we will add it to our inertia calculation.

$$MomentOfInertia = CarriageInertia + ScrewInertia + RotorInertia$$

$$CarriageInertia = Mass*(\frac{Pitch}{2*\pi})^2 = 1.015kg*(\frac{4mm}{2*\pi})^2 = 0.41kg.mm^2$$

$$ScrewInertia = \frac{Mass*Radius^2}{2} = \frac{\pi*Radius^2*Length*Density*Radius^2}{2}$$

$$= \frac{\pi*Length*Density*Radius^4}{2} = \frac{\pi*350mm*0.00785g/mm^3*6mm^4}{2} = 5.59kg.mm^2$$

$$MomentOfInertia = 0.41kg.mm^2 + 5.59kg.mm^2 + 6.8kg.mm^2 = 12.8kg.mm^2$$

Even if the low friction and the low advance per motor turn reduce the effective inertia for the bed, the screw has the biggest impact on inertia.

$$AccelerationTorque = 12.8kg.mm^2 * 4712rads/s^2 = 60319kg.mm^2/s^2 = 60.319mN.m$$

The torque required to drive a bed with a screw is more than **three times higher** than with a belt. However, keep in mind that the rotational speed for the pulley is about 10 times lower than with the ball screw (4500 RPM). The stepper motors aren't designed for such speed, thus the ball screw shouldn't be able to move faster than around 100 mm/s with this set-up. A higher pitch screw could help. For small and affordable 3D printers, belts are the way to go. On larger and heavier ones, ball screw will be the best choice.

Firmware

The first step in printing fast is to make sure our firmware can handle our required speed. We'll take a look mostly about maximum axis speed. This example will be based on Repetier firmware, but the equivalent configuration should be very similar between firmware.

Step Frequency

300mm/s is very fast and we need to make sure our microcontroller can handle this speed. Let's consider we have the following configuration:

- 1.8° Stepper motor (200 full steps per rotation)
- Stepper drivers configured at 16 µsteps
- 80 steps per mm (very common GT2 20 teeth pulley)

We can check the stepper driver input pulse frequency based on our setup:

$$StepperFrequency = StepsPerMm \times MaximumSpeed = 80 steps/mm \times 300 mm/s = 24000 steps/s$$

24 000 is quite a lot of steps per second. The theoretical limit for 8 bit based microcontrollers is around 40 000. However, at this speed, there is no more room for computation. The clever firmware programmer uses tricks such as the:

```
#define STEP_DOUBLER_FREQUENCY 10000
```

Or

```
#define ALLOW_QUADSTEPPING 1
```

Starting from 10 000 steps per second, the program will double the steps, and reduce its computation by half. The same logic applies to quad stepping. At 300mm/s, we are in quad stepping. Make sure it is enabled, or your microcontroller will have a bad time moving your printer at 300 mm/s.

Firmware modifications

Check the maximum speed and acceleration values. They must all be equal or above the ones we've found in part 2.

```
#define MAX_FEEDRATE_X 300
#define MAX_FEEDRATE_Y 300
#define EXT0_MAX_FEEDRATE 30
#define MAX_ACCELERATION_UNITS_PER_SQ_SECOND_X 3000
#define MAX_ACCELERATION_UNITS_PER_SQ_SECOND_Y 3000
#define MAX_TRAVEL_ACCELERATION_UNITS_PER_SQ_SECOND_X 3000
#define MAX_TRAVEL_ACCELERATION_UNITS_PER_SQ_SECOND_Y 3000
```

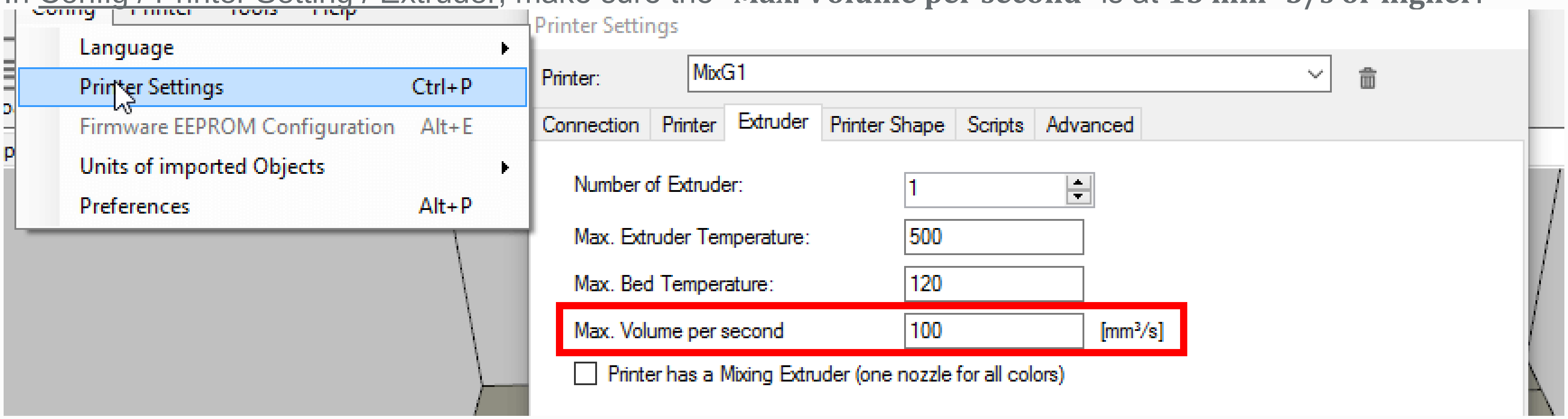
Slicer

The slicer has two option which should be checked:

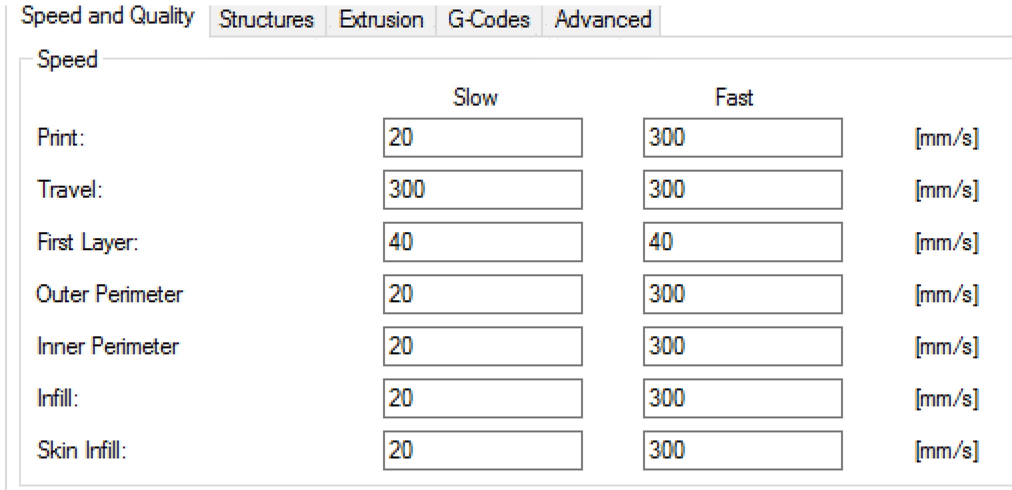
- Maximum axis speed
- Maximum flow

This example will use Repetier Host with Cura. Again, the same option should be easy to find with a different hos, controller, and slicer.

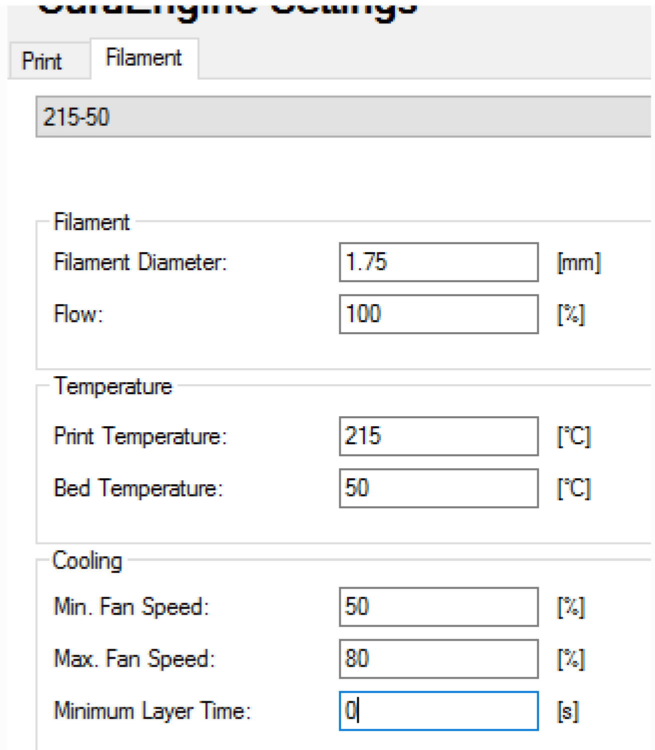
In Config / Printer Setting / Extruder, make sure the "**Max. Volume per second**" is at **15 mm^3/s or higher**.



in Slicer / Configuration / Print / Speed and Quality, make sure all the "**Fast**" values are at **300 mm/s, except for "First Layer**".



in Slicer / Configuration / Filament , make sure the "**Minimum Layer Time**" values is **0**.


Print
Filament
215-50
Filament
Filament Diameter:
1.75
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Flow:
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Print Temperature:
215
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Bed Temperature:
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Cooling
Min. Fan Speed:
50
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Max. Fan Speed:
80
[%]
Minimum Layer Time:
0
[s]

Test

Before printing an actual part at 300 mm/s, we will need to validate that our printer can handle all the parameters.

X & Y Speed Test

The first test will consist in validating the speed of our printer. It will be done using a simple G-code program where we increase axis movement speed up to 300 mm/s. The goal is to validate that the printer isn't blocked by any configuration in the firmware.

Copy and paste this test in a Gcode file and run it! Your printer will move back and forth 100mm, from 100 mm/s up to 300 mm/s by steps of 50 mm/s each time. Each back and forth is repeated 5 times. You need to hear a difference

Extrusion Test

This test will benchmark your hotend and extruder to make sure it can handle the required plastic flow. Three things can happen during this test:

1. Everything is fine and the amount of flow is close enough to the expected command
2. The extruder motor skips steps due to the force required to push the filament
3. The actual flow is too much below the expected flow because the extruder is slipping, but not skipping. Slipping is due to poor driving design or poor spring adjustment.

Mark your filament $100\mathbf{mm}$ above your extruder and check where your mark is once the test is completed. Having more than 5mm (< 95% efficiency) is considered problematic. Either:

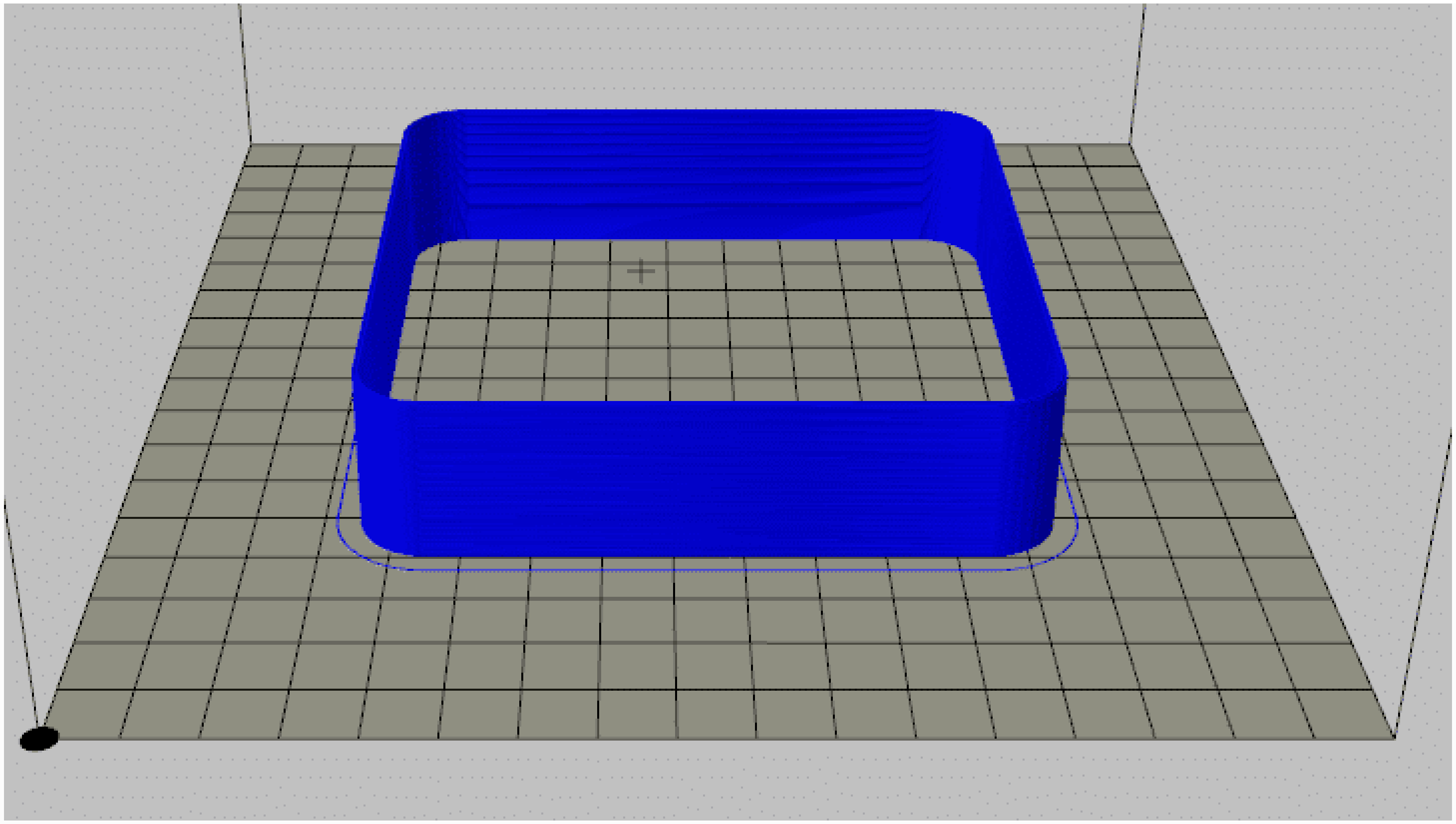
- Increase temperature
- Increase the flow
    - Please note that you might have reached your hotend and extruder limit if increasing the flow doesn’t improve anything.

Print Test

Our print will be very basic so we can easily see if something is wrong. Once this test works well, a complicated part will require fine-tuning in terms of cooling and acceleration values. As most parts have complex geometries, it is likely that the maximum speed of 300 mm/s isn’t constantly reached.

Any calibration cube can do the trick for this first print. You might need to scale it. Make sure:

- Layer height is **0.10mm.**
- Speed is **300 mm/s.**
- Part is at least **30mm long**, or your printer won’t accelerate to 300 mm/s.
- Feeds inside your Gcode are **F18000**, not lower. If it is, you have a wromg configuration on your slicer or host.



The video below shows our first print test. It is quite impressive to see a printer running at 300 mm/s!