

BOAZ: APPLYING INDUSTRIAL PRECISION-ENGINEERING PRINCIPLES TO A HIGH-PERFORMANCE DIY FDM 3D PRINTER



One Machine Built Twice!

Abhishal Kochhal (amkochhal@gmail.com)

Leland High School, 6677 Camden Ave, San Jose, CA 95120, USA

Motivation

Almost every convention in hobby printing is inherited from RepRap: printed structural parts, idlers on M5 screws, threaded-rod Z, rails aligned by eye. Those choices were optimized for a machine that could copy itself, not for one that could hold a tolerance.

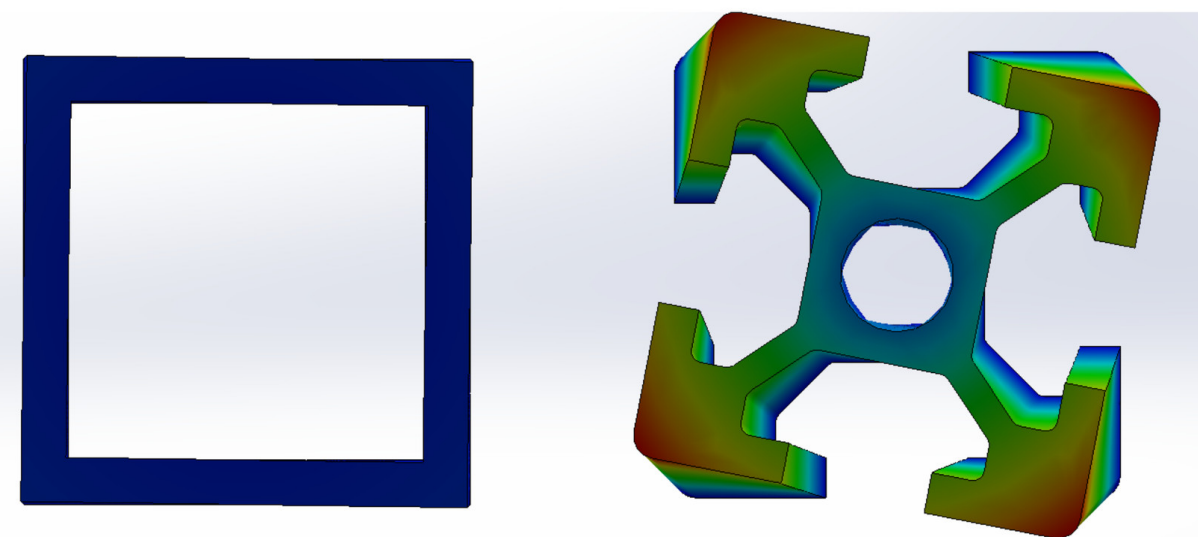
Claim: the persistent quality gap is not a materials problem and not a kinematics problem. It is a *measurement* problem, and it was solved a century ago in the next workshop over. Five practices from machine-tool building transfer directly:

- **Rigidity first:** gusset joints, not blind joints. The clearance is what lets a frame be trammed
- **Sandwich, don't cantilever:** idler stacks trapped between plates on machined standoffs
- **Reference against granite:** dial indicator on a granite plate, never against the frame you are correcting
- **Exact constraint:** a three-point Maxwell kinematic bed that trams itself on three motors
- **Sense, then decide:** eddy probe, accelerometer, driver telemetry

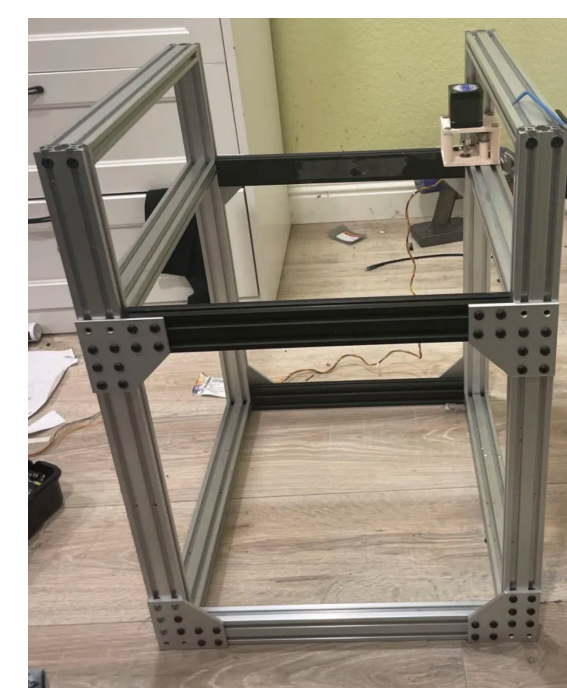
The test. Boaz is a CoreXY machine on a 20×40 extrusion frame: MGN12H rails, a carbon-fibre X beam, triple belted Z with a Maxwell coupling, an ATP-5 tooling-plate bed, Klipper on TMC5160 drivers at 48 V. It was built once with hobby practice and once with machine-shop practice, on the same design. The comparison class is other machines a reader might build, not a factory product. Eight criteria were fixed before the rebuild, each with a number and a measurement procedure:

- Skew < 0.1° and axis error < 0.2% on a Califlower artifact
- A printed threaded lid that engages and turns freely
- Bed mesh envelope ≤ 0.2 mm over the full print area
- Ten or more production plates started without jogging Z
- Pressed-idler runout < 0.001" TIR, four angular positions
- One dominant resonance peak; ≥ 20,000 mm/s² recommended
- A #SpeedBoatRace Benchy in 20 min or less at acceptable quality
- Fifty or more parts a day over a multi-day contract

Rigidity



Torsion in a square tube against T-slot extrusion of the same size. The slots cut the shear path around the section; the closed tube carries it continuously.



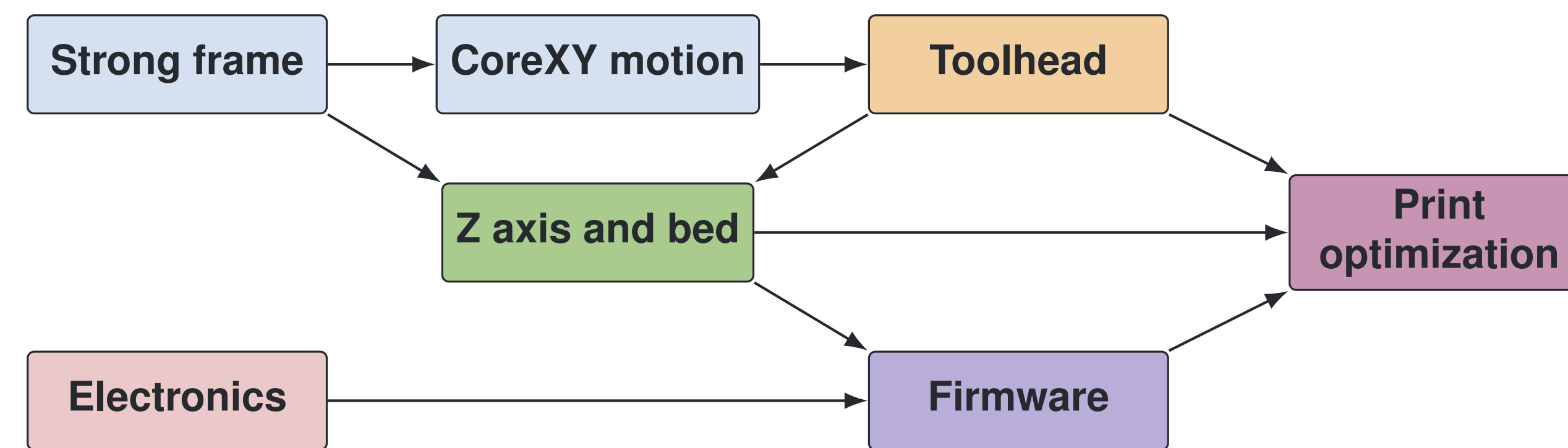
The first motion system, mocked up in printed PLA on the frame.

Frame: 20×40 extrusion, gusset plates at every corner. Blind joints were tried first and failed three ways: the angle is inherited from the saw cut, deep blind taps seize in aluminium, and three bolt axes meet at a box corner. Gusset clearance holes are what make tramping possible.

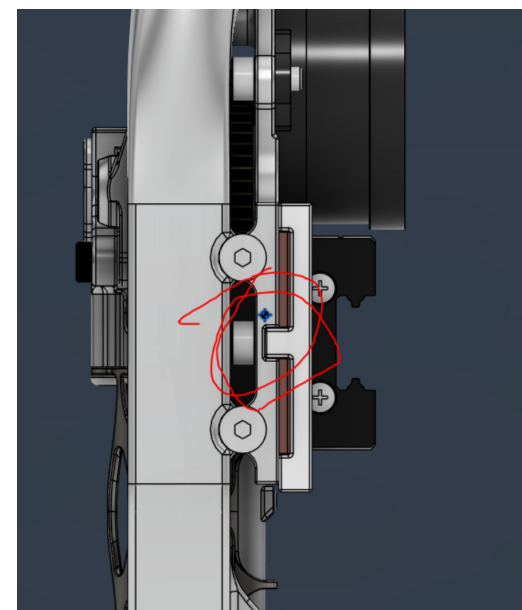
Gantry: torsion is the beam's critical load, and for a closed section $J \approx 4A_m^2 t/s$, with the enclosed area squared. Extrusion has no enclosed-area term. Use tube.

Printed structure: the PLA mock-up answered questions CAD had already answered and misled on the two that mattered, bearing seats and pin fits. Printed Z actuators later bent under belt tension. Load-bearing and locating parts went to sheet metal and machined spacers; plastic was demoted to brackets and ducts.

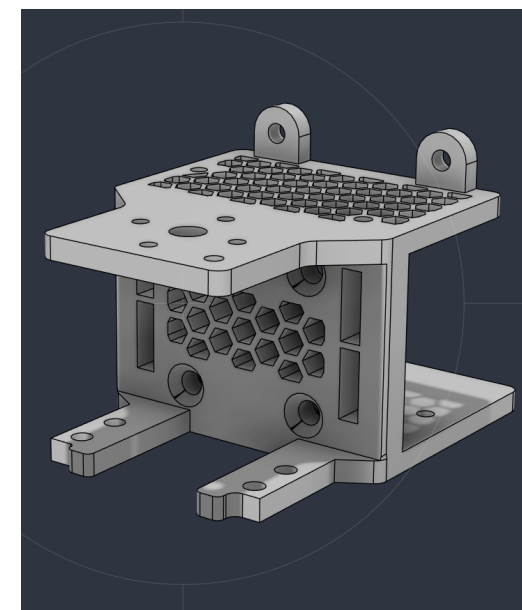
Innovation



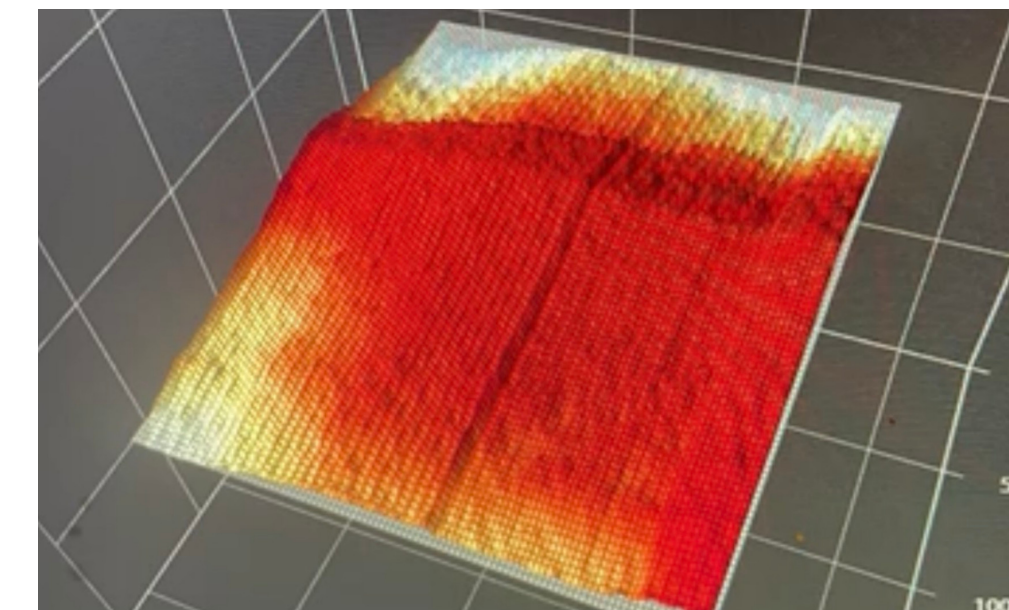
The build graph, drawn before any aluminium was cut; simplified here from the book's version to its seven top-level nodes. The frame blocks the motion system, which blocks any judgement about print quality: a frame error found late invalidates every conclusion after it.



Left: toolhead centre of mass in the plane of motion, forward of the X carriage. Drive force through the centroid gives translation, not rotation. Right: CAD of the toolhead body, printed in aluminium by SLM.



A 100×100 eddy-probe mesh of the ATP-5 bed, taken in minutes: 0 to 0.2 mm, ten thousand points against the touch probe's seventy.



Mechanics → **measurement** → **software**. The graph fixes the order. Bed and gantry rebuilds first; then eddy probing and accelerometer sweeps; only then skew correction, slicer tuning and input shaping. Compensation polishes a machine that is already true. It cannot create one.

Precision



Runout verification: squared between granite blocks, the indicator reads the idler face at several angles and heights. Unequal readings between heights mean a tilted pin, which steers the belt.

The 0.05 mm lesson. Dowel holes reamed to *nominal* pin size give a clearance fit: idlers lean and prints turn grainy. With eight or more idlers in a CoreXY loop, per-idler eccentricity does not average out; it accumulates as a position-dependent belt-path error. The rebuild reams 4.95 mm against a 5.000 mm pin, a nominal **0.05 mm interference**: a heavy press that yields the aluminium round the hole, where the preferred H7/p6 fit allows at most 0.02 mm. All twenty pressed assemblies were then measured; those above 0.001" TIR were remade.

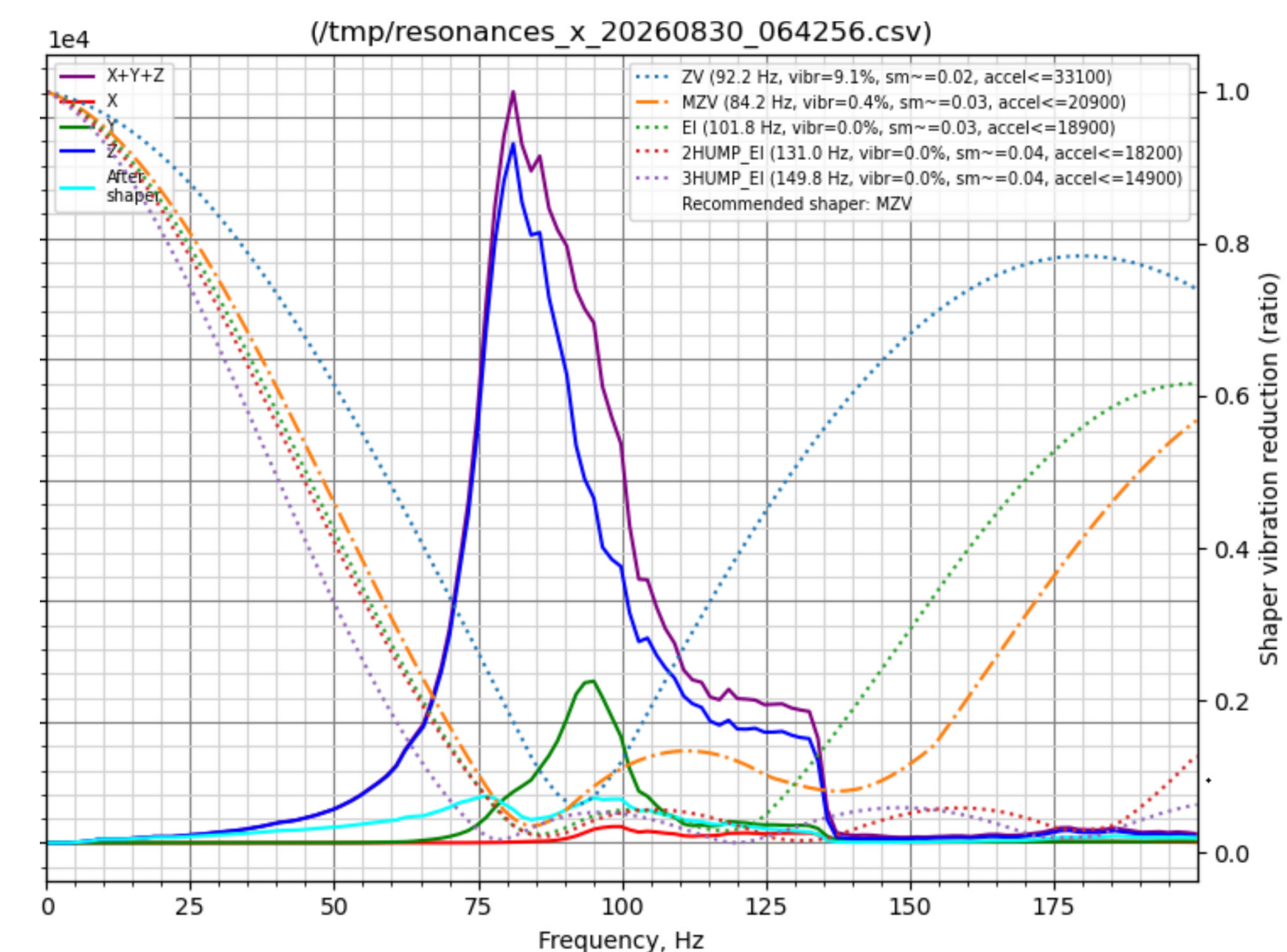
Never reference the frame. Y rails set to printed jigs good to 0.2 mm left the frame visibly bending as the gantry traversed. Trammed by indicator against clamped granite, the same rails ran full travel with no visible deflection.



Rail parallelism: the gauge rides the carriage and reads a granite block clamped to the frame.

Results

16:00 Benchy, first attempt (20 min target)
1,000 part PETG contract (lost to a \$300 machine)
8× flatter bed mesh (1.6 mm to 0.2 mm)
< 0.001 in locating runout, TIR



Input shaper sweep along X: one dominant peak, 20,900 mm/s² permitted under MZV. The Y sweep shows two peaks and caps the machine at 9,500 mm/s², short of the 20,000 target. No matched before/after sweep exists.

At equal print time the smokestack is cleaner and the bow and stern carry fewer artifacts. One paired print is an anecdote, not a margin. **The contract, reported honestly:** about 50 boxes a day for ten days, against ≈60 from a \$300 Elegoo Centauri Carbon beside it. **Boaz lost.** What it did establish is functional tolerance: threaded lids that engage freely, which the first build could not print, and about 100 consecutive plates with no Z-offset jogging.



Boaz, 16 min



Hev-Ort, 16 min

Conclusion: eleven dogmas, each with evidence

Each rule was earned by a failure on the first build and a measurement on the second. A rule without evidence attached is an opinion.

1. Stiff frame in large-section extrusion, gusset-joined, more joints than strength requires
2. Enclose the machine
3. Enclose the electronics separately
4. Design the toolhead for flow, cooling and centre of mass
5. Load-bearing and locating parts in sheet metal and metal spacers
6. Idlers on dowel pins in reamed holes, ≈0.05 mm interference on a 5 mm pin
7. Square the frame on granite, during assembly
8. Align rails and verify pressed joints against external granite, never against the frame
9. Remove mass from what moves; add it to what does not
10. Adopt sensing that removes the human
11. Calibrate with printed artifacts, and again after every mechanical change

What one machine built twice shows. Seven of eight criteria met; acceleration on Y fell short, and Boaz lost a production race to a \$300 machine. What differed between its two builds was whether the precision practice was executed. That difference was large, measurable, and visible in every part.

Companion book

29 chapters and the eleven rules, each with its evidence attached.
Scan the code, or write to amkochhal@gmail.com

