

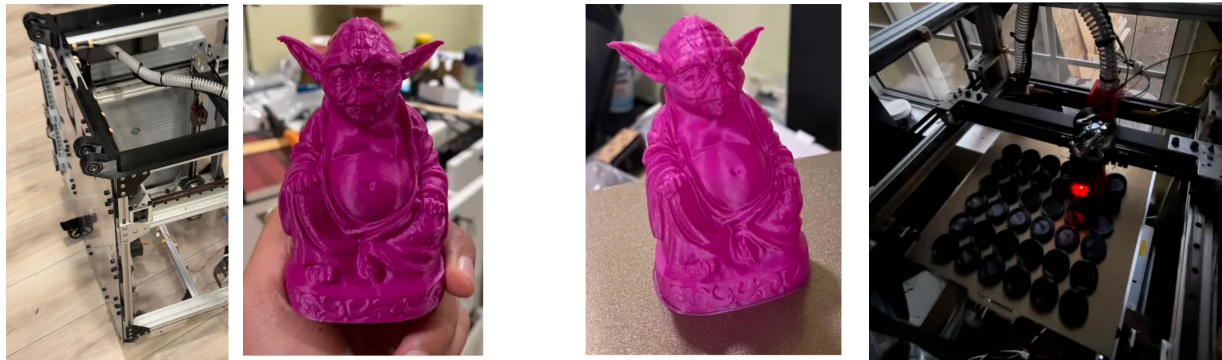
DIGITAL FABRICATION

Boaz: A DIY Printer Built Like a Machine Tool

I built the same CoreXY printer twice. Once with hobby habits, once with machine-shop habits. Same design, mostly the same parts. A dial indicator was the difference.

By Abhishal Kochhal

Leland High School, 6677 Camden Ave, San Jose, CA 95120, USA · amkochhal@gmail.com



Boaz in its final configuration; a detail print that stresses XY accuracy and layer stacking at once; and plates of PETG medicine boxes from the production contract.

The printers you can buy keep getting better and more closed at the same time. Proprietary toolheads, locked firmware, parts you cannot repair. The open machines in the RepRap tradition stay wonderful to learn on, but most of them wobble, ring and drift in ways their CNC cousins never would. That is not a materials problem and not a kinematics problem. RepRap set out to build a machine that could make copies of itself from the cheapest parts around, and it answered that question well. Accuracy was a different question. Machine-tool builders answered it a century ago.

Boaz is my attempt to borrow their answers: a CoreXY printer on a two-tier 20×40 mm extrusion frame, built twice. The first time I followed the right principles with the wrong technique. The second time I fixed the technique and changed almost nothing else. Same design, same kinematics, mostly the same parts. That makes the first build a control, which is the only reason any of this is worth writing down.

The rebuilt machine prints a Speedboat-ruled Benchy in 16 minutes, holds 0.2 mm on threaded parts, and ran a 1,000-piece PETG contract at about 50 boxes a day across roughly a hundred plates, with nobody touching the first layer on any of them. A \$300 Elegoo next to it did 60 a day. If your goal is boxes per day, buy the Elegoo. The comparison that matters here is not Boaz against a factory machine. It is Boaz against Boaz.

Five Habits Worth Stealing

Stiffness before squareness. A square frame that flexes is not square while it is moving. The toolhead throws around 10 N of reaction into the frame and reverses tens of times a second, which prints as banding that gets worse with speed. Second moment of area goes as the cube of depth, so section size is the cheapest stiffness you can buy. I used 20×40 mm extrusion with generous gusset plates. The uprights should have been 40×40, since the Z actuators load those in bending.

Exact constraint. A rigid body has six degrees of freedom, so hold it at exactly six points and no more. Bolt it down at nine and the six extra points add stiffness, not accuracy. They inject stress that the plate absorbs by bending, in a pattern set by assembly order that cannot be adjusted out. Your firmware then compensates for a shape the machine created itself.

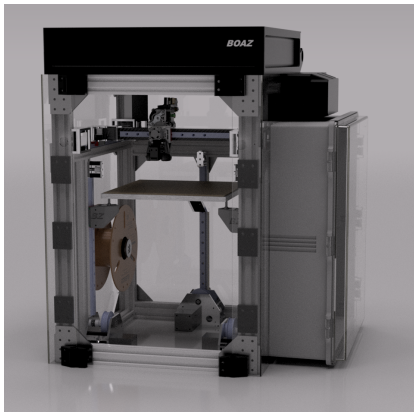
Kinematic couplings. Boaz's bed sits on a three-point Maxwell coupling: three balls in three radial v-grooves, each point lifted by its own belted Z actuator. Nothing but its own weight stresses the plate. Tilt becomes an adjustable degree of freedom, so Klipper's Z_TILT_ADJUST corrects it mechanically before every print instead of smearing it into a mesh. Each ball slides along its groove as the plate heats.

Interference fits where things locate. An M5 screw's shank runs about 0.2 mm undersize so the thread can be rolled, so a bearing riding on that screw sits anywhere inside 0.2 mm of play. It does not stay

put. Belt tension pulls it to whichever side the net force is on, and that side changes as the toolhead moves. Homing cannot remove a direction-dependent error. Treat eight idlers as independent and the expected path-length error lands near $\sqrt{8} \times 0.1 \approx 0.28$ mm. Layer artifacts show up at a few tens of microns.

Metrology during assembly, not after. Every reference in this machine traces to a granite plate and a dial indicator, and every reading was taken while the joint could still be changed. Align a rail to the frame it is bolted to and you measure nothing, because the error you are hunting lives in the reference.

Build, Fast-Forwarded



The machine as drawn. Plates are extruded from one 2D master sketch, so the belt runs, idler centres and rail lines are inputs to the model instead of numbers measured back out of it.

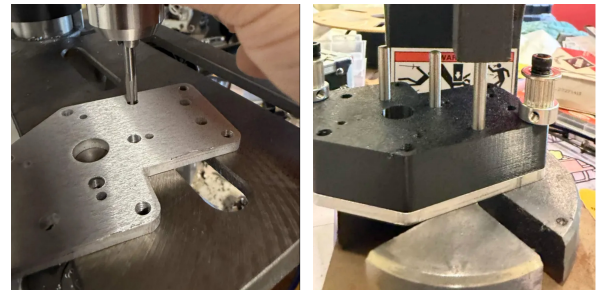
Classic CoreXY: two stationary motors, crossed 9 mm reinforced belts, MGN12H rails. Take a 300 g motor off a 700 g gantry and achievable acceleration rises about 75% before you change anything else. The X beam is a carbon-fibre tube. Steel and aluminium are nearly identical in specific stiffness, so swapping one for the other buys less than you would think, while carbon sits in a different class and damps well. Its 1 mm wall is thin enough that a rail fastener crushes it, so every fastener gets an internal standoff cut to the exact height of the cavity.

Z is three belted actuators at 1:5; three is what makes the kinematic bed possible, and belts cost none of the travel a ballscrew eats. A Raspberry Pi runs Klipper against a BigTreeTech Octopus Pro. The XY motors run TMC5160s on a separate 48 V supply, a 240 W Meanwell NDR-240, because a stepper winding is an inductance and torque at speed comes down to how fast you can force current into it against back-EMF. A CPAP blower on the frame feeds the toolhead so the carriage stays light. The machine is enclosed, with a hinged top so the gantry stays reachable, and the electronics live in a sealed box of their own below.

Power got budgeted on paper before anything shipped: bed 220 W, XY motors 72 W, Z motors 108 W,

hotend 100 W, extruder 48 W, blower 50 W, controller and fans 25 W. That was the first build; it summed to 623 W on a 600 W Meanwell supply, and the mismatch is deliberate. The sum assumes every load at peak in the same instant, which never happens. Heaters settle to a duty-cycle average and motors hit peak current only under acceleration. Realistic worst case is both heaters warming up with the motors idle, about 345 W. Size against that, not against the bound, and buy from someone who publishes derating curves. Six hundred watts from an unbranded supply is not 600 W at 40 °C inside a closed machine. The rebuild's 350 W Keenovo mat pushed the heat-up case to 475 W on the same supply, with the XY motors gone to their own rail, which is why the derating curve now matters.

What Broke (Learn From Me)

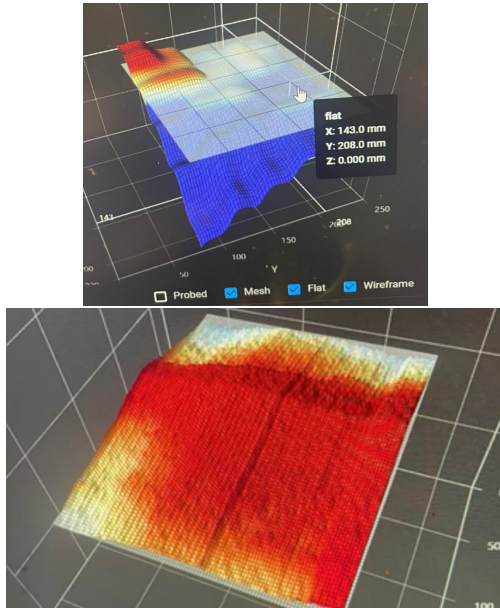


Left: reaming to 4.95 mm. The reamer sits in the drill press for perpendicularity but gets turned by hand, so spindle runout cannot open the hole up. Right: pins pressed through a jig that holds them square to the plate.

Press fits, wrong in three directions. I reamed dowel holes to the pin's nominal 5 mm, on the belief that a press fit meant a hole the same size as the pin. That is a clearance fit. The reamer also ran under power in a drill press with about 0.05 mm of spindle runout, and a reamer that is not running true cuts a hole bigger than itself. The pins then turned out to measure 0.04 mm *under* nominal, because I bought them cheap and never checked. One joint ended up shimmed with a strip of plastic bag. Other joints went the opposite way, pressed at 0.2 mm of interference on the theory that if some is good, more is better. That much force on a 5 mm pin drives it in crooked, and a tilted idler steers the belt. Not one first-build press fit landed between the two extremes.

The fix is five steps and no heroics. Draw the hole 0.2 mm under, so reaming sets the finished size rather than the cutting process. Micrometer the pins when they arrive: a fit is a relationship between two parts, and you can only machine one of them. Ream by hand to 4.95 mm against a measured 5.000 mm pin: 0.05 mm of interference, a heavy press that yields the aluminium round the hole, well beyond the 0.02 mm an ISO 286 H7/p6 fit allows at this size. Press through a jig. Then measure every assembly on granite at sev-

eral angular positions *and at several heights*: equal runout top and bottom means the pin is offset but parallel, which you can live with, while unequal runout means it is tilted, which you cannot. Acceptance was 0.001 in total indicated runout. Assemblies that failed got remade.



Left: the MK52 PCB bed as installed, +0.4 to −1.2 mm, a 1.6 mm envelope against a 0.2 mm first layer, worst between the mounting points. Right: the ATP-5 plate read by the eddy probe on a 100×100 grid, 0 to 0.2 mm.

The PCB heatbed. A Prusa MK52 mounted at five of its nine holes warped +0.4/−1.2 mm. Every first layer needed an operator riding the Z offset as the tool-head crossed the plate, which disqualifies a machine meant to run unattended. My first instinct was to support it better: all nine holes, shim each standoff flat. That failed twice over. The rack was less stiff than the plate, so the rack's joints yielded first, and lifting a thin plate at one point only moves the deviation into the spans either side. Flatness has to be bought in the plate. The replacement is cast ATP-5 tooling plate, and I sized its thickness against gravity rather than heat. Sag on three supports falls as $1/h^2$, so 1/8 in would hold $18.9\mu\text{m}$ of self-weight error. The 5/16 in plate I used holds $3.0\mu\text{m}$.

Printed structure in the load path. The three Z actuator bodies were PLA, meant as placeholders. Belt tension in a Z actuator is a standing load, present whenever the machine is assembled, and printed plastic creeps under it near the bed's heat. They stayed in through the whole first production run, so every number I collected in that period came off a part I already knew was wrong. Print your brackets and ducts. Make load paths and locating features out of metal.

Belt tension folklore. Tighter is not better, and sequential is worse. Tension one CoreXY belt and then the other and the net moment racks the gantry, and ev-

ery part made in that period carries the skew. Tension both together, iterating, checking gantry squareness as you go. Matched tension on good reinforced belts also ended the skipped teeth, and a skipped tooth is an unrecoverable coordinate shift. While you are there, draw a tensioner for the Z belts. Mine had none, because the CAD had none, so tensioning them meant stretching a belt by hand into printed clamp teeth and hoping the three actuators came out alike. A tensioner is a few plates, a screw and an afternoon in CAD. Skipping that afternoon does not save it. You spend it again at every assembly.

Fixes That Mattered

A BigTreeTech Eddy probe now sweeps a 100×100 mesh in a few minutes. A touch probe pays a deceleration, a deploy, a touch and a retract for every single point, and no firmware makes that cheaper; an inductive coil reading its own change in inductance over metal never touches at all. Two catches. It needs a conductive target and reads the steel print sheet, not the plate. It also drifts with temperature, so the calibration has to include a thermal model. Skip that and the probe is accurate at one bed temperature and wrong at every other, wrong by an amount that looks like a real change in bed height.

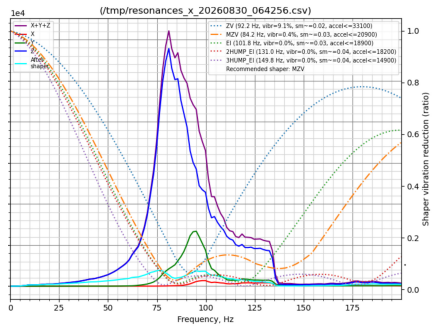
One reversal from that upgrade is worth carrying home. On the warped bed I had pushed Klipper's bicubic tension parameter to maximum, on the theory that a badly deviating bed needs maximum compensation. It did nothing. Tension controls the curvature of the interpolated surface *between* probed points, and no interpolation recovers a shape the probe never sampled. On the dense mesh the same maximum setting overcompensated visibly and had to come back down. Software compensation is interpolation between measurements. It is for residual error, not for a defective part. When a compensation parameter has to be pushed to its limit before it helps, the problem is upstream of the compensation.



#SpeedBoatRace Benchies at the same 16 minutes: Boaz on the left, a Hev-Ort on the right. The smokestack is cleaner and the bow and stern carry fewer artifacts, both cooling-limited features, so credit goes to the duct and blower. One paired print is an anecdote, not a margin.

The Califlower artifact measured what was left: a residual racking too small for a machinist square to

catch on a frame this size, and too large for a 0.2 mm functional tolerance to absorb. You print it, then measure X, Y and both diagonals. The diagonals are the whole point. A scaling error moves X and Y and leaves the diagonals in proportion, while a skew moves them differentially. The tool computes the angle and hands you the firmware correction. Threaded lids started assembling. Correcting skew is not fixing skew, so if that correction ever starts growing, read it as a symptom.



The X-axis resonance sweep after the rebuild. One dominant peak, clean roll-off, shaped response under 0.1 across the band, and 20,900 mm/s² recommended with an MZV shaper. Read a plot like this as a report card on your assembly, not as a tuning input.

Input shaping came last, and the accelerometer sweep turned out to be the most useful measurement in the project. Not for the shaper it configures, but for what the plot says about your build. One dominant peak with a clean roll-off means one well-defined compliant mode, which is what a properly constrained structure looks like; that is Boaz's X sweep. Several peaks, or a broad noisy hump, means loose joints, binding rails or a flexing frame trading energy at similar levels; that is its Y sweep, capped at 9,500 mm/s². A shaper cancels one identified mode well and cannot cancel a forest of them, and the attempt costs print quality directly, since heavier shaping rounds corners and smooths detail. Mechanical work is what made shaping cheap on X. Sequence matters: mechanics, then measurement, then software.

Steal These Rules

Rigidity first, because nothing downstream fixes a frame that moves. Metal for load paths, plastic for brackets and ducts. Exact constraint beats clamping harder. Precision lives at the interfaces: fits, preload, tension, not the price of the parts. Measure before you tune, and measure against something you did not build. Budget power, travel and tolerance on paper before you spend. Enclose the machine, and enclose the electronics separately: an open shelf under an open frame is why Boaz never ran overnight, and that cost more throughput than any mechanical limit did.

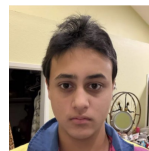
Then fix causes, not symptoms. Every quick patch in this project resolved something and destroyed the information I needed to diagnose whatever I measured

next. The plastic shim made the machine assemblable and left an eccentric, creeping joint I could no longer separate from the others.

None of these techniques are new. They are ordinary practice for anyone who builds mills and lathes, and have been for decades. What was not obvious is that they scale down to a machine that pushes plastic. A dial indicator and a granite block cost less than a set of rails. You can have the RepRap spirit and machine-shop manners on one frame, and the manners are learnable, one dial-gauge reading at a time.

WHAT YOU'LL NEED

- 20×40 mm extrusion (use 40×40 uprights) with laser-cut gusset plates at every joint
- Granite reference plate, machinist square of known grade, dial indicator: the cheapest precision in the build
- CoreXY kit: 2 NEMA 17 steppers on the frame, 9 mm reinforced GT2 belts, toothed and smooth idlers, laser-cut plates on machined metal stand-offs
- Closed-section gantry beam (carbon fibre) with an internal standoff at every rail fastener
- MGN12H rails, light preload, and a grease *thinner* than the datasheet's NLGI 1; Mobilux EP1 made the axes stiff
- 3× belted Z actuators (1:5) in metal, each with a tensioner (mine had none), plus a three-ball Maxwell coupling
- 5/16 in cast ATP-5 or MIC-6 tooling plate, 350 W silicone heater bonded below, magnetic sheet above
- Raspberry Pi and a Klipper board (e.g. BTT Octopus Pro), 60 V-rated TMC5160 modules on a 48 V rail, branded 600 W 24 V PSU plus a 240 W 48 V supply for the XY pair
- BigTreeTech Eddy probe, ADXL-class accelerometer, remote CPAP blower with a distributed-outlet duct
- 5 mm ground dowel pins, a 4.95 mm hand reamer, a micrometer, an arbor press and a pressing jig



Abhishal Kochhal is a twelfth grader at Leeland High School in San Jose. He has sold 3D-printed drone parts and printer components since 2022, builds competition robots with FRC team 604, and flies as a certified drone pilot. He is looking for an internship in 3D printing.

The full engineering write-up is available as a companion paper: design reasoning, failure analysis, the eight success criteria fixed before construction, and the measurement procedure behind every number here. Photos are from its figure set. Write to amkochhal@gmail.com or [linkedin.com/in/abhishal](https://www.linkedin.com/in/abhishal).