CNC ROUTERS

The complete reference poster — how they work · anatomy · motion and electronics · tooling · materials · feeds and speeds · G-code · safety

DESIGN & TECHNOLOGY

3-axis gantry router · computer numerical control

1 · WHAT IS A CNC ROUTER?

A **CNC (Computer Numerical Control) router** is a computer-driven milling machine that moves a spinning cutter (end mill) along **X** (left–right), **Y** (front–back) and **Z** (up–down) to carve parts from wood, plastic, foam and soft metal. A human designs the part on a computer; motors follow programmed toolpaths with ~0.01–0.1 mm precision — far beyond hand routing.

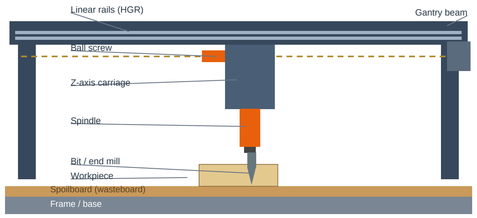
- **Subtractive** — starts from a solid sheet/block and removes material
- Cuts 2D profiles, 2.5D pockets and full 3D carved shapes
- Rotary axes (**A** = rotate, **C** = tilt) make 4/5-axis machines for cylinders and undercuts
- Right-hand rule: +X right, +Y away, +Z up (most gantry routers — check your manual)
- History: Numerical Control demoed in 1952 (MIT + Parsons, Cincinnati Hydrotel); hobby CNC exploded ~2010 with Arduino + GRBL and free CAD/CAM

2 · THE DIGITAL WORKFLOW

Stage	What happens	Typical tools
CAD	Draw the 3D model	Fusion 360, Onshape, FreeCAD, SolidWorks
CAM	Pick bits, set feeds and speeds, generate toolpaths	Fusion 360 CAM, VCarve, Carveco, Estlcam
Post-process	Convert toolpaths to machine G-code	CAM post-processor (GRBL, Mach3, ...)
Control	Home, jog, load and run the G-code	Easel, UGS, Candle, bCNC, gSender
Cut	Motors move the spindle along the paths	GRBL (Arduino/ESP32), Mach3/4, LinuxCNC

CAD creates the geometry; CAM decides how to cut it (bit, depth, speed, direction); the post-processor translates that into G-code the controller executes line by line.

3 · ANATOMY OF A GANTRY ROUTER



Side view: the gantry beam rides on linear rails; the Z carriage lowers the spindle into the workpiece sitting on the spoilboard. X runs along the base, Y is into the page, Z is up/down.

Part	Role
Frame	Rigid steel/aluminium base; rigidity = accuracy (welded steel or 2020/4040 extrusion)
Linear rails	Guide each axis (HGR15/20 rails + trucks, V-wheels, round shafts)
Drive	Converts motor rotation into motion (ball screw, lead screw, rack and pinion, belt)
Motors	Move the axes (NEMA 17/23/34 steppers, or closed-loop servos)
Spindle	Holds and spins the bit (trim router or 1.5–3 kW VFD spindle)
Controller	The brain — runs G-code, drives the motors (GRBL, FluidNC, Mach3, LinuxCNC)
Limit switches	Homing and crash protection (mechanical or optical end stops)
Spoilboard	Replaceable MDF wasteboard; resurface (fly-cut) to keep flat
Dust shoe	Chip extraction — shop vac + cyclone separator

4 · MOTION SYSTEMS

System	Speed	Accuracy	Cost	Notes
Lead screw (ACME + anti-backlash nut)	0.5–2 m/min	0.1–0.3 mm/300 mm	$	Simple and cheap; anti-backlash nut essential; wears with time
Ball screw	up to 10 m/min	0.02–0.05 mm/300 mm	$$$	Recirculating balls, low friction, near-zero backlash — the professional standard
Rack and pinion	10 m/min+	0.1–0.5 mm/300 mm	$$	Long beds; needs spring-loaded anti-backlash pinion
Belt drive	fast, quiet	medium	$	Stretch and backlash; light duty (often the X axis only)

Guides: HGR linear rails are stiffest and most accurate; V-wheels on extrusion are cheap and forgiving on imperfect frames; round shafts are budget. Remember — a flimsy frame ruins even a perfect ballscrew.

5 · ELECTRONICS AND CONTROL

Component	Typical choice	Notes
Stepper motor	NEMA 23 (0.6–3 N·m)	NEMA 17 = small machines, NEMA 34 = heavy. Open-loop: can skip steps when overloaded
Servo / closed-loop	Encoder feedback	No lost steps, faster and stronger, costs more
Driver	DM542, TB6600, TMC2209	Set current to the motor rating; microstepping 1/8–1/16 smooths motion
Controller	GRBL (Arduino + CNC shield), FluidNC (ESP32), Mach3/4, LinuxCNC	GRBL = hobby standard; Mach/LinuxCNC = professional
Power supply	36–48 V DC	Keep power wiring away from signal wires; use shielded motor cable

6 · SPINDLES AND MOTORS

Trim router	VFD spindle
Makita RT0701, DeWalt DW611 — 10,000–30,000 RPM, 0.75–1.25 HP, 1/8–1/2 in. collets, air-cooled. Cheap (~US$80), LOUD, brushes wear, little torque at low RPM	1.5–3 kW, 3-phase + VFD speed control, 6,000–24,000 RPM, ER11/ER20/ER25 collets, water- or air-cooled. Quiet, constant torque, runout under 0.01 mm — but ~10x the cost

- ER collet sizes: ER11 = 1–7 mm, ER20 = 1–13 mm, ER25 = 1–16 mm, ER32 = 2–20 mm
- Seat the bit fully, keep collets clean, never run with a loose nut
- **Runout check:** dial indicator on the bit shank, spin slowly — 0.01–0.05 mm is fine; more means rough cuts and broken bits

7 · BITS AND TOOLING (END MILLS)

Bit type	Best for	Notes
Up-cut spiral	Fast chip removal	Rough bottom, tearout on top; pairs with a dust system
Down-cut spiral	Clean top edge	Pushes the part down; chips pack in the slot; rough bottom
Compression	Plywood, sheet goods	Up-cut tip + down-cut top = clean on both sides
Ball nose	3D carving	Finishing passes with a small stepover
V-bit (60°/90°)	Engraving, signs	V-carved lettering and chamfers
Flat end mill	Pockets and profiles	Square corners; 2- or 4-flute
O-flute (single)	Acrylic, plastics	One big flute = chips clear, no melting

Materials and coatings: HSS = cheap, flexible, dulls fast. Solid carbide = rigid, stays sharp 5–10x longer, brittle — the CNC standard. Coatings: TiN/TiAlN (aluminium, heat), diamond (carbon fibre, abrasive composites). **Flutes:** 1 = plastics, 2 = wood, 3–4 = aluminium on rigid machines; more flutes = smoother finish but less chip space.

Rule of thumb: use the shortest bit that reaches — deflection grows with length cubed.

8 · FEEDS AND SPEEDS — THE CUTTING FORMULA

Feed (mm/min) = Chipload (mm per tooth) x RPM x number of flutes

chipload = thickness of the chip each tooth peels off

Worked example: 6 mm 2-flute bit in softwood at 16,000 RPM with chipload 0.15 → 0.15 x 16,000 x 2 = **4,800 mm/min**. Start around 3,000 and tune by ear: smooth whine = right; squeal/chatter = RPM too high or feed too low; bogging = too deep or too fast.

- Stepover: 40–50% of bit diameter roughing; 5–10% finishing (ball nose 5–8%)
- Depth per pass: max 1x bit diameter softwood, 0.5x hardwood, 0.2–0.4x aluminium; acrylic = full depth with a 1-flute in thin sheet
- **Climb milling** (cutter rotates with the feed): cleaner finish, less force — rigid machines only
- **Conventional** (cutter rotates against the feed): safer with backlash or weak hold-downs; rough with climb, finish with climb

9 · G-CODE ESSENTIALS

Code	Meaning
G0 / G1	Rapid move / straight cut at feed rate
G2 / G3	Arc clockwise / counter-clockwise
G17 / G18 / G19	XY / XZ / YZ plane
G20 / G21	Inches / millimetres
G90 / G91	Absolute / incremental coordinates
G28	Return to machine home
M3 / M5	Spindle on (CW) / spindle stop
M6 / M30	Tool change / end of program

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G21 G90 ; mm, absolute
G17 ; XY plane
G0 X0 Y0 Z5 ; rapid to start
M3 S12000 ; spindle ON, 12,000 rpm
G1 Z-3 F300 ; plunge 3 mm
G1 X60 Y40 F1500 ; cut
G2 X70 Y50 I5 J0 ; arc
G0 Z10 ; retract
M5 M30 ; stop, end
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Zeroing (touch-off): jog the bit to the part corner/top, zero X/Y/Z — the machine now knows where the part is (WCS G54).

10 · MATERIALS GUIDE

Material	Bit	RPM	Chipload mm/flute	Tips
Softwood (pine, cedar)	2-flute up/down	16–20k	0.10–0.25	Fast cuts; watch grain tearout
Hardwood (oak, walnut)	2-flute	14–18k	0.07–0.15	Shallow passes, sharp carbide
Plywood	compression	14–18k	0.08–0.20	Compression bit kills fuzz
MDF	2-flute	14–18k	0.08–0.18	Very dusty — extraction essential
Acrylic	single O-flute	12–16k	0.05–0.13	Low feed = melting; small stepover
Aluminium 6061	2–3 flute	8–16k	0.02–0.06	Thin cuts, mist or WD-40 lube, climb mill
Foam (XPS)	2-flute	10–18k	0.25–0.50	Huge chiploads are fine
PCB (FR4)	carbide 1 mm	10–30k	0.01–0.03	Light cuts; carbide only

Start any new material at the low end of the chipload range with a shallow pass, listen to the cut, then push the numbers up. Keep a scrap piece for tests.

11 · WORKHOLDING — STOP THE PART MOVING

- **T-track + toggle clamps:** strong and fast; keep clamp heads below the toolpath
- **Double-sided tape:** thin or flexible parts; surfaces must be clean; watch flex
- **Screws into the spoilboard:** bomb-proof and cheap; drill through waste areas
- **Vacuum table:** best for sheet goods; needs a flat sealed spoilboard + pump
- **Vises and soft jaws:** small parts and aluminium
- **Tabs:** leave small uncut bridges so finished parts do not fly out
- Always air-cut once with Z raised to check the path before the real run

Rule: a part that moves mid-job means a broken bit. Hold it down better than you think you need to.

12 · SAFETY FIRST

1. **Safety glasses + hearing protection** — routers pass 100 dB
2. **Dust extraction and a mask** — wood dust harms lungs; never let chips pile up
3. No gloves, loose clothes or hair near spinning tools; no reaching into the machine while it runs
4. **E-stop within reach** — test it; never leave a job unattended
5. Tighten collets and check runout before each job; new bit = air test first
6. Burning wood or smoke = fire risk — fix feeds and speeds before continuing
7. Unplug to change bits; keep a fire extinguisher nearby

13 · TROUBLESHOOTING

Symptom	Fix
Chatter / vibration	Lower RPM, raise feed (more chipload), shorter bit, stiffer hold-down
Burned wood	Raise feed, lower RPM, sharper bit
Broken bits	Shallower passes, shorter bit, less runout, slower plunge
Lost steps (jagged steps in cut)	Lower acceleration/rapid speed, raise driver current, free any binding
Tearout	Down-cut or compression bit; cut the good face last; climb mill
Fuzz on plywood	Compression bit, fresh bit, climb direction
Ghosting (double outline)	Backlash — anti-backlash nuts, climb cut
Part moves mid-cut	Better workholding, add tabs, slower plunge
Rough finish	Finishing pass at 5–10% stepover, climb mill, ball nose for 3D

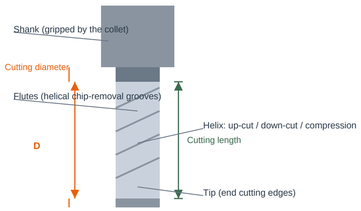
14 · CNC ROUTER vs LASER vs 3D PRINTER

	CNC router	Laser cutter	3D printer
Method	Subtractive — spinning bit	Subtractive — burn/vaporise	Additive — melted layers
Materials	Wood, ply, MDF, acrylic, aluminium, foam, PCB	Wood, acrylic, leather, card (not most metals)	PLA/ABS/PETG, resin
Detail limit	Bit diameter (~0.8 mm min)	Very fine kerf 0.1–0.3 mm	Layer height 0.05–0.3 mm
Downsides	Dust, noise, bit wear, no sharp inside corners	Smoke and smell; flat thin stock only	Slow, supports, weaker across layers
Best for	Signs, furniture, 3D carving, aluminium parts	Engraving, thin acrylic and ply parts	Prototypes, mechanisms, enclosures

15 · QUICK GLOSSARY

Term	Meaning
Spindle	Motor + collet that spins the bit
Chipload	Material removed per tooth per revolution (mm/tooth)
Stepover	Sideways distance between passes (% of bit diameter)
Runout	Bit wobble while spinning — want under 0.01–0.05 mm
Tramming	Squaring the spindle axis to the table
Climb / conventional	Cutter rotates with / against the feed direction
Backlash	Play in the drive — causes ghosting
Spoilboard	Replaceable wasteboard you cut into
G-code	The move program the machine executes
Homing	Finding machine zero with limit switches
Tabs	Uncut bridges holding the part in the sheet
Touch-off	Zeroing the bit on the part corner/top

16 · END MILL ANATOMY



- **Shank:** the smooth top gripped by the collet — 3.175 / 6.35 mm metric, or 1/8–1/2 in.
- **Flutes:** helical grooves that lift chips out; fewer flutes = bigger chip space
- **Cutting diameter D** sets slot width and stepover; inside corners can never be sharper than the bit radius
- **Cutting length** = max depth of cut; buy the shortest tool that reaches — long tools deflect
- Up-cut helix pulls chips up; down-cut pushes them down (clean top edge); compression does both

17 · CLIMB vs CONVENTIONAL MILLING

Climb: thick-to-thin chip, clean finish, pull-in force — needs a rigid machine with zero backlash
Conventional: thin-to-thick chip, rubs and heats more, pushes the part away — safer on loose machines



CLIMB milling — cutter rotates WITH the feed | **CONVENTIONAL — cutter rotates AGAINST the feed**

- **Climb:** the tooth bites at full chip thickness and cuts to zero — smooth, cool, clean finish. The cutter pulls itself into the work, so it needs a rigid frame and anti-backlash drives.
- **Conventional:** the tooth starts at zero chip, rubs, then thickens — more friction and heat, but it pushes the part away from the cutter, so it tolerates backlash and weak hold-downs.
- Practice: rough with conventional (or either), always **finish with climb**; climb-cut aluminium only on machines rigid enough to take the pull-in.

18 · RUNNING YOUR FIRST JOB — STEP BY STEP

1. **CAD:** design the part — remember tool radius: inside corners need a radius bigger than the bit
2. **CAM:** pick the bit, add a roughing pass, a finish pass, tabs, and safe Z-lifts between cuts
3. **Post-process** for your controller and load the G-code into the control software
4. **Mount the material** square on the spoilboard and hold it down hard
5. **Touch-off:** zero X/Y at the part corner and Z on the top surface
6. **Air cut** the whole job with Z raised to check the path is inside the stock
7. **First real pass:** run at 50% feed override, watch and listen — trust your ears
8. **Inspect:** measure with calipers, check edges; adjust feeds/speeds for the next part

19 · MAINTENANCE AND CARE

- **After every job:** vacuum chips and dust, wipe the rails, clean the collet and nut
- **Weekly:** lubricate linear rails and screws (light oil or grease per manual); check belt tension
- **Monthly:** check tramming (spindle square to table), tighten loose bolts, verify limit switches
- Trim-router brushes wear out every 50–100 h; water-cooled spindles need coolant checks
- Keep the spoilboard flat — fly-cut a thin skim whenever it shows deep gouges
- Store bits clean and dry; a chipped or blunt bit is a broken-part machine — replace it

20 · CHOOSING A ROUTER

- **Work area:** must fit your biggest job — 1000 x 600 mm covers most sheet goods
- **Frame:** welded steel or thick aluminium extrusion; push the gantry — visible flex means bad cuts
- **Drives:** ball screws for accuracy, rack and pinion for speed on long beds, lead screws for budget
- **Spindle:** VFD spindle for aluminium and long jobs; a trim router keeps the budget low
- **Electronics:** GRBL (Arduino/ESP32) is the hobby standard; Mach3/4 or LinuxCNC for professional
- **Don't skip:** dust shoe, limit switches, e-stop, cable chains, proper grounding
- Budget rule: **frame before spindle before electronics** — a flimsy frame limits everything

21 · PROJECT IDEAS

Project	Why it works on a router
Signs and nameplates	V-carved letters with a 60° bit — classic first job
Plywood furniture	Shelves, boxes and frames — nesting parts saves material
Jigs and templates	Repeatable drilling/cutting guides — F1 car jigs!
3D carvings and moulds	Ball-nose finishing on foam or softwood reliefs
PCBs	Isolation routing copper boards with a 1 mm carbide bit
Acrylic displays	Phone stands, light boxes, signage
Aluminium brackets	Small plates and heatsink-style parts, climb-cut with lube

Start with softwood or foam, master the workflow, then move to acrylic and aluminium.

22 · SOFTWARE AND RESOURCES

- **Fusion 360** — free education licence; CAD and CAM in one package (the hobby standard)
- **Carbide Create** — free 2.5D CAM, very beginner friendly
- **Easel** — browser-based design and control for X-Carve-style machines
- **VCarve / Aspire** — professional sign-making and v-carving CAM
- **Estlcam** — simple, powerful 2.5D CAM for hobby machines
- **UGS / Candle / bCNC** — free G-code senders for GRBL controllers
- **GRBL / FluidNC** — the open-source hobby firmware reference docs
- **Rules:** design in CAD, simulate in CAM, air-cut before you trust any new setup — and always read the feeds-and-speeds chart before pressing start.