When Input Shaping is Not Enough

A more robust vibration compensation approach
for high-precision 3D printing applications

Over the past year, multiple "high-speed" FFF printers have been introduced to the market. The product specifications and marketing messages for these printers are difficult to evaluate as there is no standard for assessing the actual effectiveness of the printer to produce high quality parts at a high speed. That is, the speed of the printer is often communicated as "up to a maximum speed of x" without addressing the quality of the part produced at a specific speed.

Ideally, we would have an agreed upon printed part(s) that would stand as an objective measure of the combination of speed and quality. A 3D printer could only qualify as a certain speed when the part is printed with an established level of dimensional precision and surface quality. Although the community sometimes uses the Benchy and/or ringing tower as a demonstration part, there is no existing quality requirements that must be met on those printed parts to confirm the actual "speed" achievement of the printer. The selection and implementation of such an objective speed/quality measure is a topic for another time; the point here is that standardized printing *quality* at a particular speed is not yet part of the discussion.

Some of the manufacturers of these "high-speed" FFF printers have been implementing improvements in their mechanical design, including adopting different designs, lightweighting their printers and adding single board computers to augment their machine control systems. Other manufacturers have opted for the stiffening approach by adding solid aluminum gantries and high powered servomotors resulting in heavier, more expensive machines that require more energy to operate.

Alternatively, some manufacturers have started using a software driven approach called *input shaping* to compensate for machine vibration that occurs when the printer is operated at high speeds. Ulendo Technologies, Inc. has been at the forefront of this transformation to software-driven vibration compensation in FFF 3D printing. The importance of software driven vibration compensation as a tool for boosting FFF 3D printing speeds was originally popularized by research at the University of Michigan led by the founder of Ulendo Technologies, Inc., Professor Chinedum Okwudire, in 2017[1]. As the 3D printing community grappled with how to introduce vibration compensation to open-source firmware, in early 2020[2] he encouraged members of the community on a public online forum to explore *input shaping* as a simpler alternative to the more-advanced FBS (filtered B -splines) approach that he had used in his 2017 research.

Then, in late 2020, the Klipper firmware team introduced input shaping into the world of open source firmware[3]. And this year, the Marlin firmware team introduced input shaping to its open-source firmware. The underlying framework for many of the available input shaping algorithms currently available in Marlin is enabled by the FT (fixed time) Motion software module contributed to the Marlin open-source project by Ulendo Technologies, Inc.

Originally put forward by OJM Smith in the 1950s, the input shaping technique (also known as command shaping) has been used in manufacturing machines for decades. But, while it can indeed provide compensation for vibration in many situations, *input shaping introduces undesirable results during the printing process, results that would not be acceptable for industrial 3D printing applications.*

What is Input Shaping?

Input shaping, a member of a class of band-stop filtering techniques, uses destructive interference between vibration responses to cancel out the vibration. Alternatively, Ulendo's underlying algorithm, FBS (filtered B -splines), is a more recent vibration compensation approach put forward in 2015 by Ulendo's founder, Professor Chinedum Okwudire. It prevents a machine from vibrating by sending the machine a command that is an inverted form of the way it naturally wants to vibrate. A very simplified way of describing what Ulendo VC does is depicted in **Figure 1**. Suppose we want a vibrating machine to travel straight. However, due to vibration it veers upward. Ulendo VC commands the machine to veer downward. In trying to follow the downward command, ends up traveling straight – which is exactly what we wanted in the first place. In other words, Ulendo VC tricks the machine into moving in the way it would have if it were a perfectly rigid machine with no vibration. Ulendo's core FBS algorithm falls into a broader class of so-called model inversion tracking controllers.

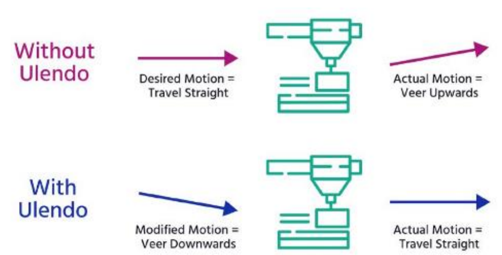

Figure 1: Ulendo VC "tricks" the machine

Ulendo VC's advantage lies in its ability to accurately measure the behavior of the machine and select the best strategy to eliminate the vibration, without the unwanted defects introduced by input shaping. Whereas input shaping uses "*delayed*" commands, Ulendo VC uses "*inverted*" commands. ***This distinction makes a world of difference in their respective performances.*** For more information on the technical reasons for this difference, refer to Ulendo's [Whitepaper Comparing Input Shaping and Ulendo VC](#).

Advantages of Ulendo VC versus Input Shaping

- **Higher Precision**

Ulendo VC can finely tune a compensation strategy so it only suppresses unwanted behavior. Input shaping compensates for vibration by suppressing a broad range of motion, which often results in *rounded corners*, or more generally, *tracking errors* between the desired path and the actual movement after the compensation is applied. While this may be acceptable for many hobby prints, users who require precision from their manufactured parts will not be satisfied with the results of a printer using input shaping. Here is an example of two parts printed at the same speed and acceleration: one with input shaping and one with Ulendo VC. The difference in precision is clear, as shown in **Figure 2.**

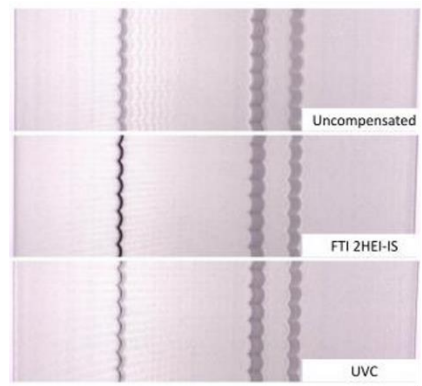

Figure 2: Ulendo VC versus input shaping

- **Improved Repeatability**

The error in the movement included by input shaping is dependent on speed and acceleration. As such, it can be difficult to consistently print a part with the same quality. Users will observe more rounding in printed parts as they print with higher acceleration. Ulendo VC maintains the part accuracy even at higher speeds and acceleration, allowing users to maintain the part quality regardless of their print configuration. This means that users can increase their speed and acceleration during a production run and have confidence that the high-speed parts will be as accurate as their low-speed prints.

- **Adaptability**

While some FFF 3D printer manufacturers have shifted to the CoreXY single extruder design to maximize the performance of the input shaping solutions, Ulendo VC is adaptable and can help to improve the performance of the machine regardless of the design. Manufacturers can keep the configuration that works best for their customers, including using multiple print heads, tool changers, cartesian or bed slinger designs and use Ulendo VC to compensate for unwanted vibration behavior. Ulendo VC can also be used to effectively compensate for unwanted vibration on 3D printers or robots with larger build volumes, which are often heavier machines, with more complex vibration behavior. With Ulendo VC, 3D printer manufacturers can maintain their preferred hardware/software platform.

- **Lower Implementation Effort**

  Manufacturers of FFF 3D printers seeking to improve the speed and quality of their machines rely on the Ulendo team to do the implementation tasks, thereby significantly reducing the amount of time to address vibration vis a vis implementing input shaping. These manufacturers redirect their engineering efforts to focus on other design aspects of their machines.

- **Less Noise**

  Ulendo's customized integrated stepping mechanism for FFF 3D Printers, uses a unique step generation method that allows for quieter operation with reduced mechanical and motor noise during typical printing operations.

Although originally designed to be implemented on newly manufactured 3D printers, Ulendo has adapted its solution to be retrofitted to printers already being used in the field. Specifically, Ulendo works with contract manufacturers or 3D printing service bureaus with a significant investment in printers they have purchased from 3D printer manufacturers or built on their own. Essentially, they can more than double the throughput of their existing investment in 3D printers.

If you are interested in supercharging the speed and quality of your extrusion-based printers, **contact us** on our website.

[1] https://www.3ders.org/articles/20171020-university-of-michigan-professor-doubles-3d-printing-speeds-using-vibration-mitigating-algorithm.html

[2] https://github.com/MarlinFirmware/Marlin/issues/16531#issuecomment-590684127

[3] https://www.klipper3d.org/Releases.html