

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.

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Boaz in its final configuration; the CAD assembly it was built from; a #SpeedBoatRace Benchy printed in 16 minutes; 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. 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. RepRap set out to build a machine that could copy itself from the cheapest parts around. Accuracy was a different question, and 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. That makes the first build a control.

The rebuilt machine prints a Speedboat-rules 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 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, and second moment of area goes as the cube of depth. Section size is the cheapest stiffness you can buy.

Exact constraint. A rigid body has six degrees of freedom, so hold it at six points and no more. Bolt a bed down at nine and the extra constraints add stiffness, not accuracy; they inject stress the plate absorbs by bending, and your firmware then compensates for a

shape the machine created itself.

Kinematic couplings. Boaz's bed sits on three balls in three radial v-grooves, each lifted by its own belted Z actuator. Tilt becomes an adjustable degree of freedom, so Klipper corrects it mechanically before every print instead of smearing it into a mesh.

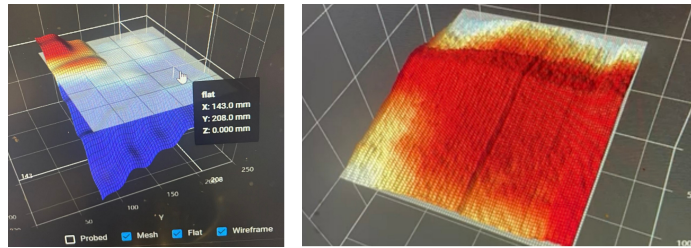
Interference fits where things locate. An M5 screw's shank runs about 0.2 mm undersize so the thread can be rolled, so a bearing on that screw sits anywhere inside 0.2 mm of play. Belt tension pulls it to whichever side the net force is on, and that side changes as the toolhead moves. Homing cannot remove a direction-dependent error.

Metrology during assembly, not after. Every reference here traces to granite and a dial indicator, read while the joint could still be changed. Align a rail to the frame it is bolted to and you measure nothing: the error you are hunting lives in the reference.

What Broke (Learn From Me)

Press fits, wrong in three directions. I reamed dowel holes to the pin's nominal 5 mm, believing 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 0.05 mm of spindle runout, and a reamer that is not running true cuts a hole bigger than itself. The pins then measured 0.04 mm *under* nominal, because I bought them cheap and never checked. 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.

The fix needs no heroics. Ream by hand to 4.95 mm against a *measured* 5.000 mm pin, press it through



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. Same machine, same firmware.

a jig that holds it square, then read every assembly on granite at several angular positions and at several heights. Equal runout top and bottom means the pin is offset but parallel, which you can live with. Unequal runout means it is tilted, which you cannot. Acceptance was 0.001 in total indicated runout, and assemblies that failed got remade.

The PCB heatbed. A Prusa MK52 mounted at five of its nine holes warped $+0.4/-1.2$ mm, so every first layer needed an operator riding the Z offset as the tool-head crossed the plate. Supporting it better failed: the rack was less stiff than the plate, so its joints yielded first, and lifting a thin plate at one point only moves the deviation into the spans next to it. Flatness has to be bought in the plate. The replacement is cast ATP-5 tooling plate, sized 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 while the 5/16 in plate I used holds $3.0 \mu\text{m}$. An eddy probe, reading the steel sheet on top, then sweeps a 100×100 mesh in minutes because it never touches the bed. Together they made the first layer hands-off; neither alone would have.

Printed structure in the load path. The three Z actuator bodies were PLA placeholders. Belt tension in a Z actuator is a standing load, and printed plastic creeps under it near the bed's heat. They stayed in through the whole first production run, so every number from that period came off a part I knew was wrong.

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 in the price of the parts. Measure before you tune, and measure against something you did not build. Budget power on paper: the first build summed to 623 W on a 600 W supply, which is fine, because the realistic worst case is both heaters warming up with the motors idle at about 345 W. 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. On the warped bed I pushed Klipper's mesh tension to maximum, expecting maximum compensation. It did nothing: no interpolation recovers a shape the probe never sampled. Software compensation is for residual error, not for a defective part. None of these techniques are new. What was not obvious is that they scale down to a machine that pushes plastic, and that a dial indicator and a granite block cost less than a set of rails.

WHAT YOU'LL NEED

- 20×40 mm extrusion (40×40 on the uprights; mine were not), 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, laser-cut plates on machined metal standoffs
- Closed-section carbon-fibre gantry beam, 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
- $3 \times$ belted Z actuators (1:5) in metal, each with a tensioner (mine had none), plus three balls in three radial v-grooves
- 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 dedicated 48 V rail, branded 600 W 24 V PSU
- BigTreeTech Eddy probe, ADXL-class accelerometer, remote CPAP blower
- 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 Leland High School in San Jose who has sold 3D-printed drone parts since 2022 and is looking for an internship in 3D printing. The full engineering write-up is available as a companion paper: *design reasoning, failure analysis, and the measurement procedure behind every number here.*