CAM

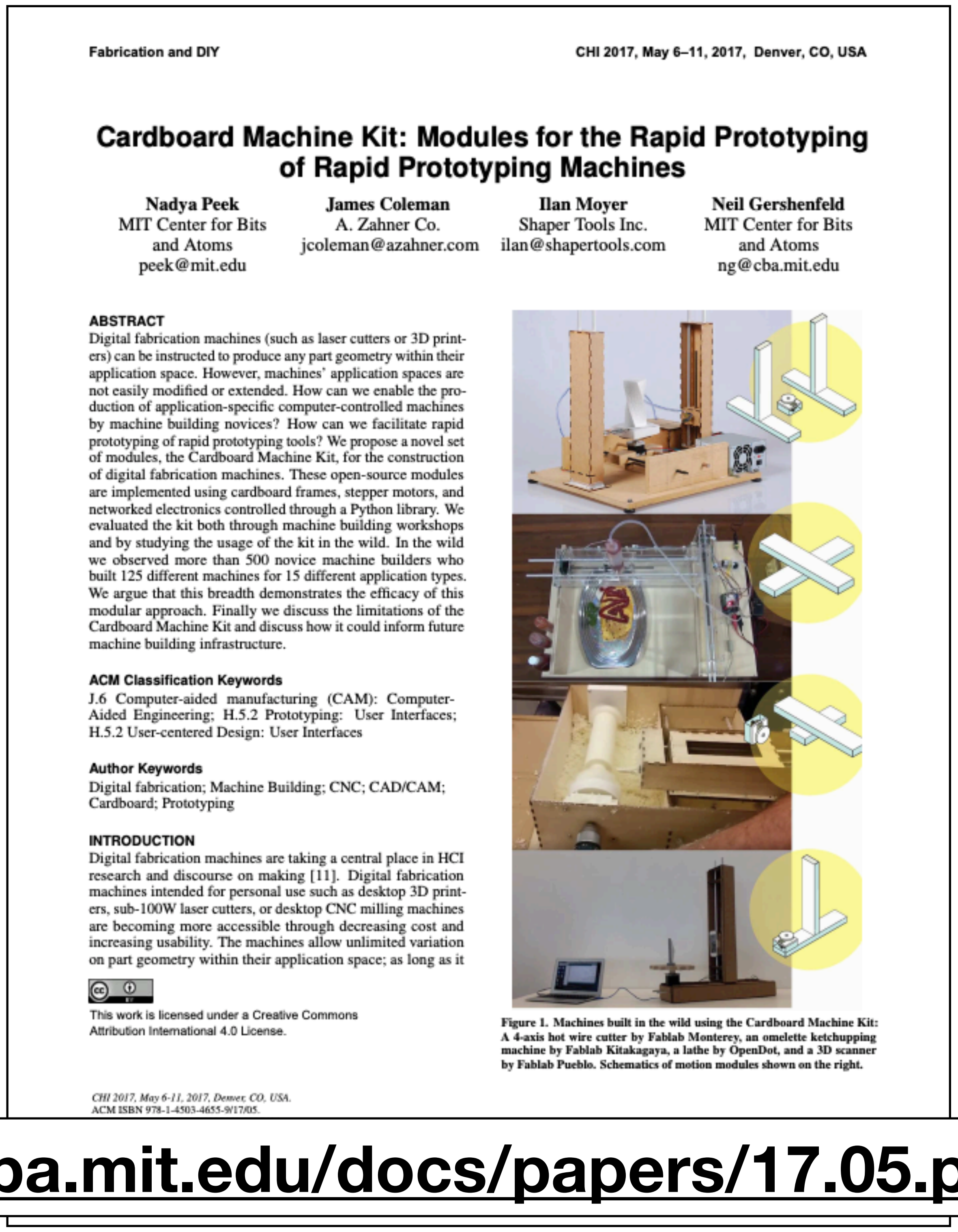
Computer-Assisted Machining
Computer-Aided Manufacturing
....

Announcements

- **Tuesday, April 30: Project Pitches**
  - **Slides:** Make yours here: https://bit.ly/2UYoHIJ
  - **Project Ideas & Inspiration**

Announcements

- **Thursday, May 2: Read & discuss two research papers:**


Fabrication and DIY — CHI 2017, May 6–11, 2017, Denver, CO, USA

Cardboard Machine Kit: Modules for the Rapid Prototyping of Rapid Prototyping Machines

Nadya Peek, MIT Center for Bits and Atoms, peek@mit.edu; James Coleman, A. Zahner Co., jcoleman@azahner.com; Ilan Moyer, Shaper Tools Inc., ilan@shapertools.com; Neil Gershenfeld, MIT Center for Bits and Atoms, ng@cba.mit.edu

ABSTRACT

ACM Classification Keywords

Author Keywords

INTRODUCTION

http://cba.mit.edu/docs/papers/17.05.peek.pdf

https://www.youtube.com/watch?v=knMRxNUEolk

Peek, Nadya, James Coleman, Ilan Moyer, and Neil Gershenfeld. "**Cardboard machine kit: Modules for the rapid prototyping of rapid prototyping machines.**" In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, pp. 3657-3668. ACM, 2017.


Computational Design of Mechanical Characters

Stelian Coros, Bernhard Thomaszewski, Gioacchino Noris, Shinjiro Sueda, Moira Forberg, Robert W. Sumner, Wojciech Matusik, Bernd Bickel — Disney Research Zurich, Disney Research Boston, MIT CSAIL

Figure 1: The interactive design system we introduce allows non-expert users to create complex, animated mechanical characters.

Abstract

1 Introduction

http://crl.ethz.ch/papers/CDMC_final.pdf

Computational Design of Mechanical Characters
Stelian Coros, Bernhard Thomaszewski, Gioacchino Noris, Shinjiro Sueda, Moira Forberg, Robert W. Sumner, Wojciech Matusik, Bernd Bickel
ACM Transactions on Graphics (Proc. ACM SIGGRAPH 2013).

CAM

Computer-Assisted Machining
Computer-Aided Manufacturing
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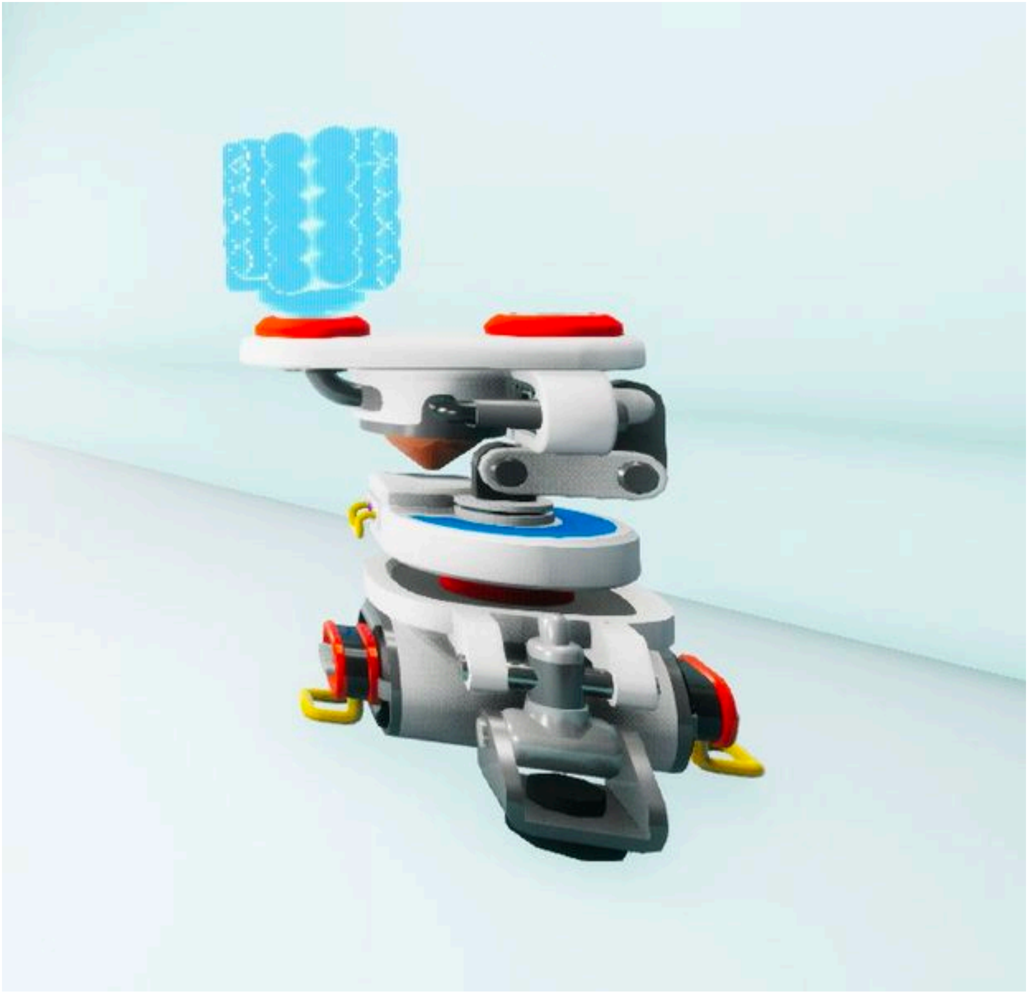
Machines making machines

https://astroneer.gamepedia.com/Printers

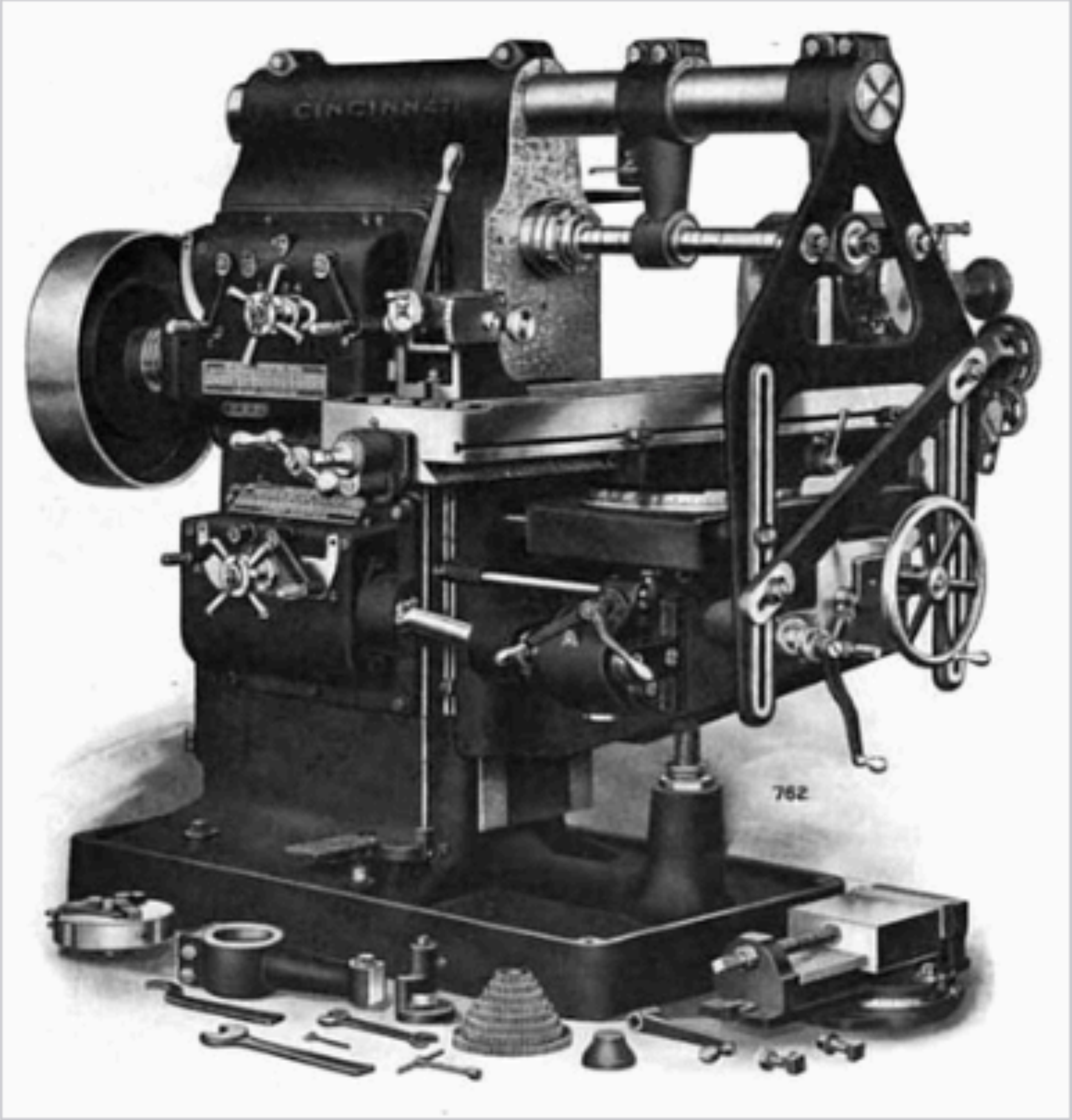
Backpack printer



Small printer

Medium printer

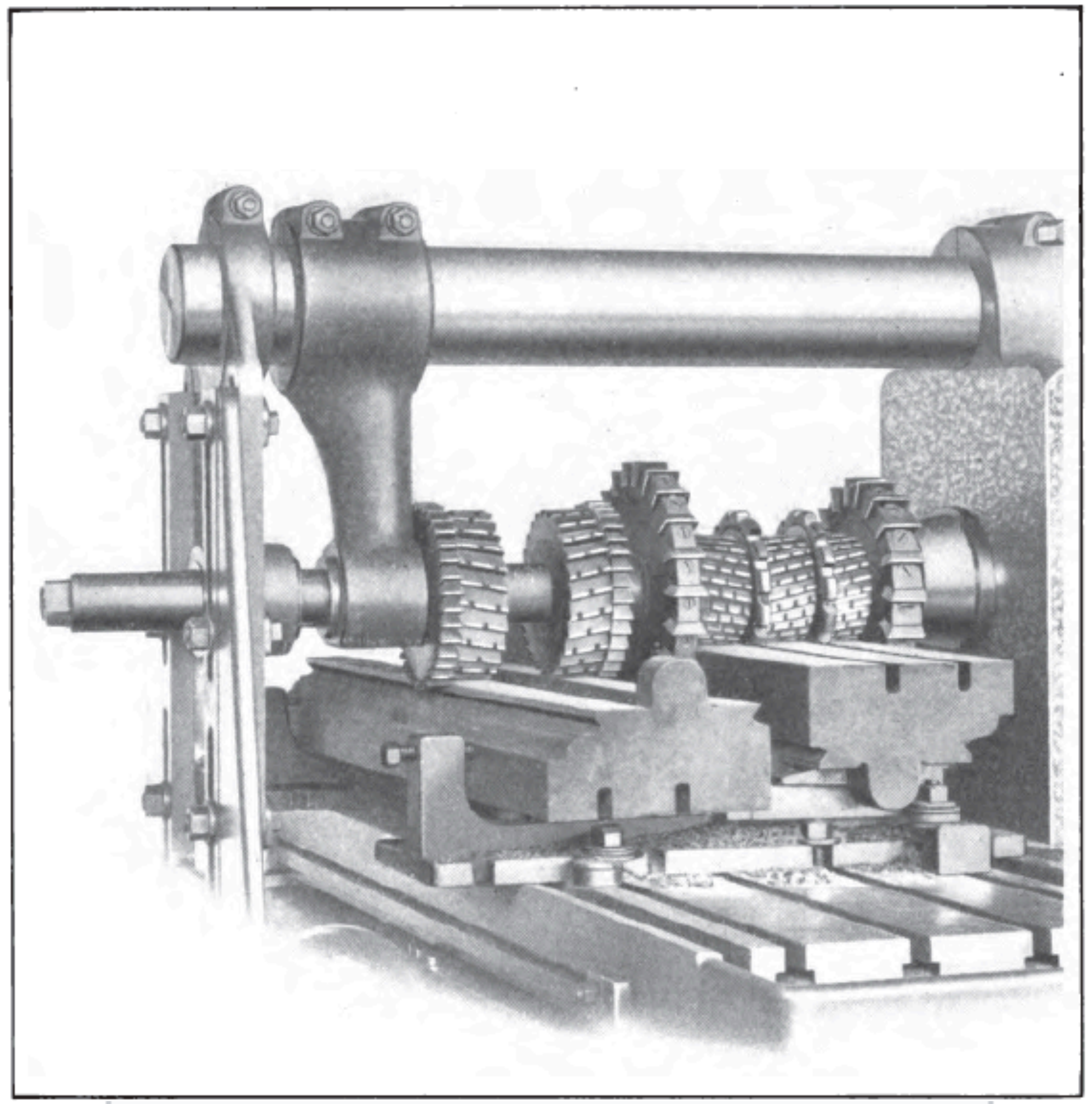
Large printer



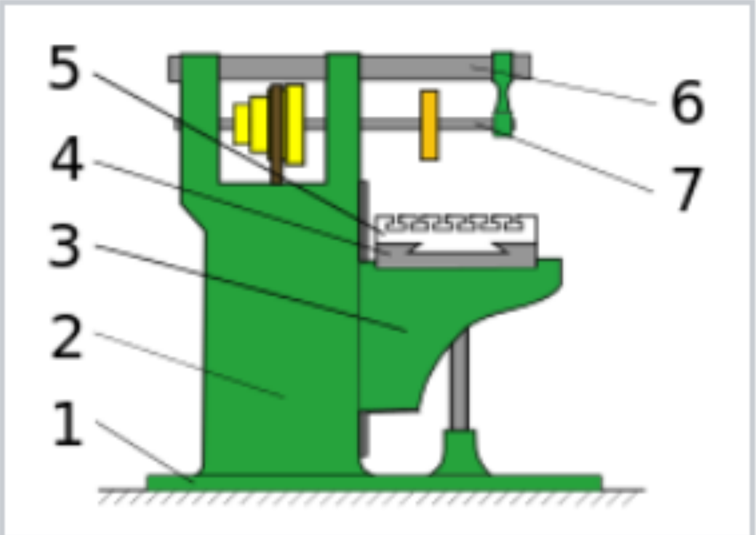
A typical milling machine of the era, built by Cincinnati Milling Machine Company. It is a horizontal, with an overarm for the arbor.

Milling Machines

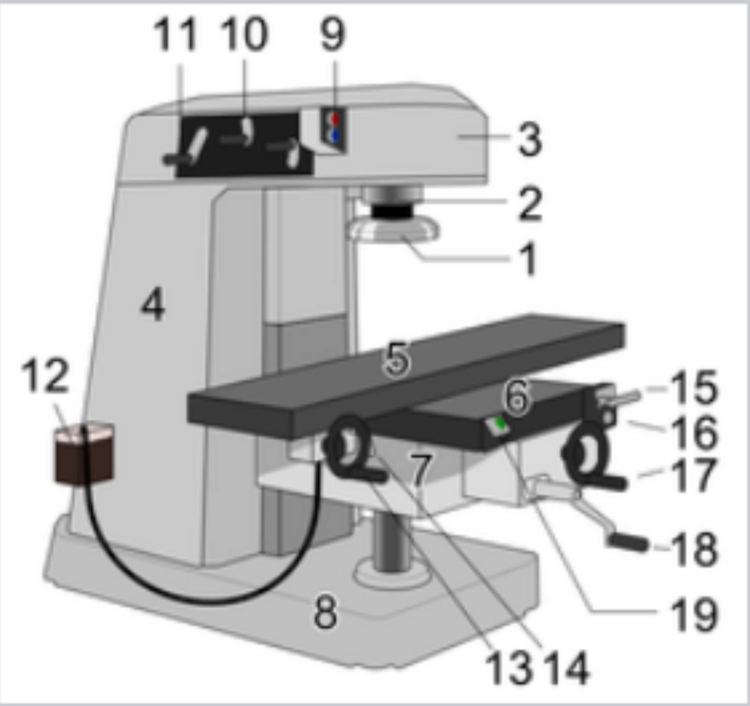
The prototypical NC/CNC machines



Heavy gang milling of milling machine tables

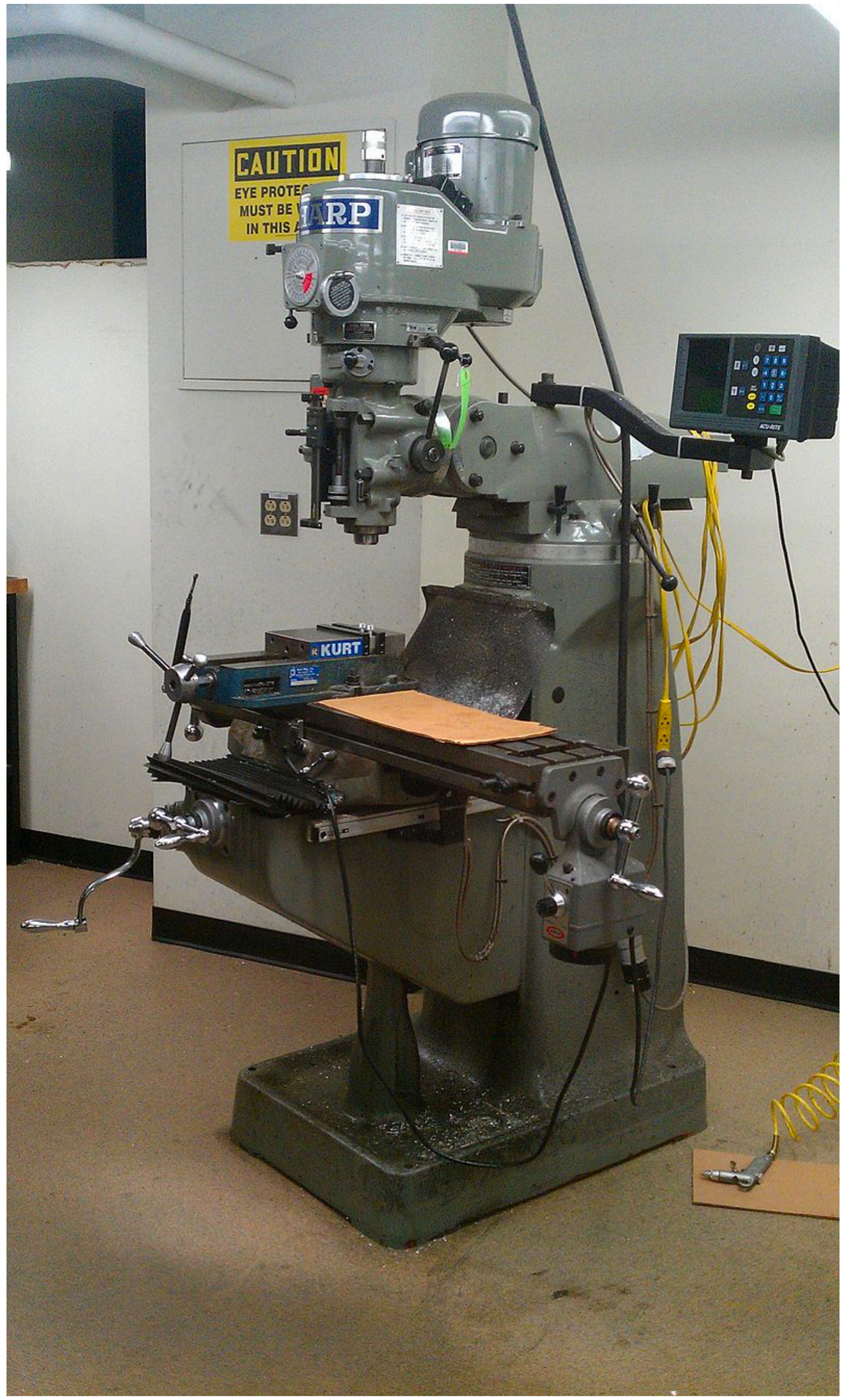


Horizontal milling machine. 1: base 2: column 3: knee 4 & 5: table (x-axis slide is integral) 6: overarm 7: arbor (attached to spindle)



Vertical milling machine. 1: milling cutter 2: spindle 3: top slide or overarm 4: column 5: table 6: Y-axis slide 7: knee 8: base

https://en.wikipedia.org/wiki/Milling_(machining)



A 3-axis clone of a Bridgeport-style vertical milling machine

An Automatic Machine Tool

Feedback control has begun to advance in the working of metals. Presenting the first account of a milling machine that converts information on punched tape into the contours of a finished part

by William Pease

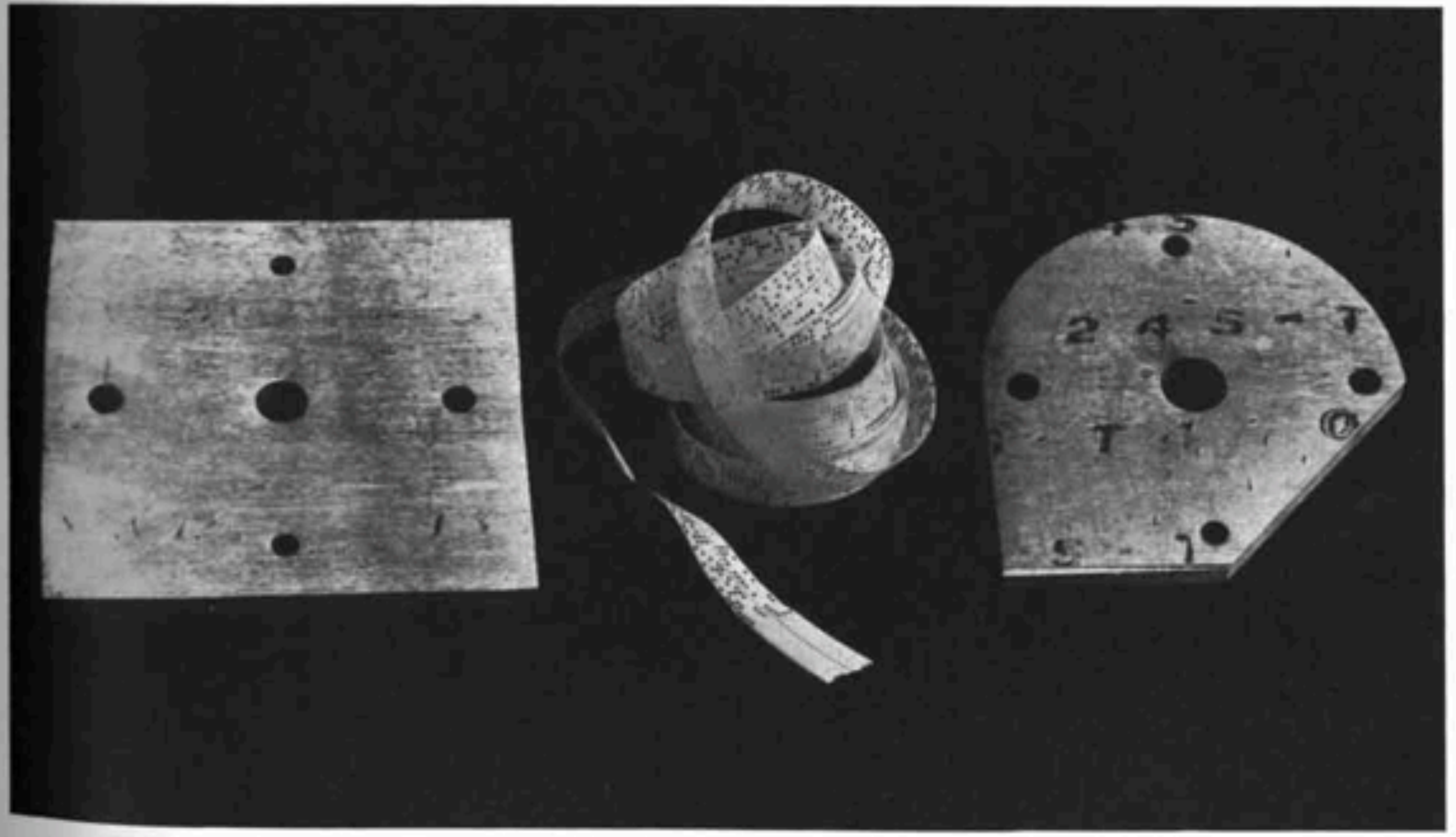
THE metal-cutting industry is one field in which automatic control has been late in arriving. The speed, judgment and especially the flexibility with which a skilled machinist controls his machine tool have not been easily duplicated by automatic machines. Only for mass-production operations such as the making of automobile parts has it been feasible to employ automatic machinery. New developments in feedback control and machine computation, however, are now opening the door to automatization of machine tools built to produce a variety of parts in relatively small quantities.

The problem will be clearer if we first review briefly the history of machine tools and their relationship to manufacturing processes. The story begins in the last quarter of the 18th century. Prior to that time the tools of the millwright, as the machinist of that day was called, consisted chiefly of the hammer, chisel and file. His measurements were made with a wooden rule and crude calipers. His materials were prepared either by hand-forging or by rudimentary foundry casting. Crude, hand-powered lathes were already in existence, but they were used only for wood-turning or occasionally for making clock parts.

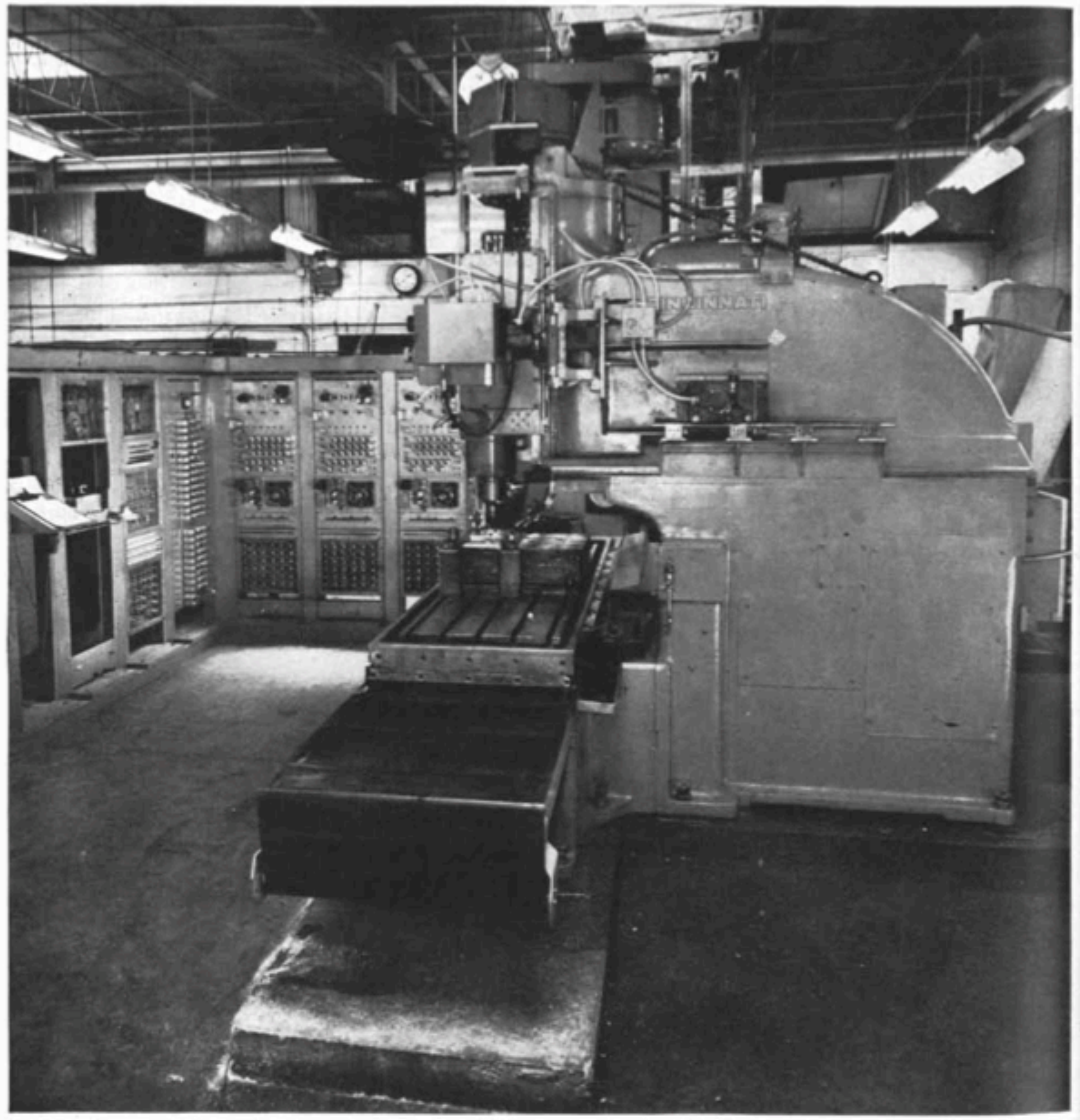
The first machine tool in the modern sense of the word was a cylinder-boring device invented in 1774 by John Wilkinson. Wilkinson is by no means as well-remembered as James Watt, but it was his invention that enabled Watt to build a full-scale steam engine. For 10 years Watt had been struggling vainly to turn out a cylinder true enough for the job. After one effort he reported in discouragement that in his cylinder of 18-inch diameter "at the worst place the long diameter exceeded the short by three-eighths of an inch." But in 1776 Watt's partner, Matthew Boulton, was able to write: "Mr. Wilkinson has bored us several cylinders almost without error; that of 50 inches diameter, which we have put up at Tipton, does not err the thickness of an old shilling in any part." The importance of Wilkinson's boring machine cannot be overestimated. It made the steam engine a commercial success, and it was the forerunner of all the large, accurate metal-working tools of modern industry.

Another productive Englishman of the same period was Joseph Bramah. His inventions included one of the most successful locks ever devised, the hydraulic press, various woodworking machines, the four-way valve, a beer pump and the water closet. To manufacture his inventions he and an associate, Henry Maudslay, created several metal-cutting machines. The most significant of these was a screw-cutting lathe with a slide rest and change gears remarkably like our modern lathes.

THE NEXT great step forward in machine technology was pioneered by Eli Whitney. Although he is remembered mainly as the inventor of the cotton gin, his greatest contribution was an innovation of much more general import: interchangeability of manufactured parts. In 1798 Whitney, hav-



SAMPLE PRODUCT of the automatic machine tool described in this article is the cam shown at right. The instructions which direct the cutting of the cam from a square blank are encoded on paper tape.



MACHINE AND CONTROL are shown here in entirety. For details of the control panels (*left*) see pages 104 and 105. The machine has universal motion: the "head," holding the cutting tool, moves vertically; the "cross slide" moves the head back and forth across table; the table moves from side to side under tool. The control system coordinates all three motions simultaneously to perform the operations shown on the opposite page.

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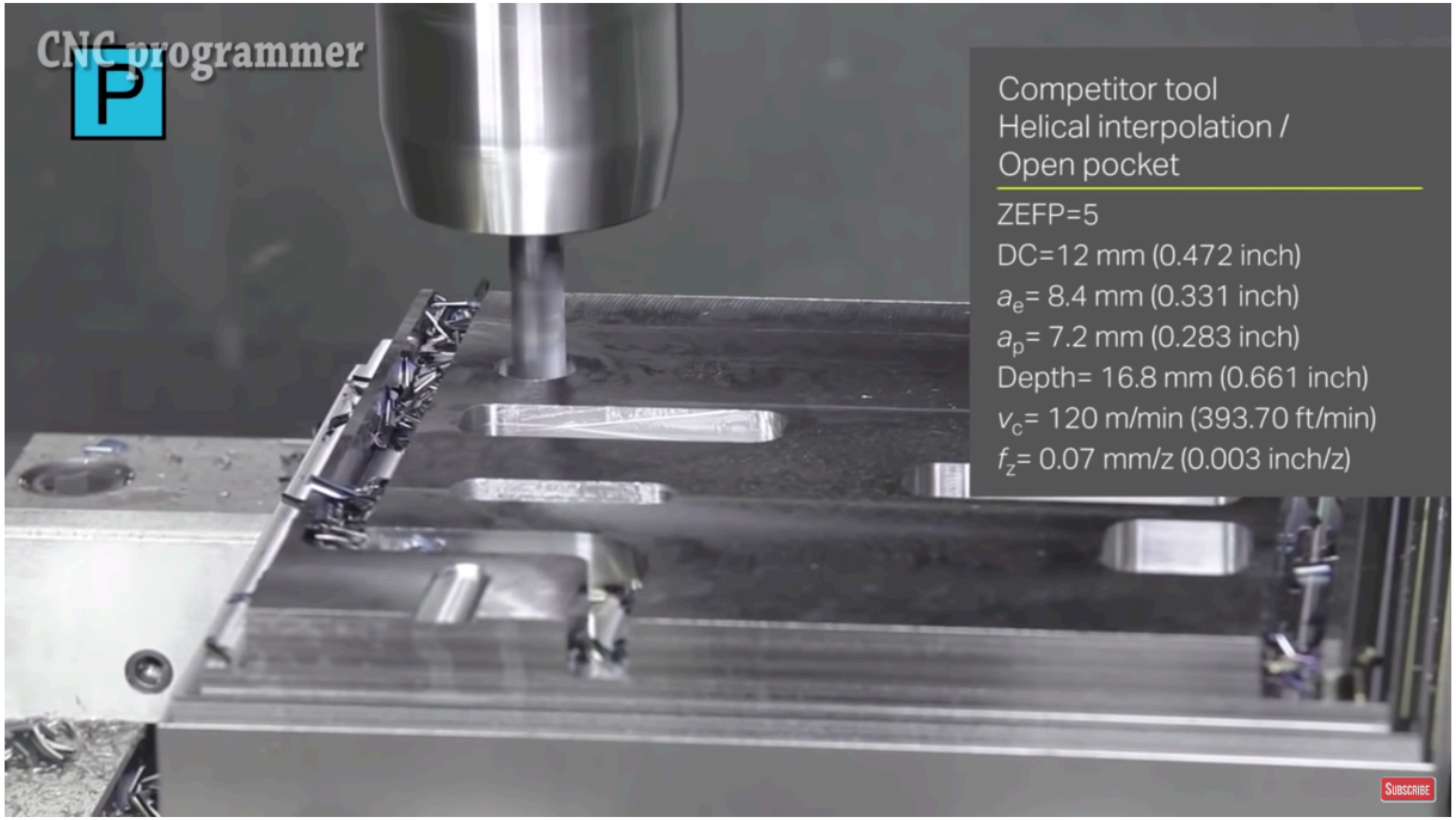
Scientific American article, 1952

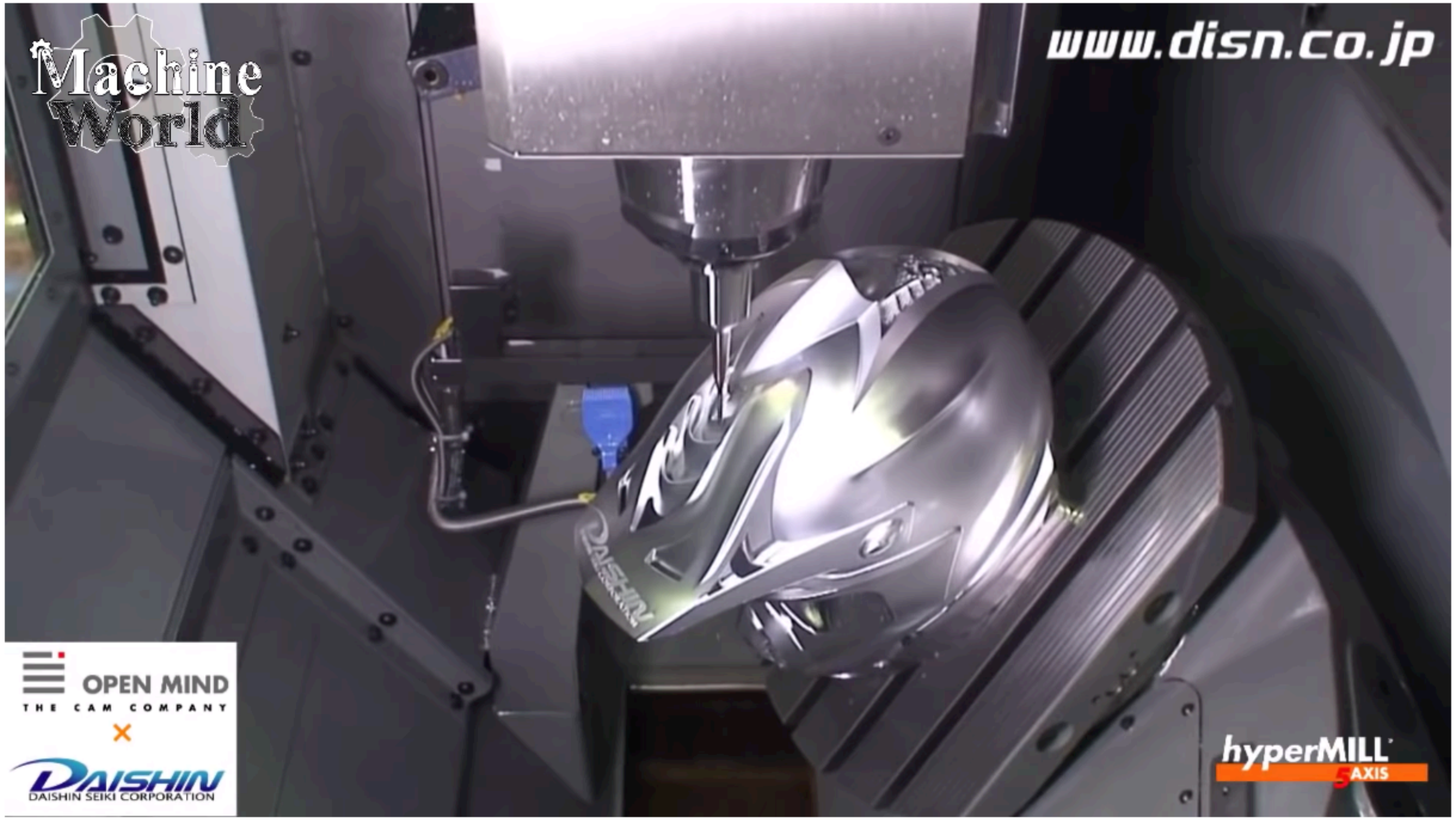
https://cs448m.github.io/lectures/cam/scientificamerican0952-101.pdf

CNC Cutting



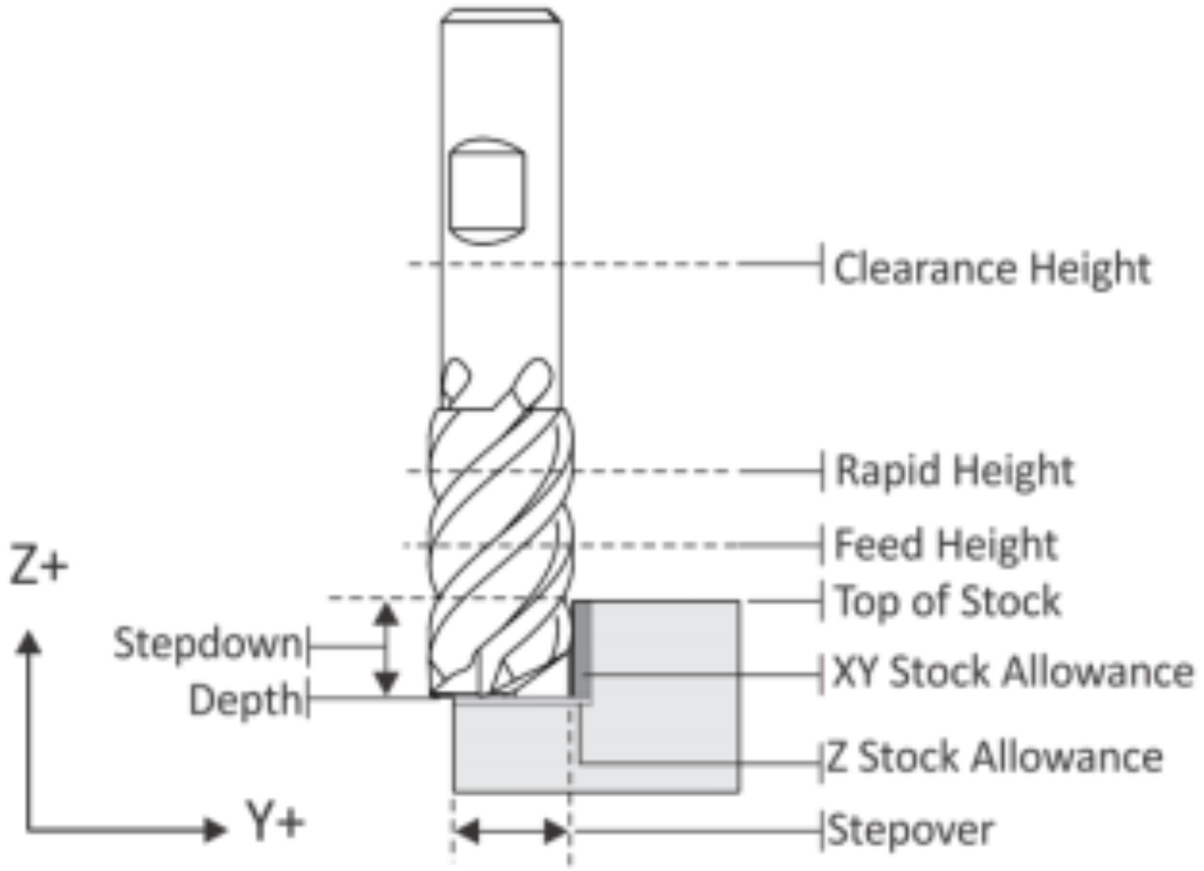
https://www.youtube.com/watch?v=4y9sEdrs0Xk

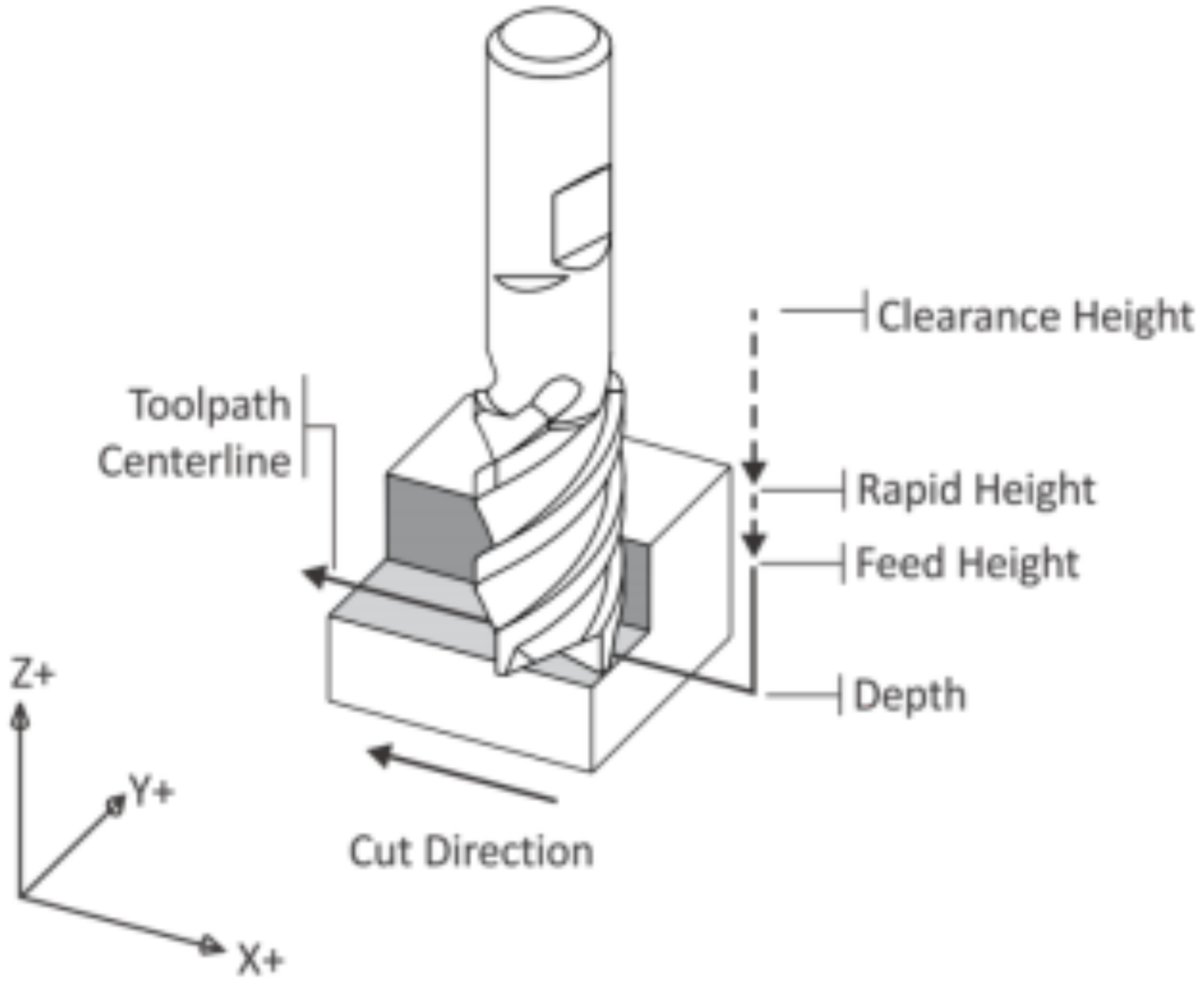
CNC Machine & Milling Compilation



https://www.youtube.com/watch?v=8H-0lI7kxbg

Toolpath Lingo





- **X, Y, and Z Allowance** is the amount of material remaining on either the finished wall (XY) or floor (Z) of a part that needs to be removed in future operations. Sometimes also called "Stock to Leave."
- **Stepover** determines how much material is removed radially, or left and right, by a tool each time it passes in the XY direction.
- **Stepdown** is the amount of material that gets removed axially, or vertically, with each pass of your cutting tool. Multiple passes may be needed to get to a final depth.
- **Top of Stock** designates the top face of the stock being used to make the part, which can be used as a reference point for machining processes.
- **Feed Height** is the height a tool will position itself to before starting to feed at the cut feedrate before it enters the material, usually set to some safe distance above the top of stock.
- **Retract Height** is the height a tool will retract to between moves within the same operation, usually set some safe distance above the feed height.
- **Clearance Height** is the height a tool moves at between individual operations, usually set to 1.000in above the top of a stock.
- **Toolpath Centerline** is the path the tool will take as it moves along a toolpath. The diameter of the tool needs to be taken into consideration to make sure that the tool cuts at the desired

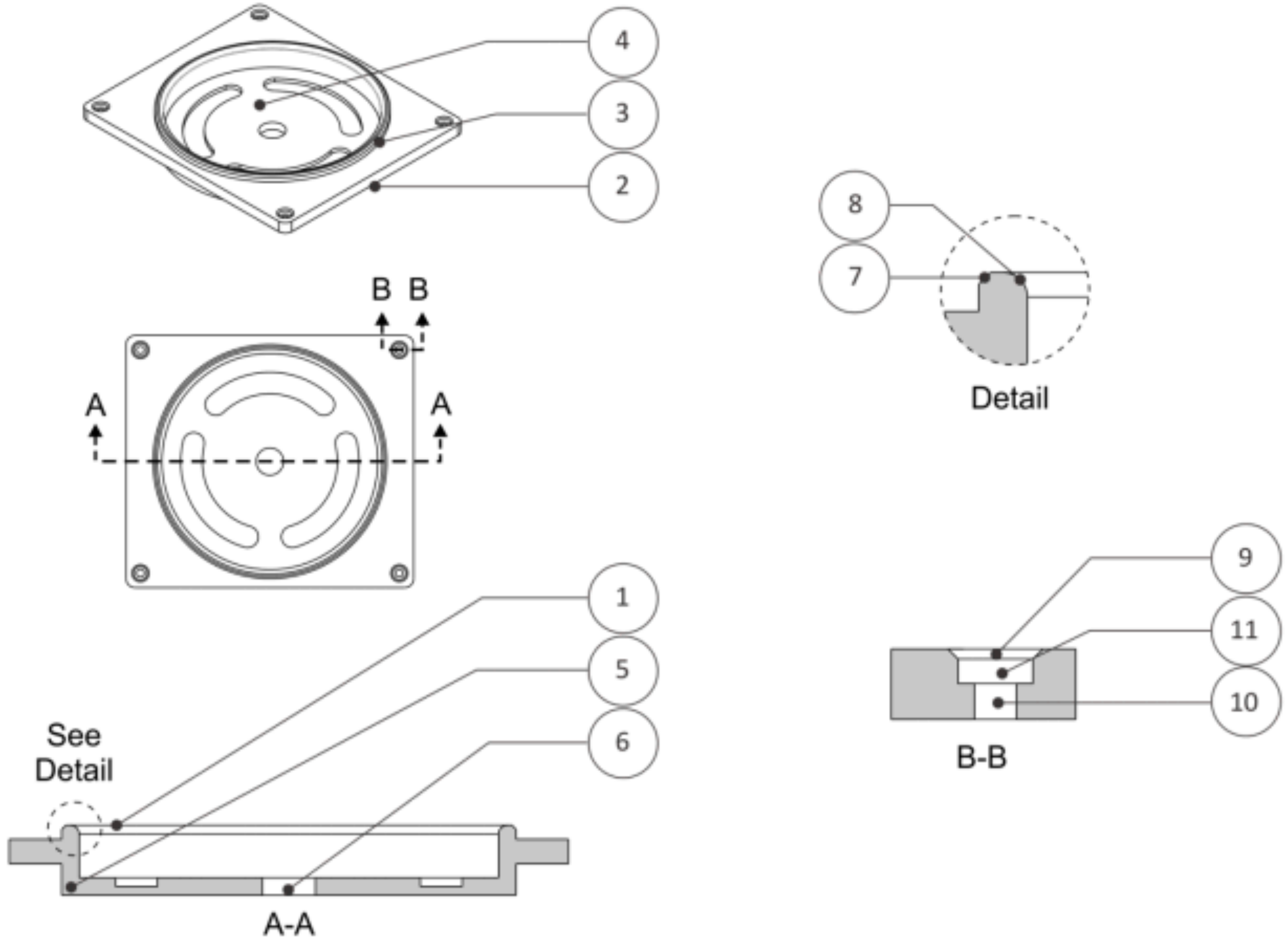
https://www.autodesk.com/products/fusion-360/blog/10-2d-cnc-milling-toolpaths/

Types of CNC Toolpaths

Toolpath	Uses
Face	Finishing the face of a part.
Contour	Machining loops, open pockets, stick fonts, dovetails, keysets, or saw cuts.
Chamfer	Deburring and creating chamfers using either a tapered mill or center drill.
Fillet	Creating fillets using a Corner Rounding Tool.
Pocket	Roughing or finishing pockets of various shapes and sizes.
Slot Mill	Machining straight slots or arc slots.
Drill	Creating spot drill, tapped, bore, or reamed holes.
Bore	Making holes, typically greater than .75in diameter.
Thread Mill	Machining ID threads over .75in diameter, milled OD threads of any size, or custom threads.

https://www.autodesk.com/products/fusion-360/blog/10-2d-cnc-milling-toolpaths/

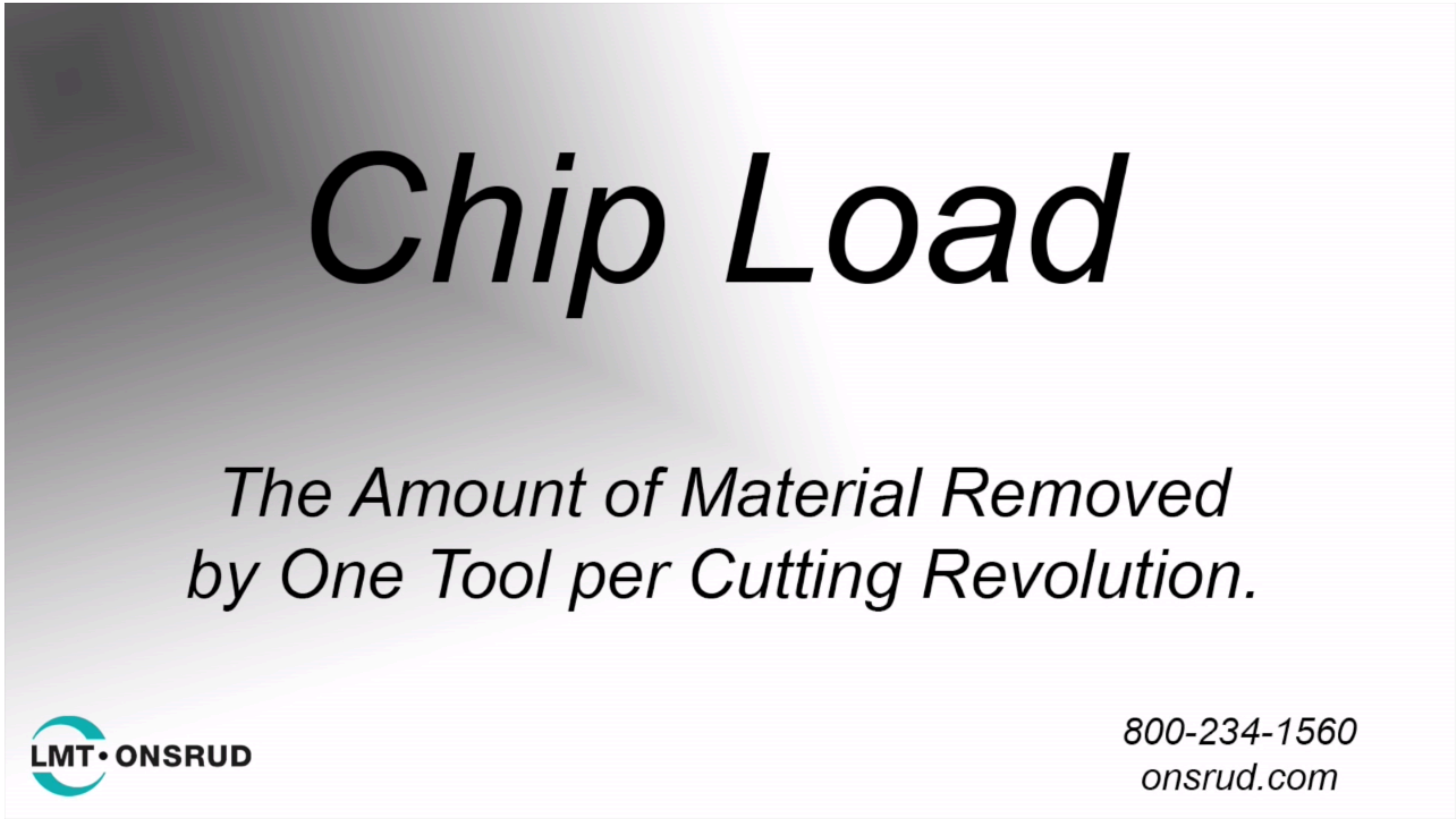
Example: Part with 11 Toolpaths



Step	Toolpath	Comments
1	Face	Roughs and finishes to the highest flat surface of part.
2	2D Contour	Machines the outside of the part.
3	2D Contour	Machines outside of circular boss.
4	2D Pocket	Roughs and then finishes the circular pocket.
5	Slot Mill	Mills the arc slots.
6	Circular Pocket Mill	Machines the center through holes. Depending on size, a drill could also work here.
7	Chamfer	Uses a 2D contour and chamfer mill to create 45° angle.
8	Fillet	Uses 2D contour and corner round tool to make fillet.
9	Spot Drill	Pre-drills holes to prevent drill drift and to make a chamfer.
10	Drill	Machines holes.
11	Circular Pocket Mill	Machines counterbore.

https://www.autodesk.com/products/fusion-360/blog/10-2d-cnc-milling-toolpaths/

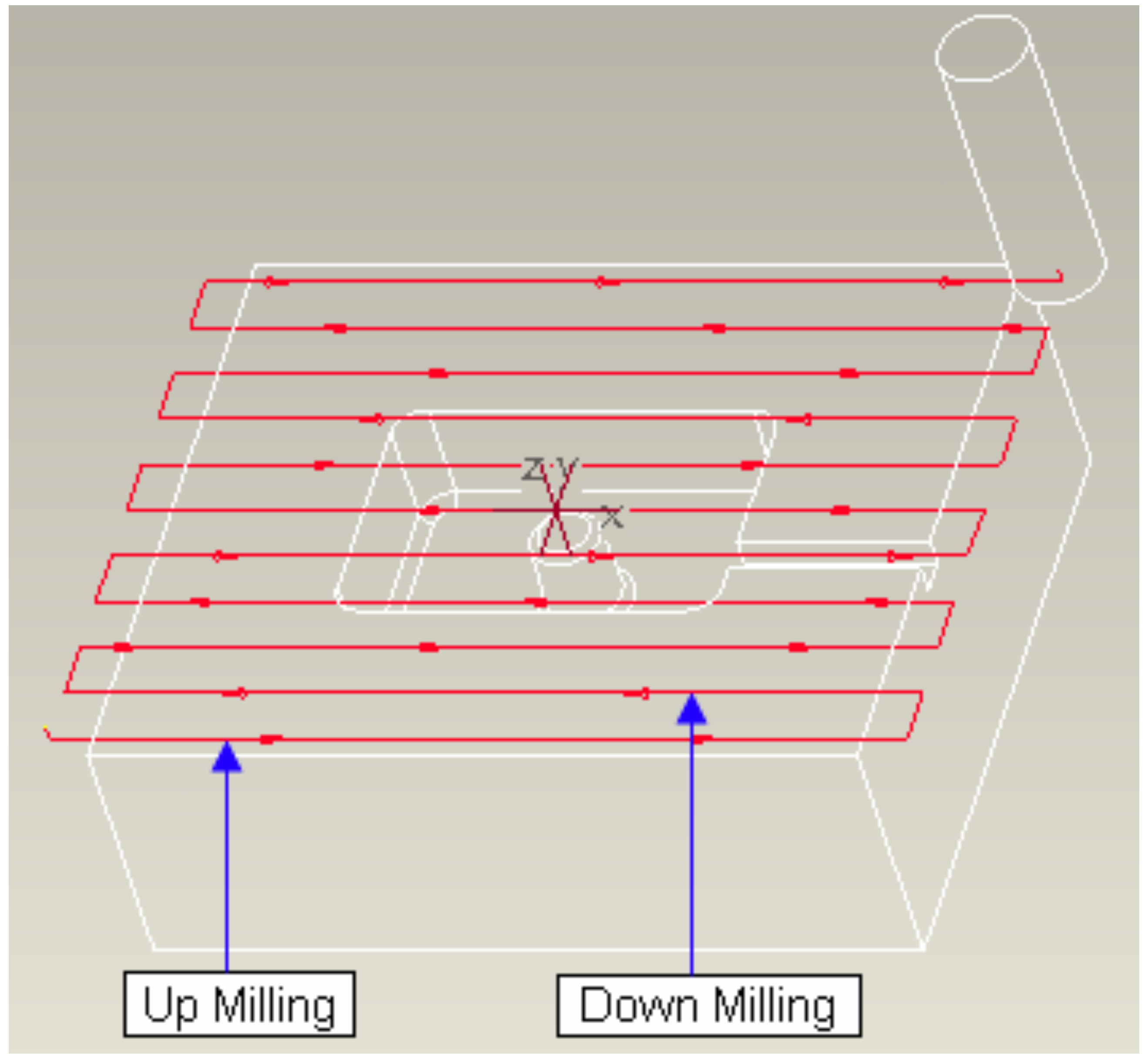
Calculating Speeds and Feeds



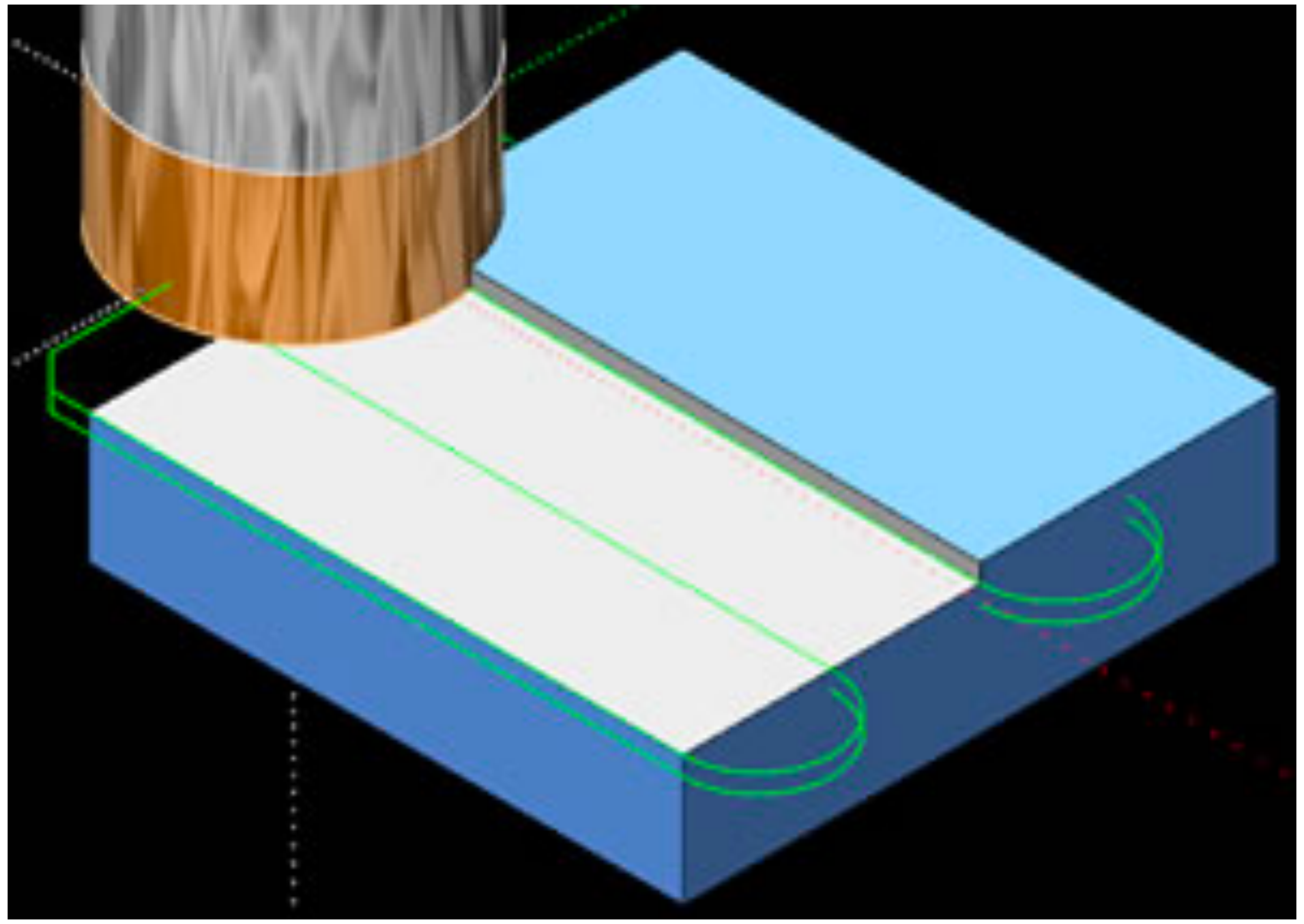
https://www.youtube.com/watch?v=JPvBzaA3GY0

Face Milling

http://cuttingedgeconversation.blogspot.com/2013/09/tips-for-purchasing-face-mill-cutter.html

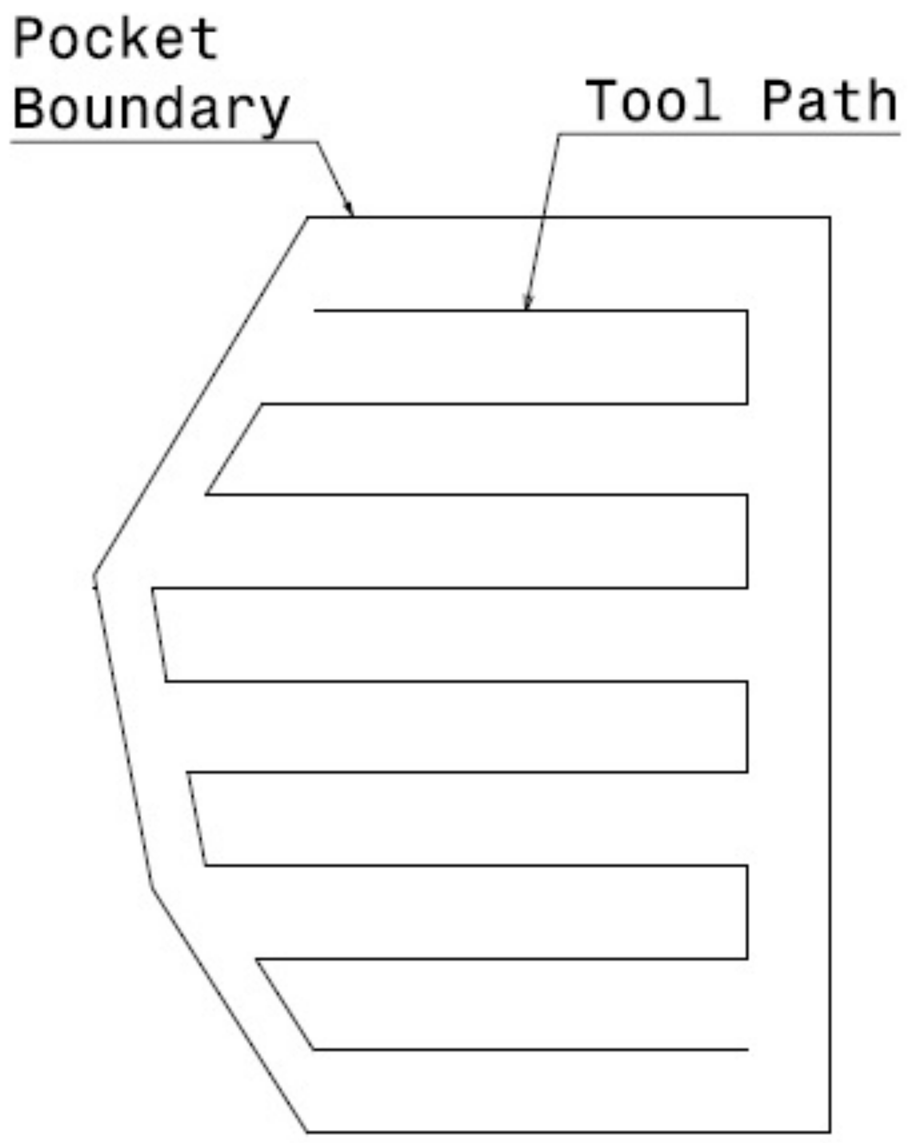


http://www.proetutorials.com/tutorials_nc/FaceMilling.htm

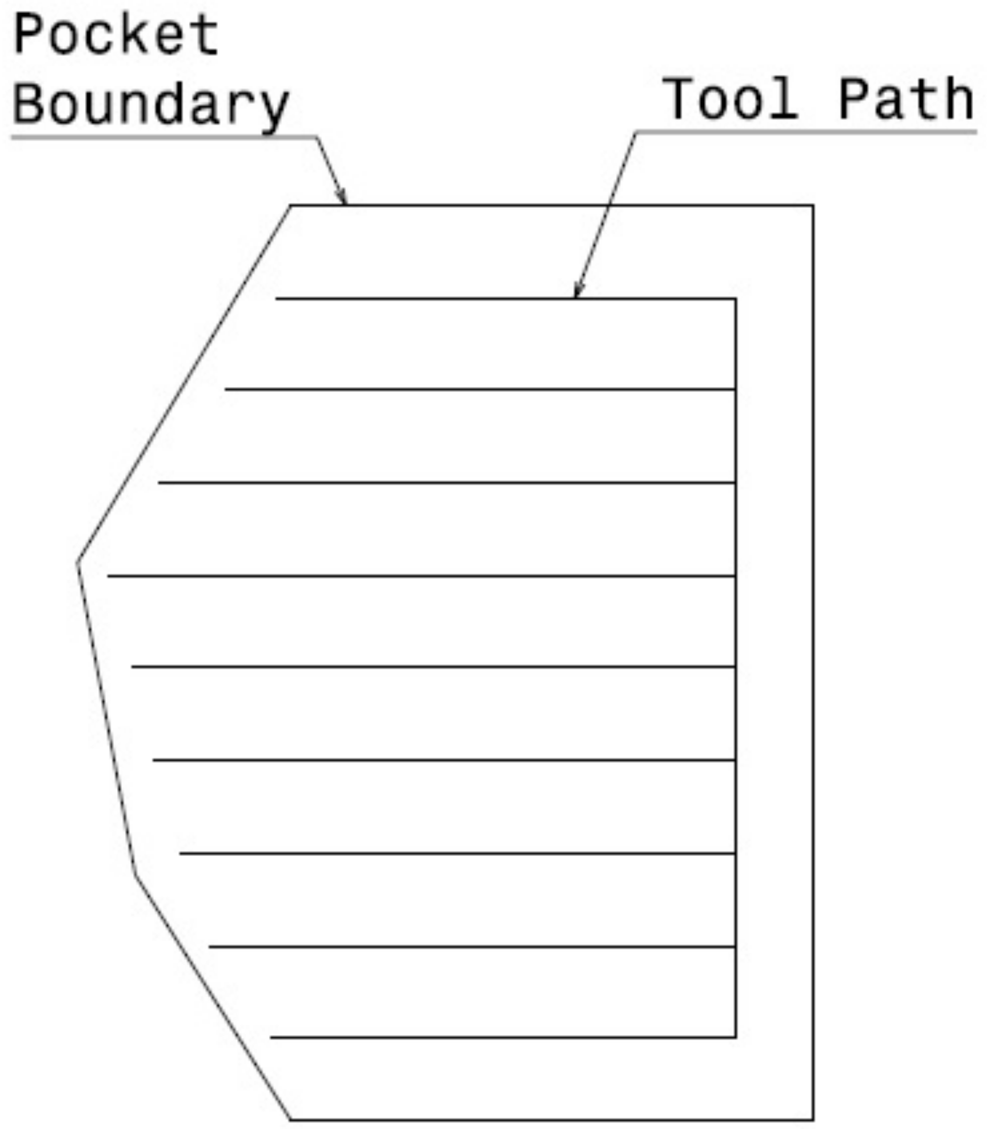


https://bobcad.com/2d-toolpath-why-you-need-it/

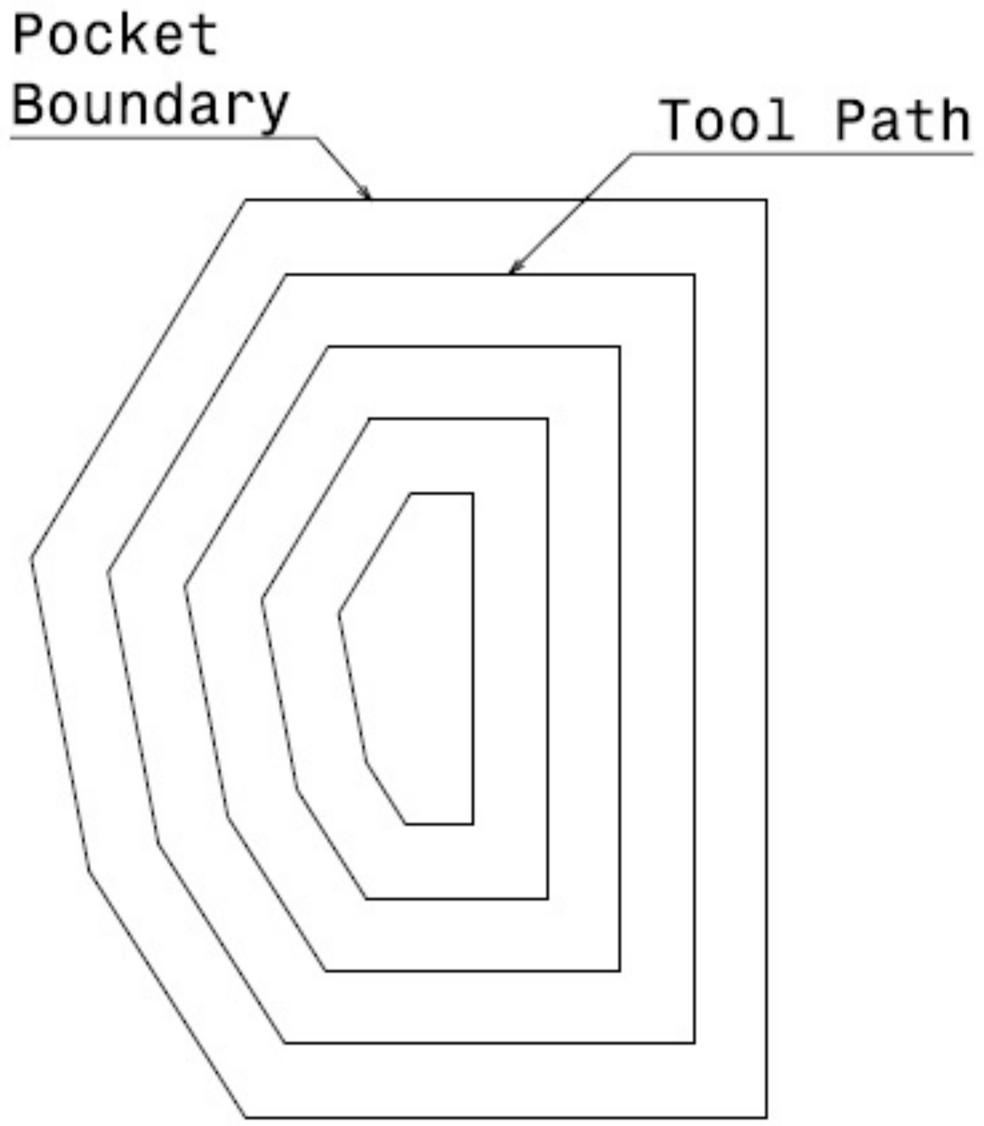
Pocket Milling Toolpaths



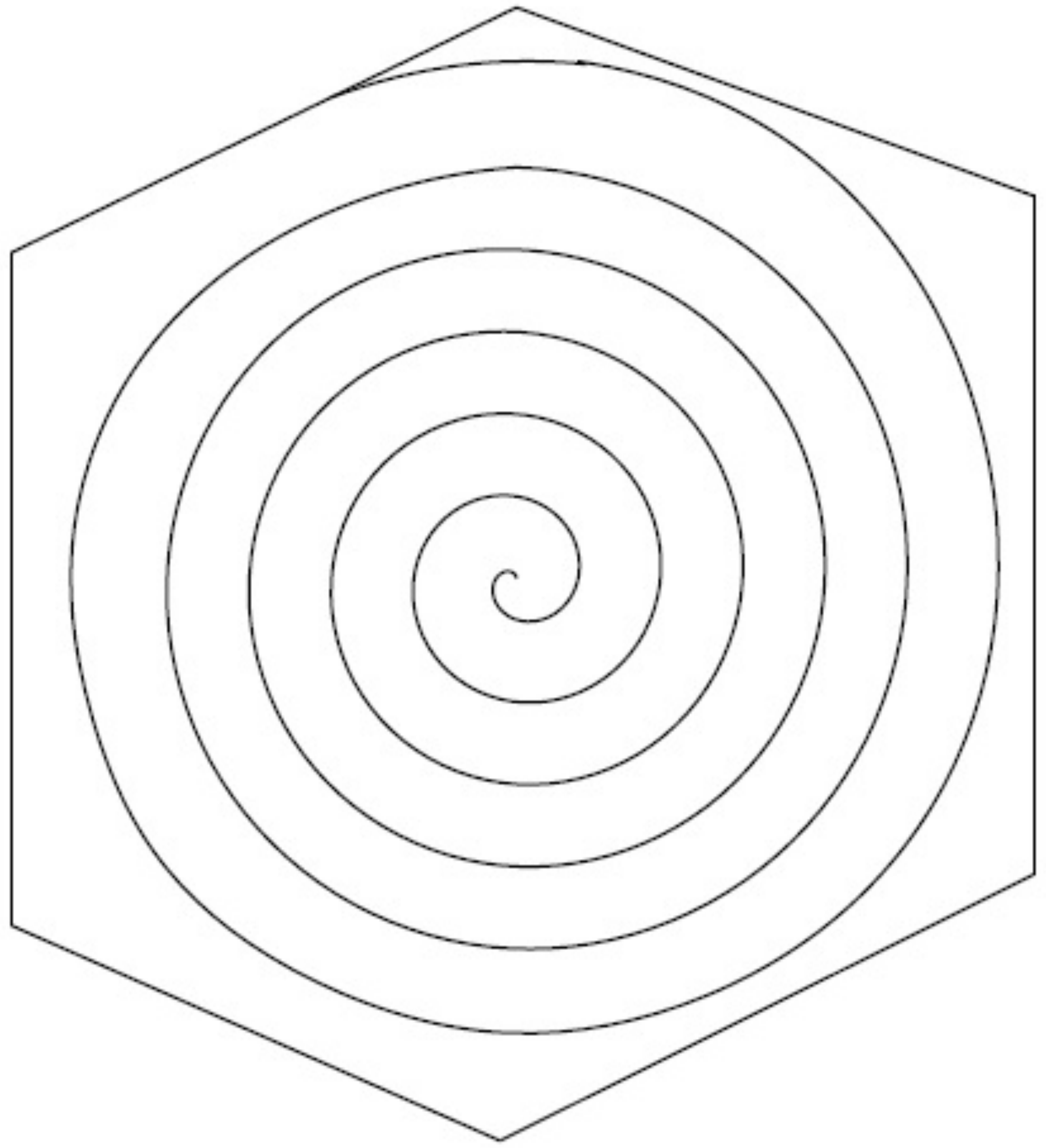
Zig-zag tool path



Zig tool path



Contour-parallel tool path
(c.f. Voronoi schemes for
convex pocket decomposition)

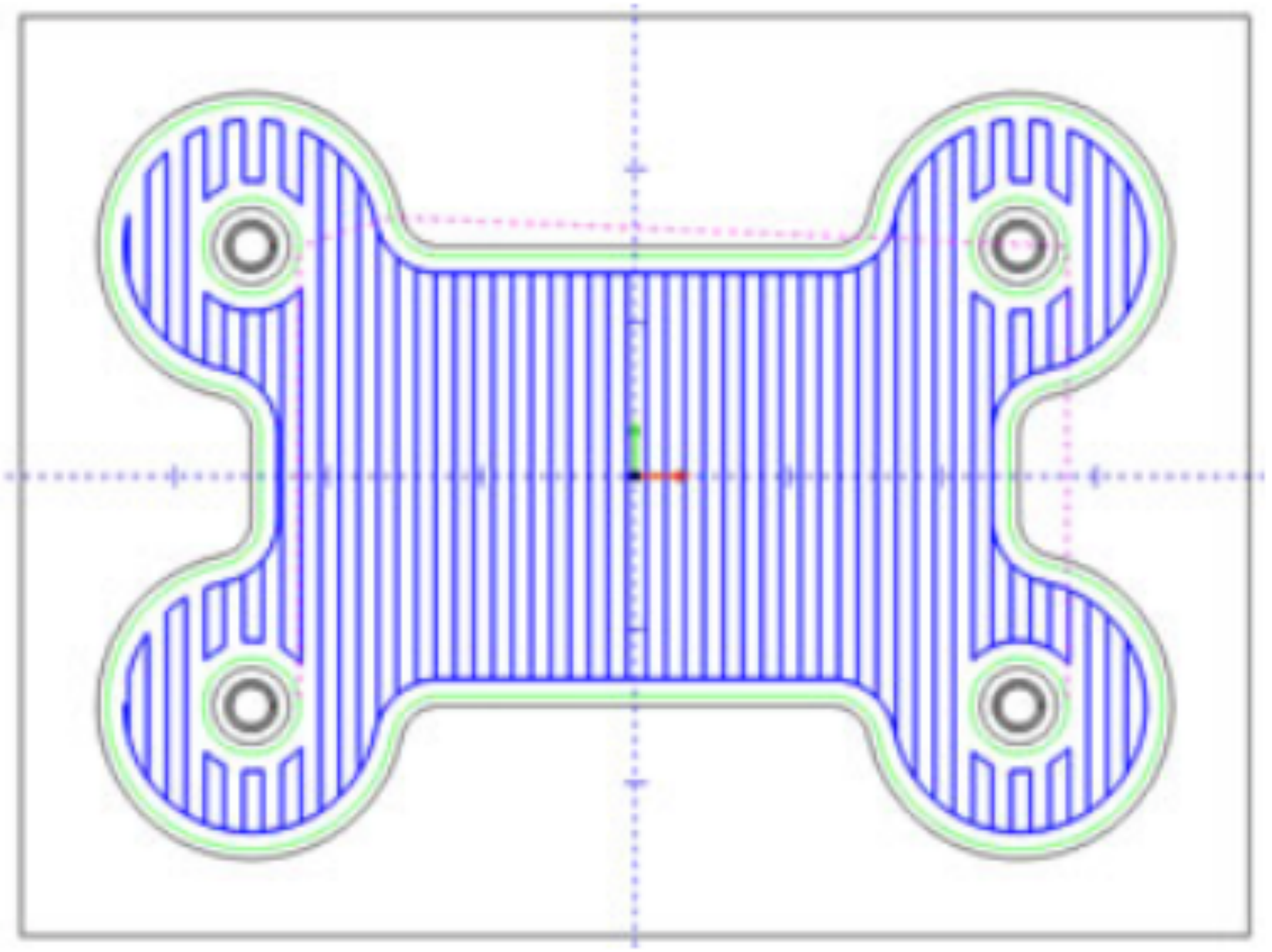


Curvilinear tool path

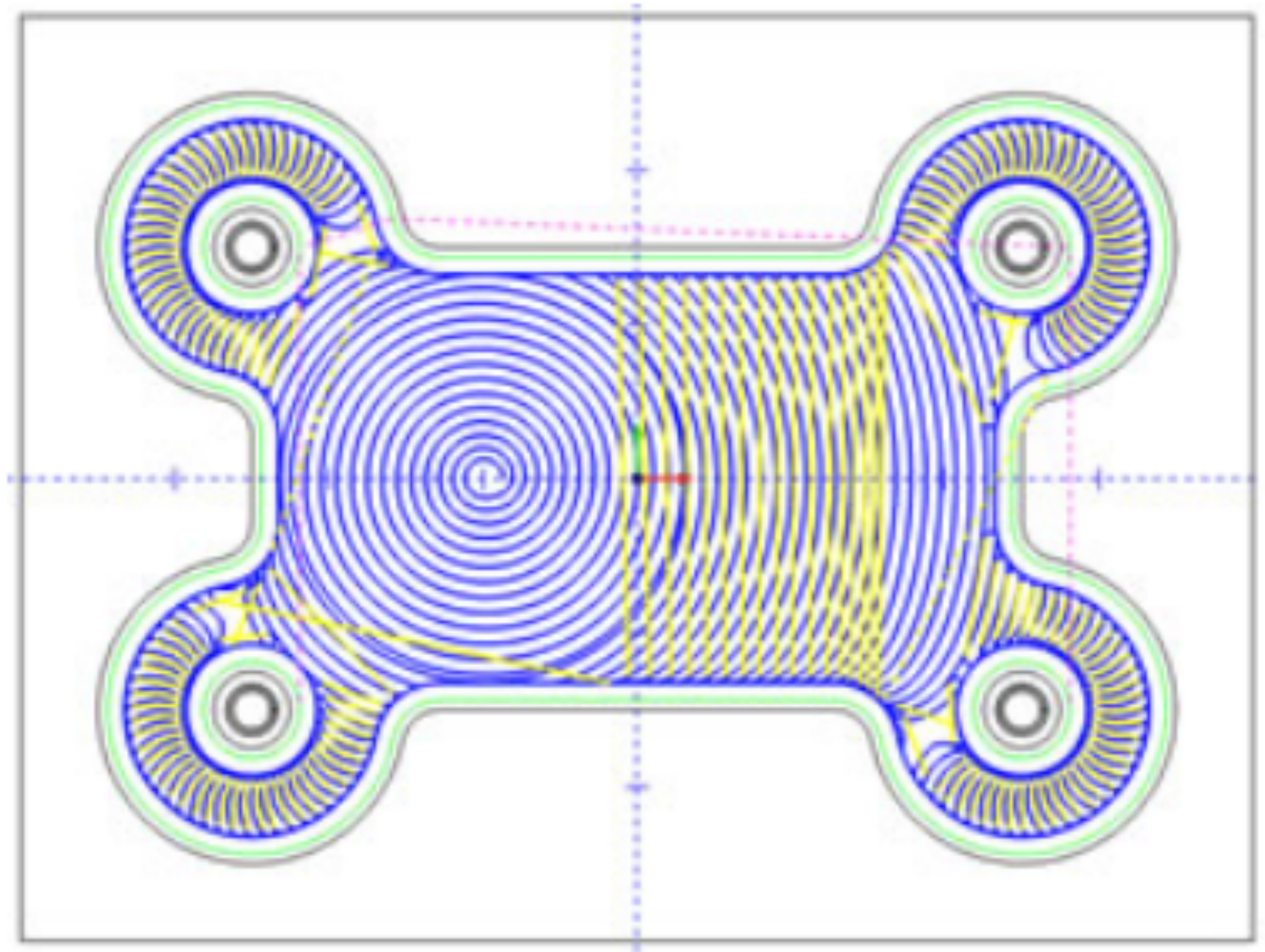
https://en.wikipedia.org/wiki/Milling_(machining)

Pros/Cons: Machining time, idle time, tool wear, machine chatter, tool acceleration/deceleration, surface quality, cutting speed

Toolpath Optimization



Traditional Pocket Toolpath

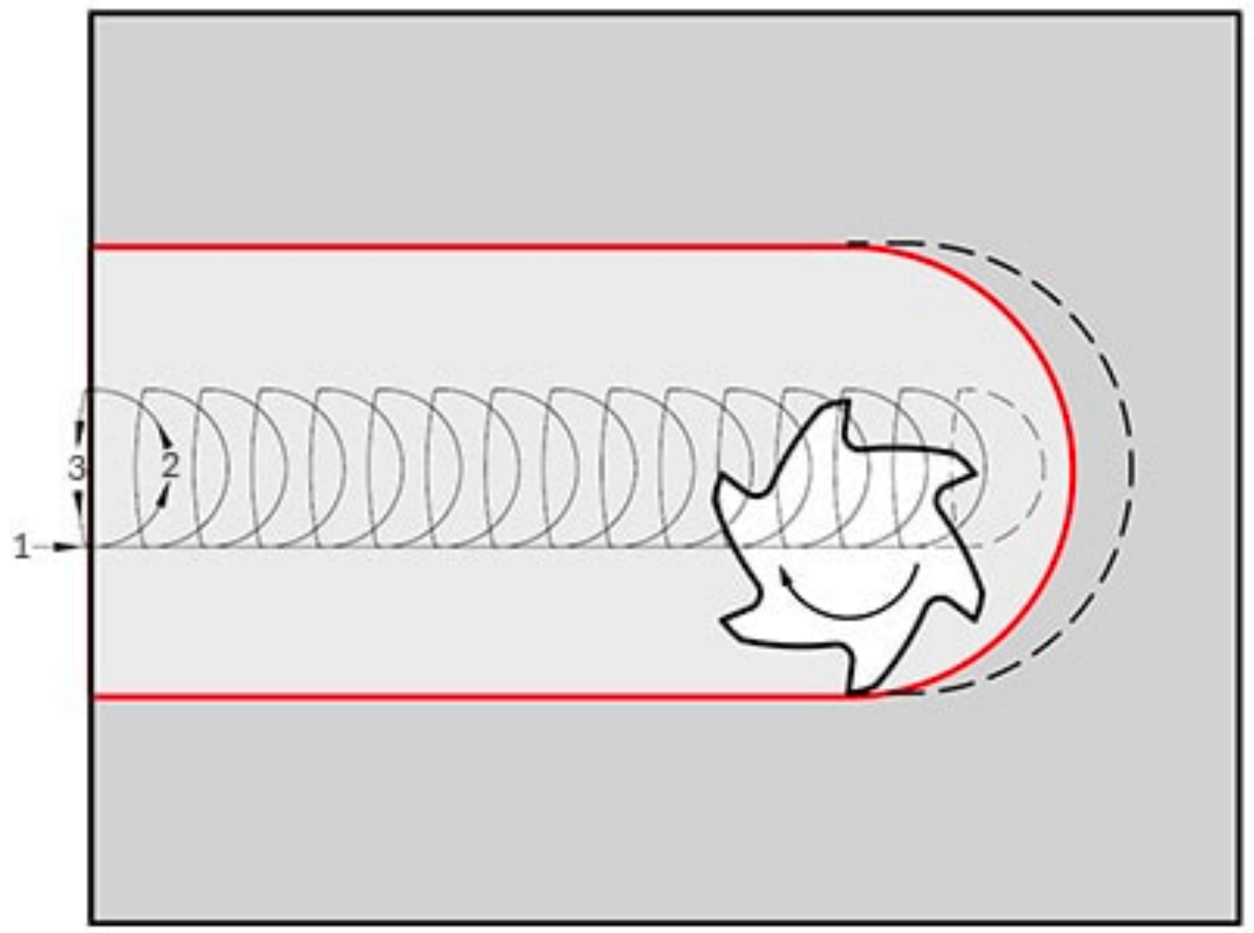


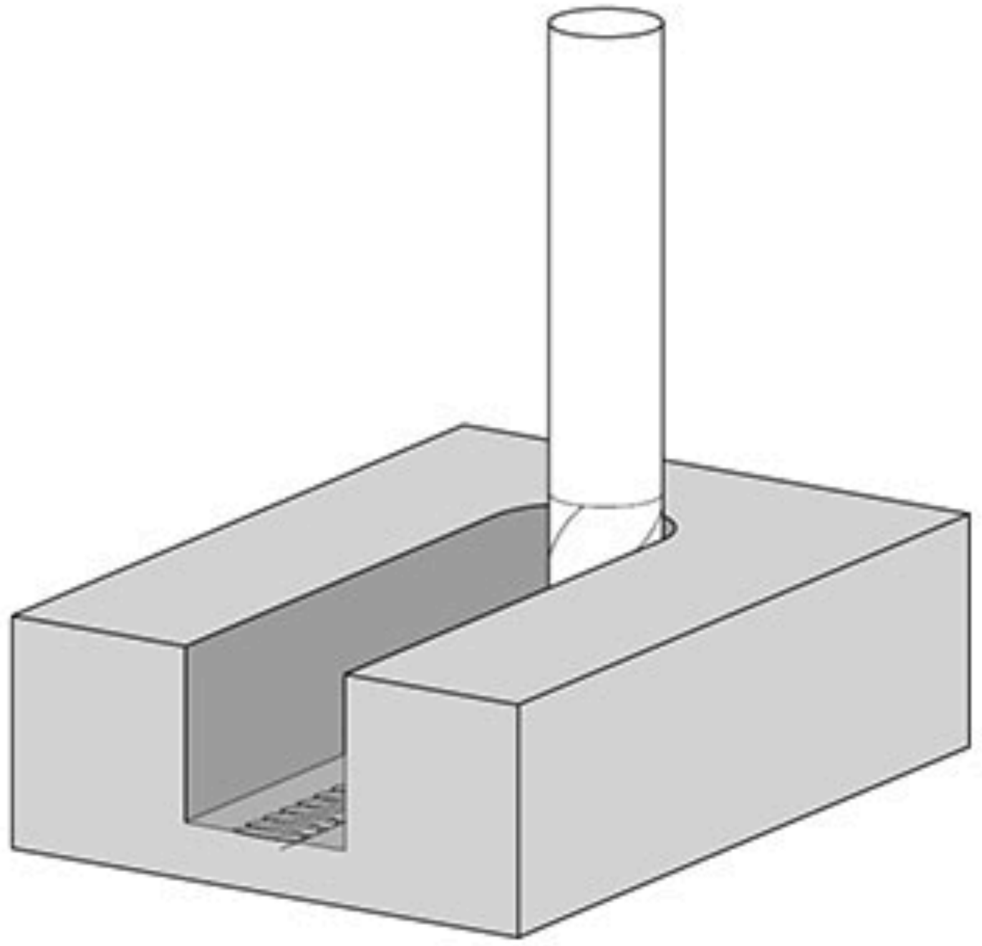
High Speed Pocket Toolpath

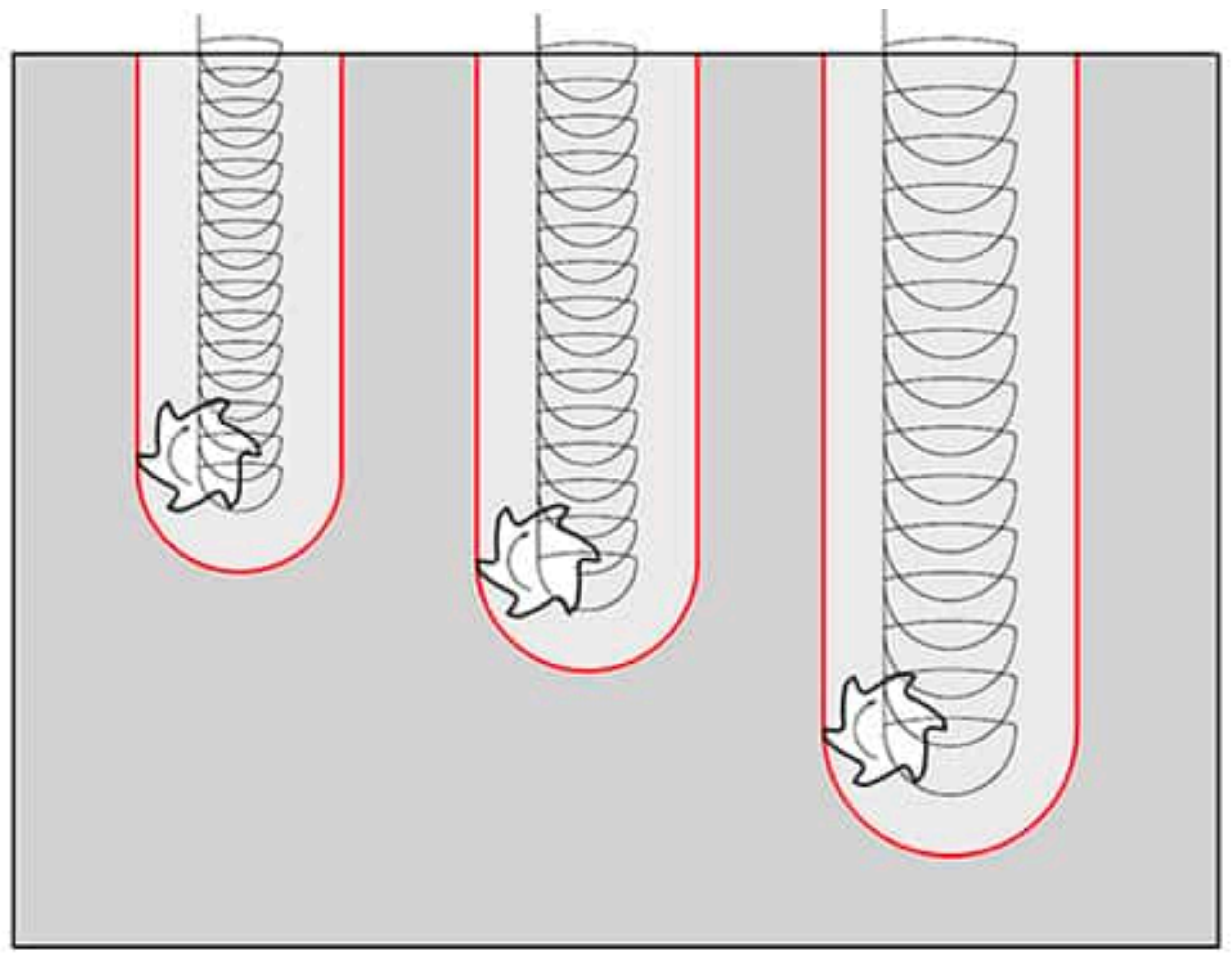
"The basic theory behind high speed toolpath is that there is a constant engagement during cutting, constant chip load, a minimal amount of feed rate loss due to the stop and go movements in traditional toolpath and the ability to increase cutting speeds due to the circular (trochoidal) machining motion. Additional intelligence can be developed into high speed toolpath that takes into consideration areas that have already been machined as well as automatic tool repositioning."

https://bobcad.com/2d-toolpath-why-you-need-it/

Optimization: Trochoidal Milling

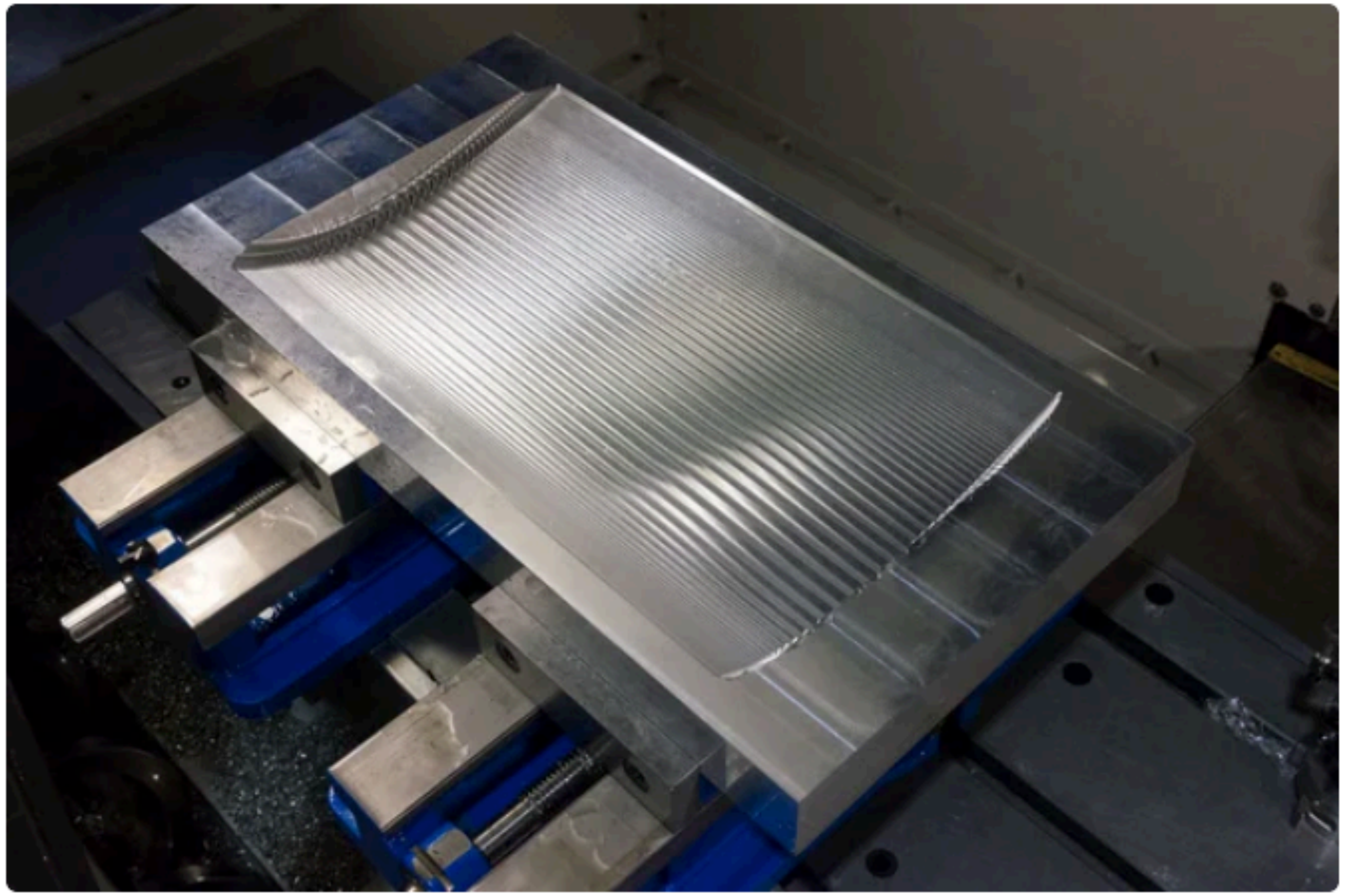






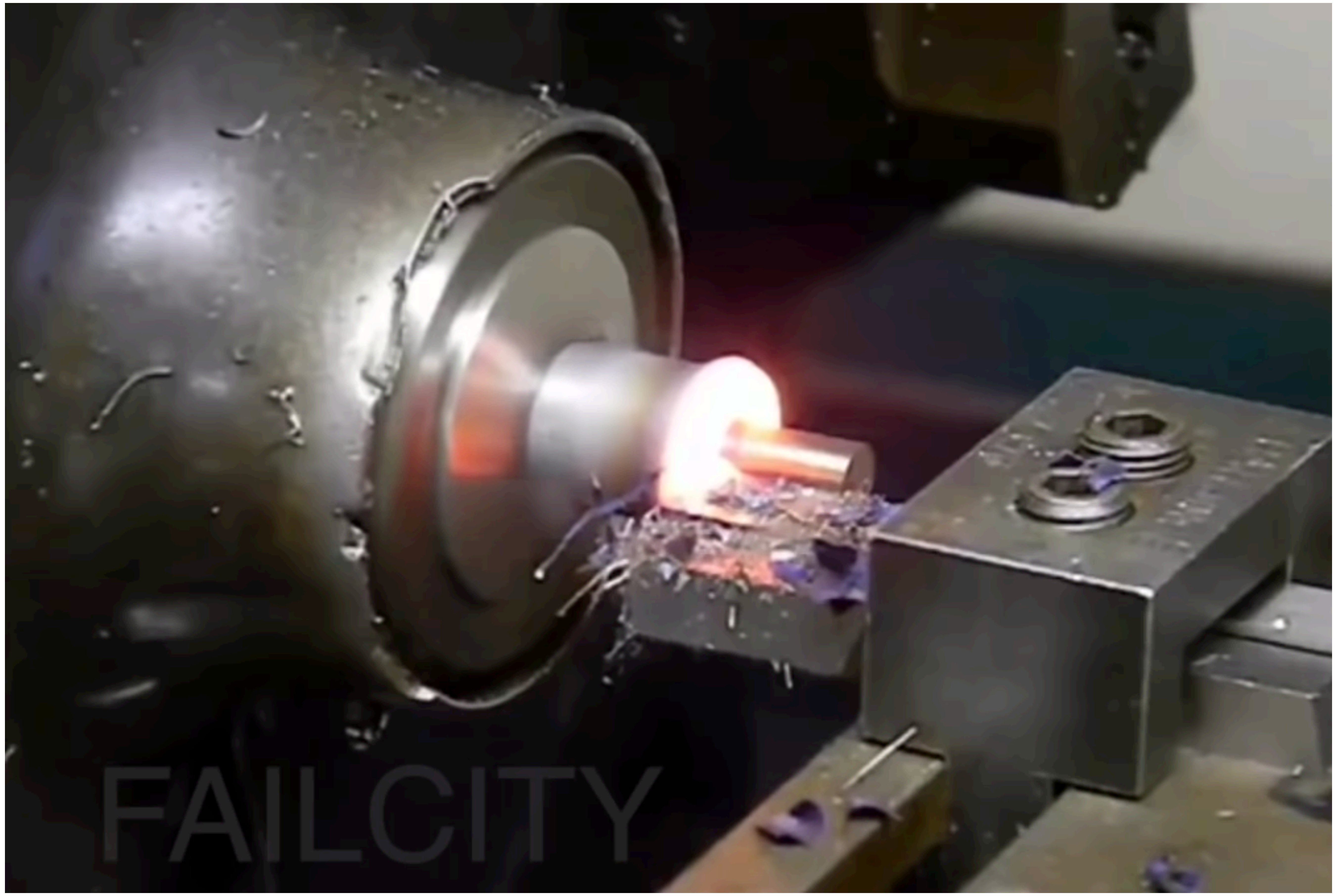
https://www.harveyperformance.com/in-the-loupe/introduction-trochoidal-milling/

Custom Toolpaths



https://www.instructables.com/id/Drawing-CNC-Toolpaths-to-Define-Custom-Surfaces/

CNC CAM Fails



https://www.youtube.com/watch?v=PsFNeiAu04M

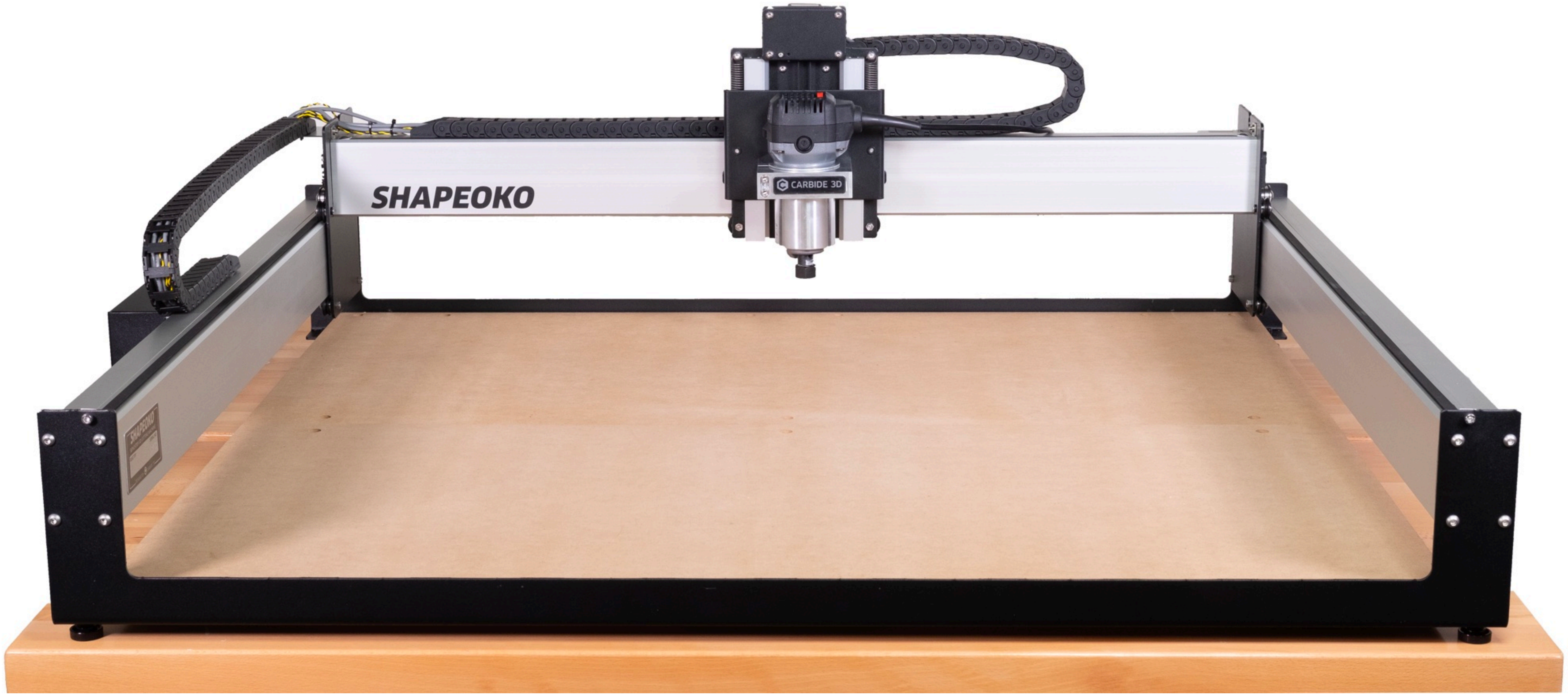
CNC (3D) Printers for Makers

CNC Routers for Makers

X-Carve

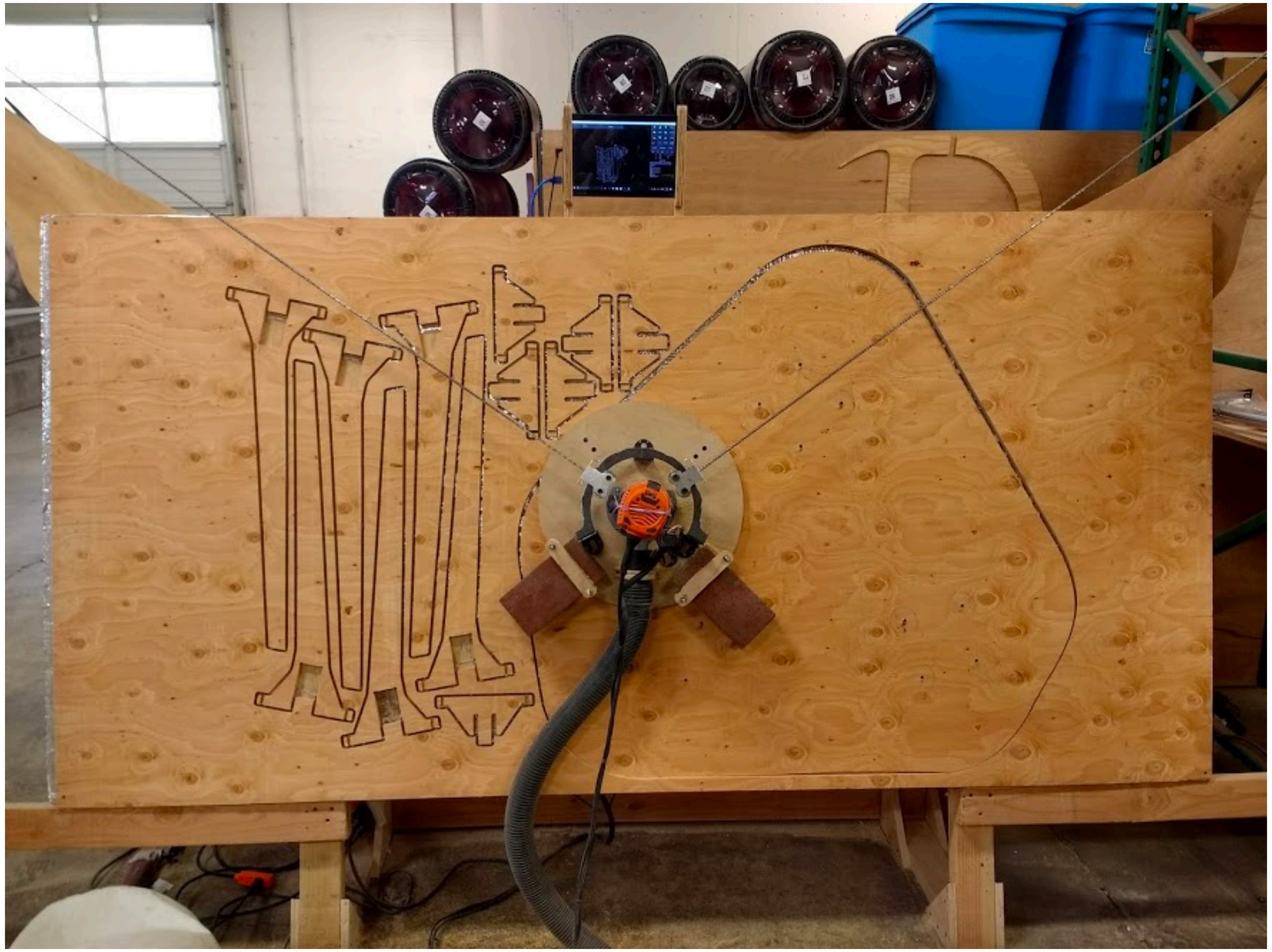
https://www.inventables.com/technologies/x-carve

Shapeoko



https://carbide3d.com/shapeoko/

Maslow



https://www.maslowcnc.com/

Larger CNC Machines

https://www.youtube.com/watch?v=IaufzuOSigs

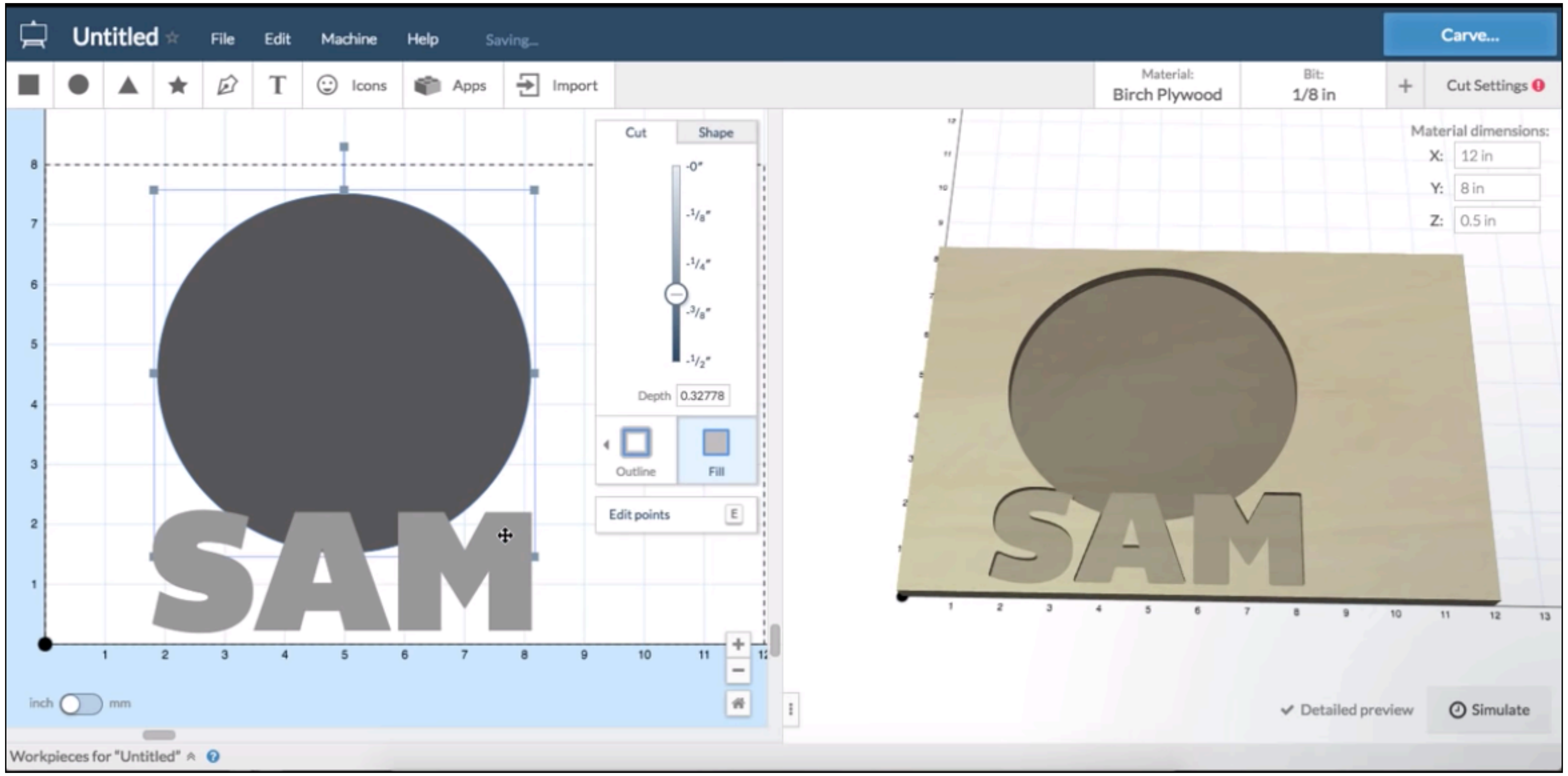
Some Software Tools

CAD/CAM Companies

Bicycle Forest Inc.		BikeCAD	CAD	Parametric CAD software for bicycle frame design and bicycle fitting.[1] Available for Linux, Mac OS and Windows.
Bricsys		BricsCAD	CAD	CAD software and development platform unifying the familiar feature set of native dwg with 2D tools and 3D direct modeling on Windows, MAC and Linux
Cad-Capture		AssetCapture	CAD	
		AssetLink	CAD	
CADENAS		CADENAS eCATALOGsolution	CAD	CAD-System To Build Electronic Product Catalogs for Mechanical Market
		CADENAS AECsolutions	CAD	CAD-System To Build Electronic Product Catalogs for Architecture Market
		CADENAS PARTcommunity	CAD	CAD-Community and Portal to provide Free 3D CAD Models
		CADENAS PARTserver	CAD	CAD-Portal to provide Free 3D CAD Models
		CADENAS PARTsolutions	CAD	CAD-Part Management System to provide 3D Models and connect to ERP+PLM
		CADENAS BIMcatalogs	CAD	CAD-Community and Portal to provide Free 3D CAD BIM Models
CADEX		CAD Exchanger	CAD/CAE/CAM	CAD Exchanger GUI is an application to import and visualize the 3D models, export to target formats, make basic measurements and mark-up, create clipping views, capture screenshots, customize import and export.
CADMAI		CADMAI	CAD	CADMAI is a CAD framework which can either be used as a standalone CAD application or as an integration module for 3rd party applications or SOA environments
				CADMAX Solid Master is Windows-based CAD software that offers 2D drafting, 3D

https://en.wikipedia.org/wiki/List_of_CAx_companies

Easel



https://www.youtube.com/watch?time_continue=89&v=nNSqHzCvgrU

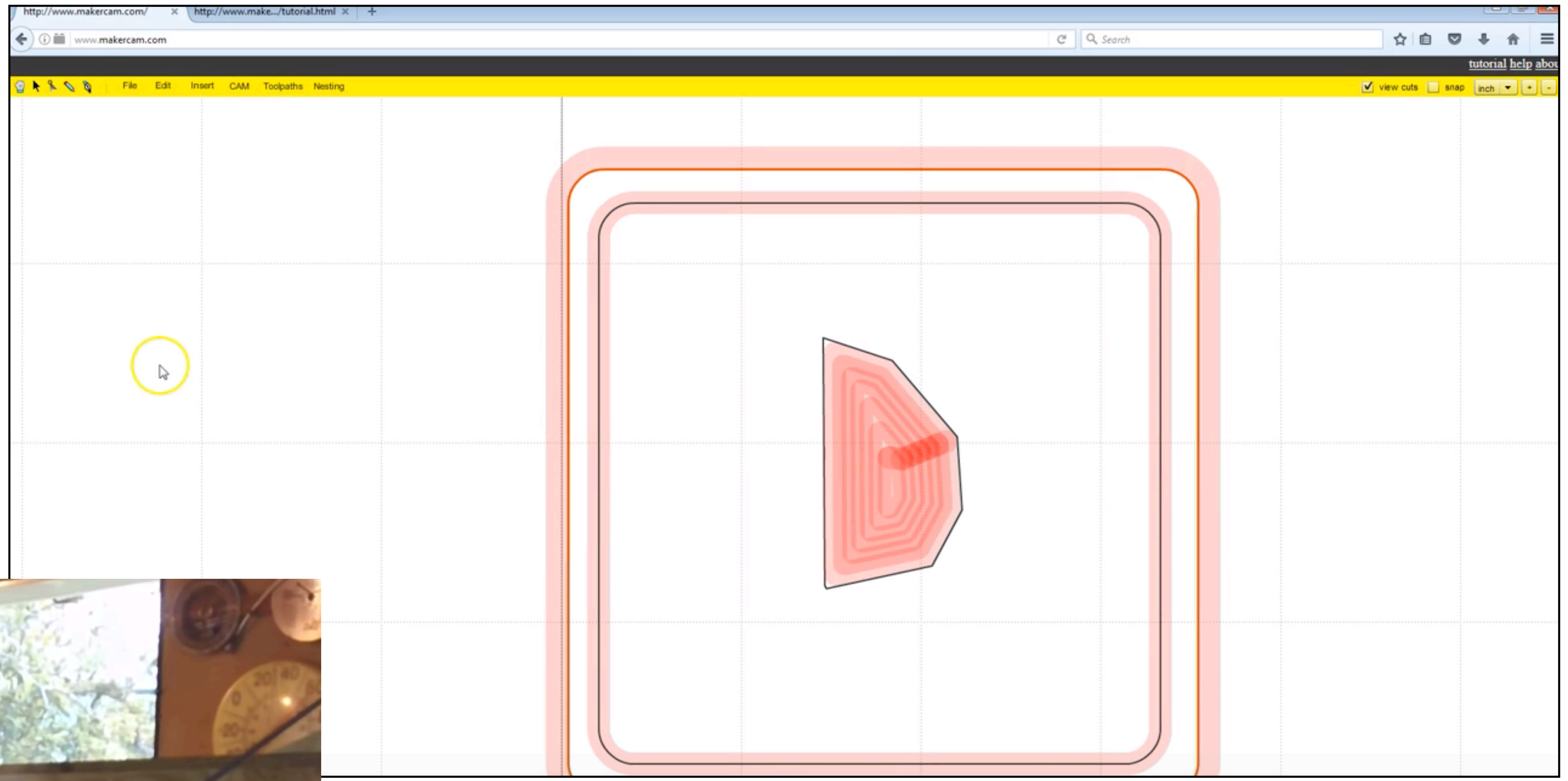
https://www.inventables.com/technologies/easel

makercam.com

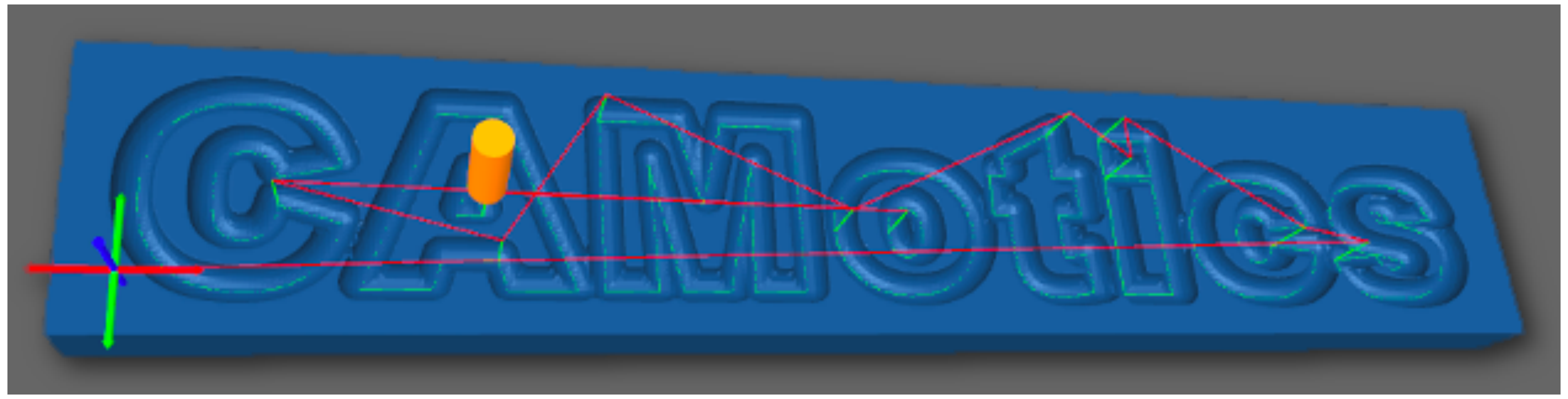
A flash-based 2.5d CAM and nesting program that outputs standard G-Code for use in CNC fabrication devices.

Features:

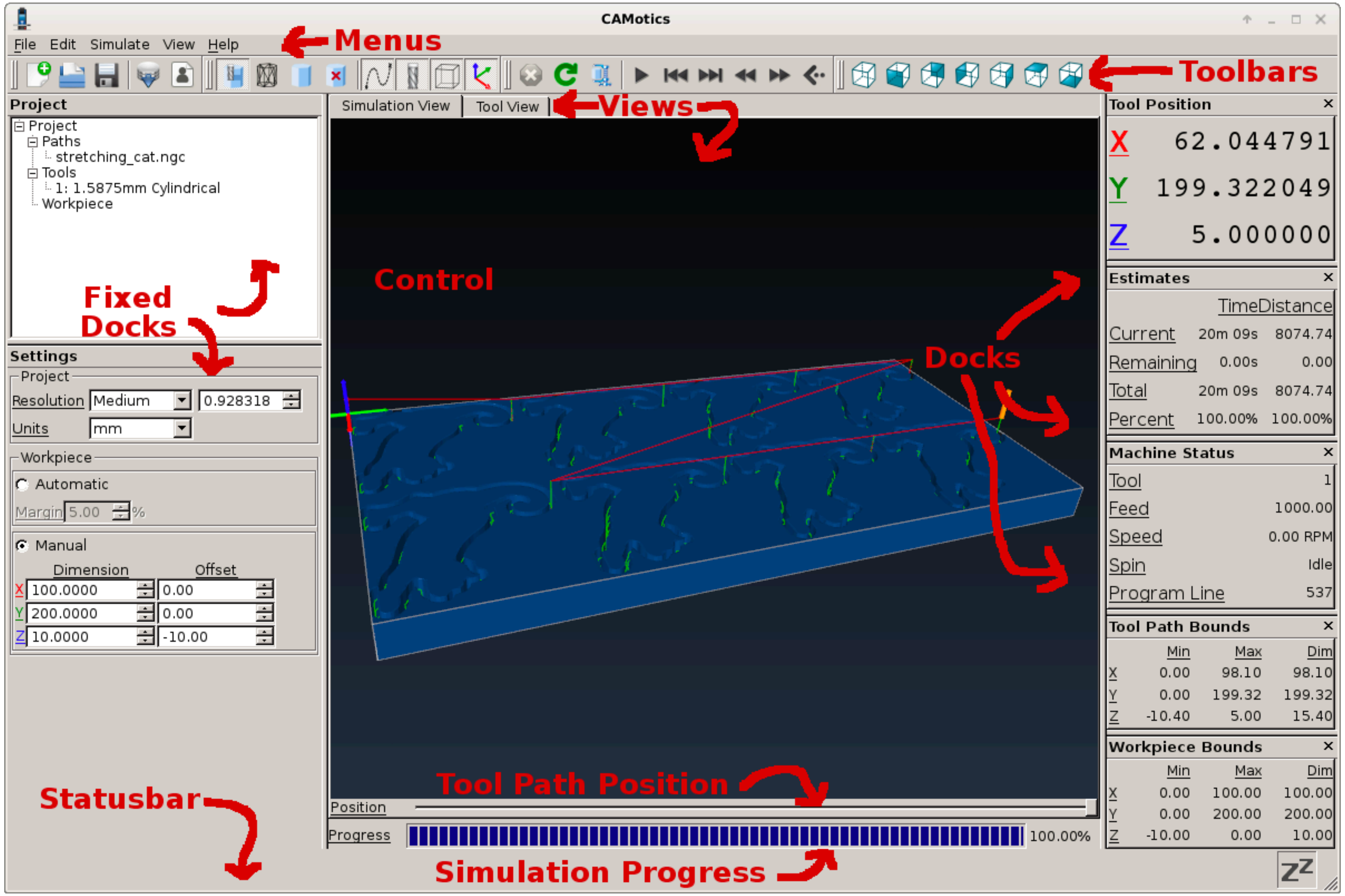
- - arbitrary profiles, pockets, and drilling operations
- - true shape nesting
- - automatic island detection
- - sketch-to-CAD tool for easy prototyping
- - svg import and export
- - gcode generation



https://www.youtube.com/watch?v=ocmYJlFGjXY



- https://camotics.org
- https://github.com/CauldronDevelopmentLLC/CAMotics
- Open-Source Simulation & Computer Aided Machining
  - A 3-axis CNC GCode simulator
  - Tool Path Language (TPL)



TPL: Tool Path Language

TPL code is JavaScript with a library of built-in functions which allow you to generate tool paths. It looks like this:

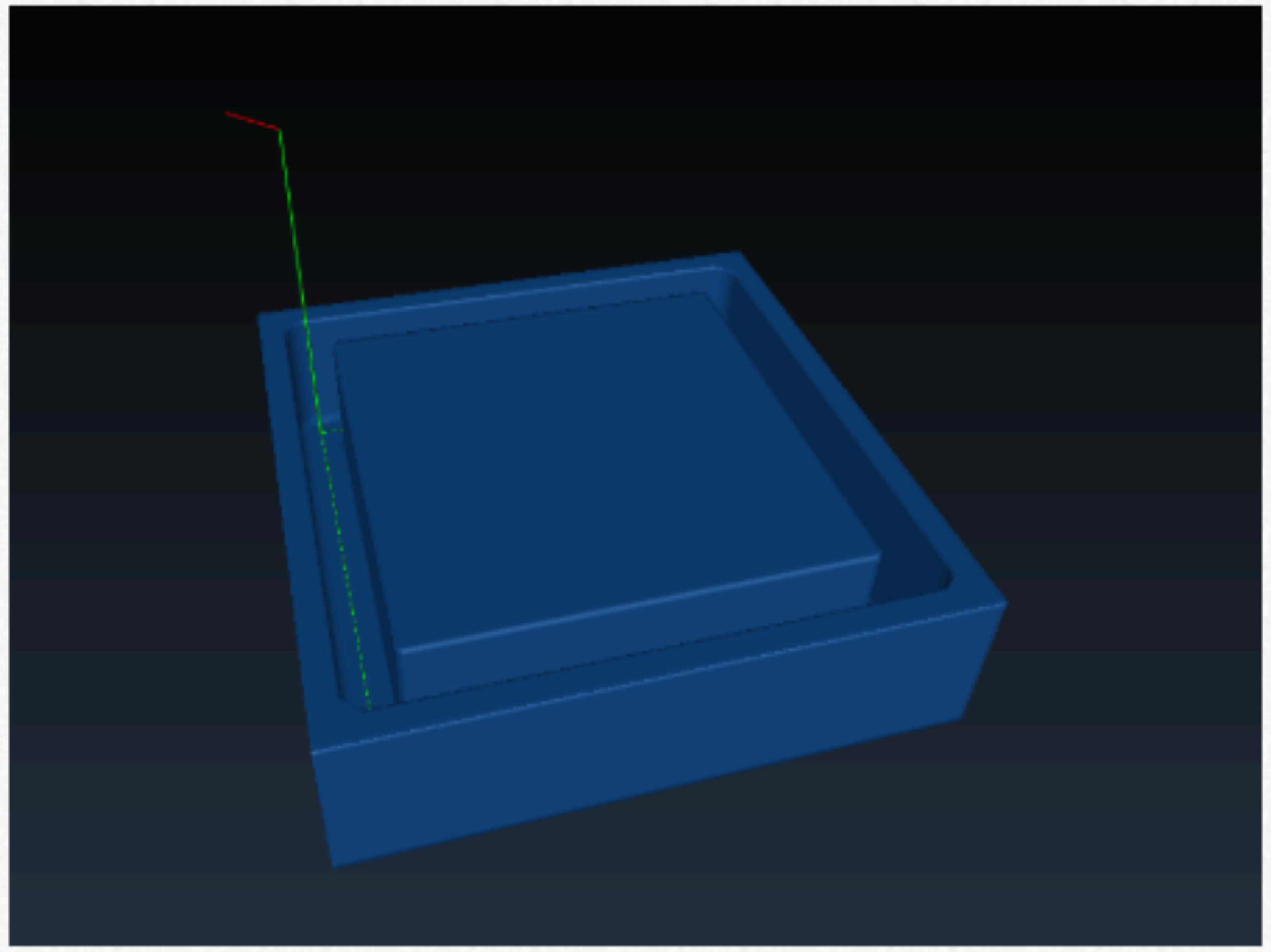
```
feed(400);      // Set the feed rate to 400 millimeters per minute
tool(1);        // Select tool 1

rapid({z: 5}); // Move to a safe height of 5mm
rapid({x: 1, y: 1});  // Go to start position
speed(2000);    // Spin at 2000 RPM in the clockwise direction

cut({z: -3});   // Cut down to depth
cut({x: 11});   // Cut to second corner
cut({y: 11});   // Cut to third corner
cut({x: 1});    // Cut to forth corner
cut({y: 1});    // Cut back to begining

rapid({z: 5}); // Move back to safe position
speed(0);       // Stop spinning
```

The CAMotics simulator shows the result:



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https://tplang.org

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cut({y: 1});    // Cut back to begining

rapid({z: 5}); // Move back to safe position
speed(0);       // Stop spinning
```

```
> tplang example.tpl

G21
(File: example.tpl)
F400
G0 Z5
G0 X1 Y1
M3 S2000
G1 Z-3
G1 X11
G1 Y11
G1 X1
G1 Y1
G0 Z5
M5
M2
```

TPL: Tool path generation with matrices

```
function square(depth, safe) {
  rapid({z: safe});
  rapid(0, 0);

  cut({z: depth});

  cut(1, 0);
  cut(1, 1);
  cut(0, 1);
  cut(0, 0);

  rapid({z: safe});
}

feed(400);

scale(3, 3);
rotate(Math.PI / 4);
translate(1, 1);
square(-1, 2);

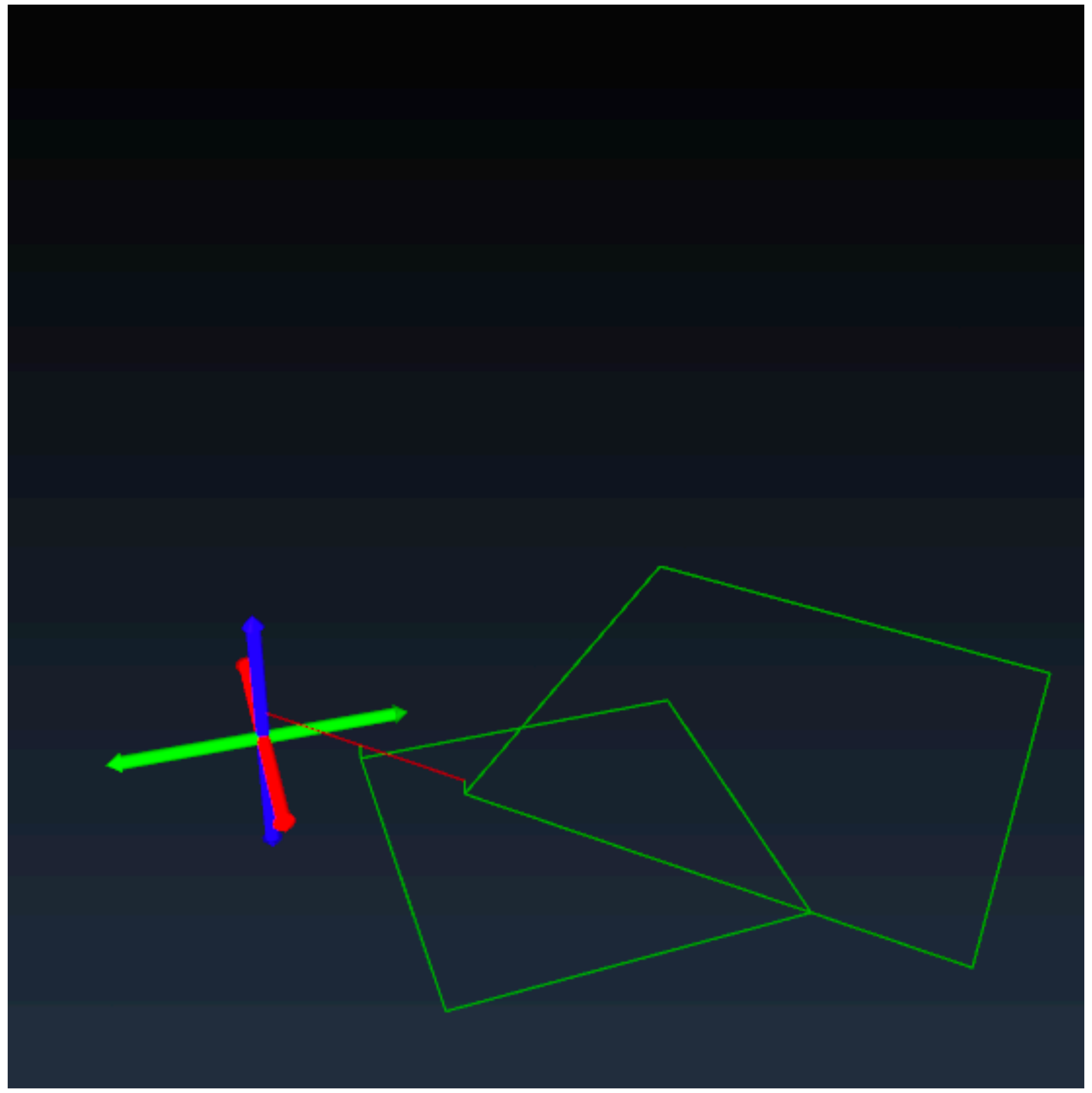
loadIdentity();
scale(2, 2);
translate(0.5, 0.5);
square(-1, 2);
```

tplang

```
> tplang matricesTest.tpl

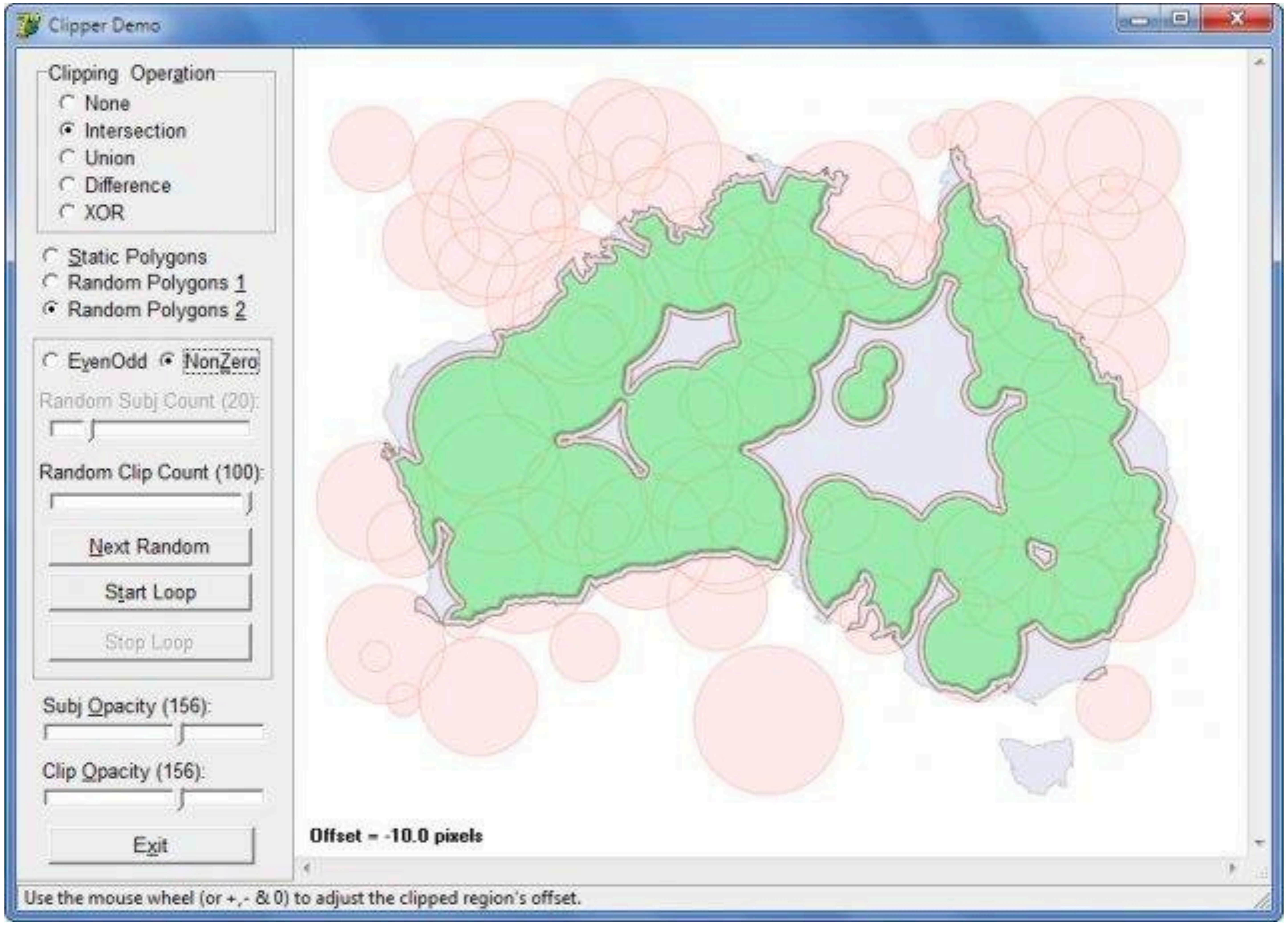
G21
(File: matricesTest.tpl)
F400
G0 Z2
G0 X0 Y4.24
G1 Z-1
G1 X2.12 Y6.36
G1 X0 Y8.49
G1 X-2.12 Y6.36
G1 X0 Y4.24
G0 Z2
G0 X1 Y1
G1 Z-1
G1 X3
G1 Y3
G1 X1
G1 Y1
G0 Z2
M2
```

sim



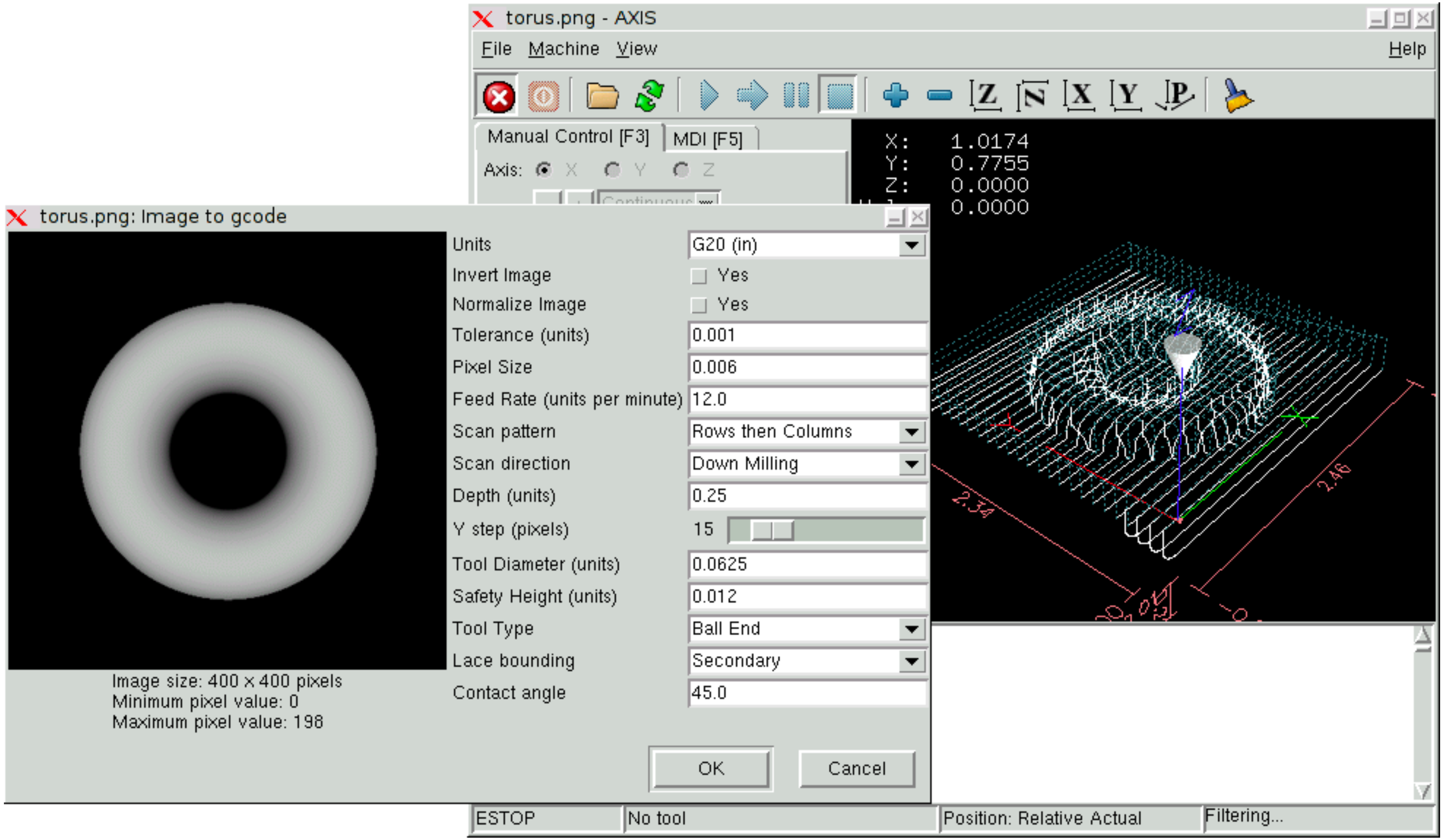
https://github.com/CauldronDevelopmentLLC/CAMotics/blob/master/doc/tpl_matrices/tplang_matrices.md

offsetting



Clipper: Polygon and line clipping and offsetting
https://sourceforge.net/projects/polyclipping/

Image-to-gcode: Milling "depth maps"

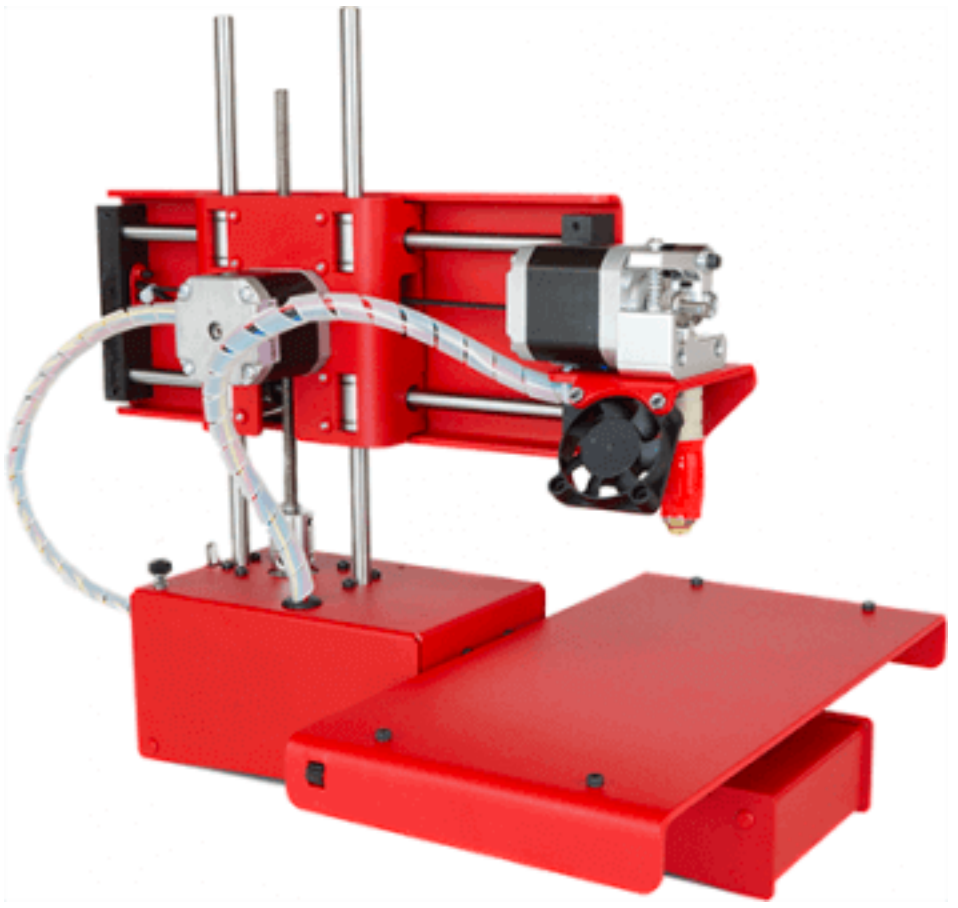


http://www.linuxcnc.org/docs/2.4/html/gui_image-to-gcode.html

CNC challenges: Novel Kinematics

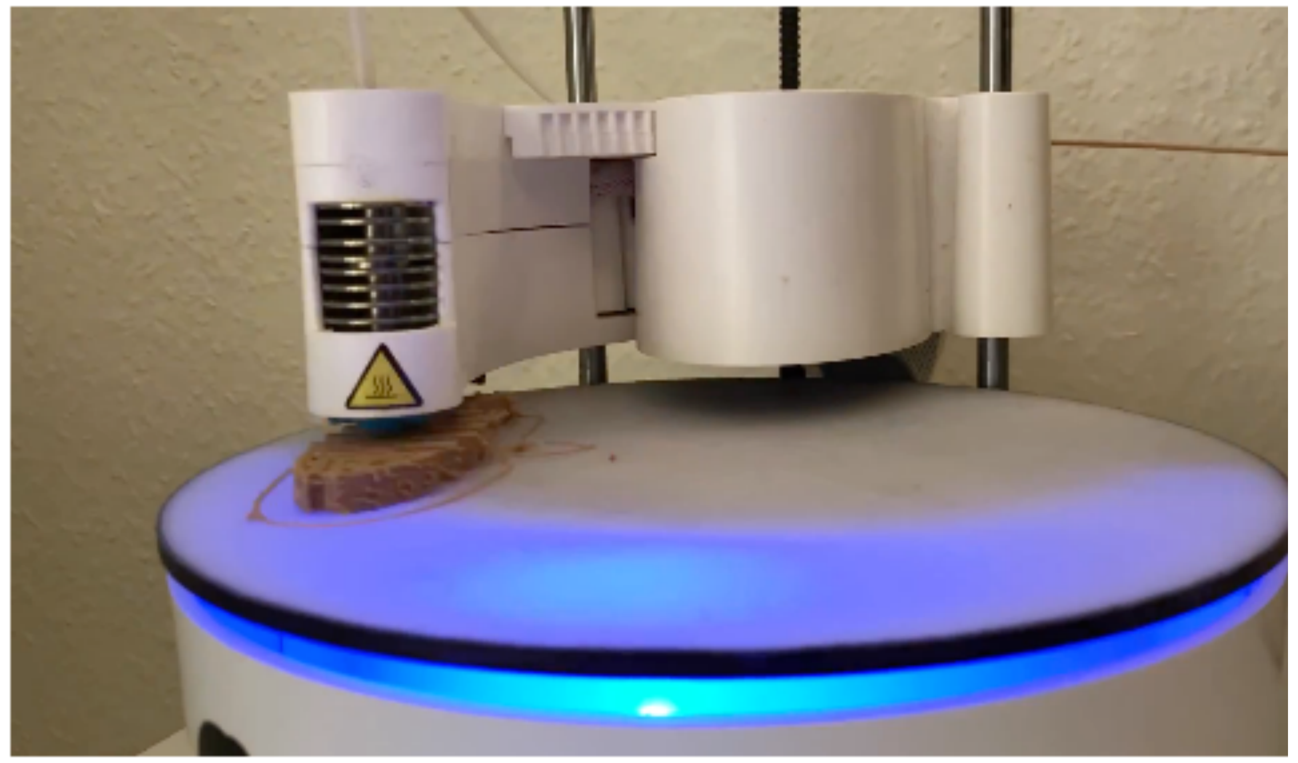
Example: Control of 3D printers

Cartesian 3D printer



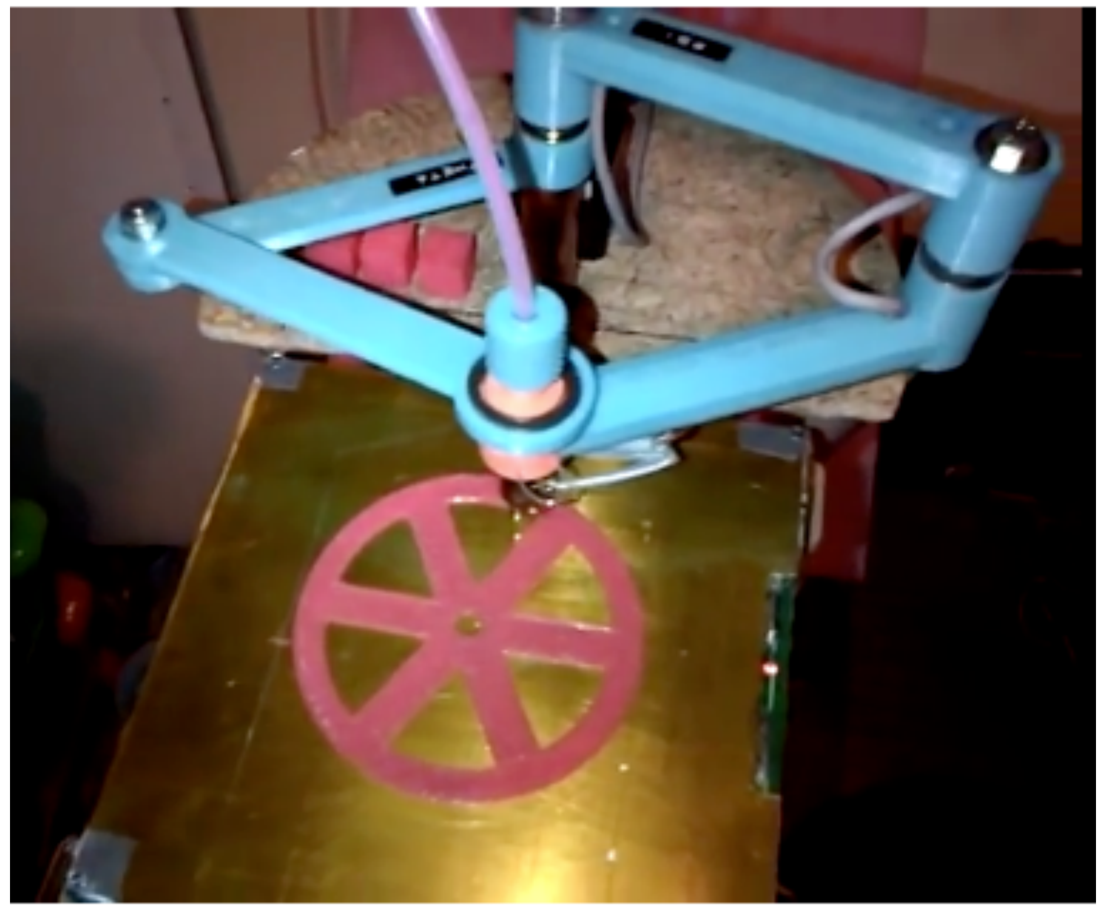
Delta 3D printer

Polar 3D printer



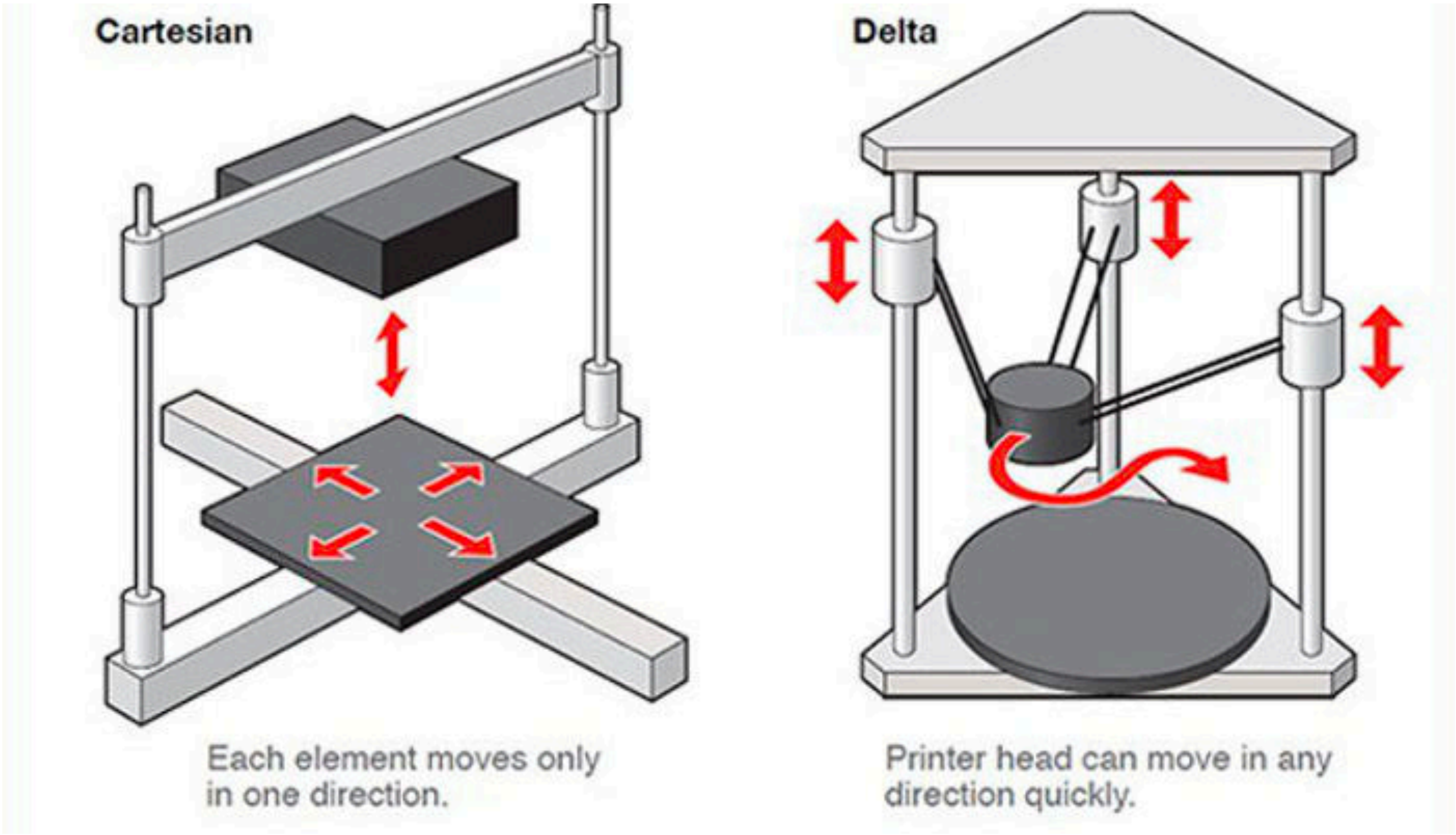
https://www.youtube.com/watch?time_continue=10&v=R7DaGoTDKbI

Scara 3D printer



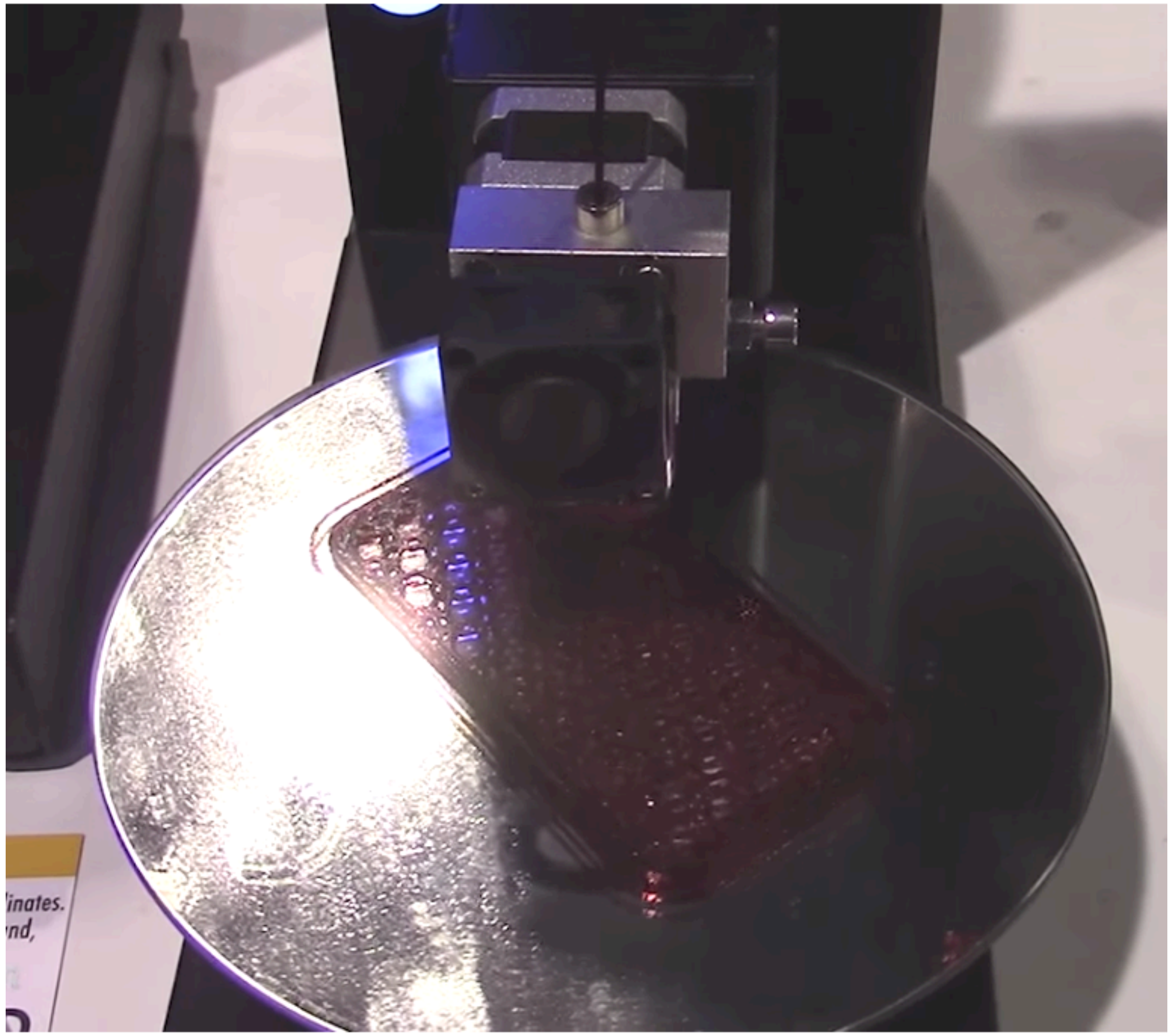
https://all3dp.com/know-your-fdm-3d-printers-cartesian-delta-polar-and-scara

How would you control each of these using grbl?



https://www.3dnatives.com/en/four-types-fdm-3d-printers140620174/

Example: Polar3D Printer



- Simple mechanics
- Large workspace
- Light printer (10 lbs)

https://www.youtube.com/watch?time_continue=0&v=R7DaGoTDKbI

Other CNC Challenges

- New machines (kinematics, peculiarities, etc.)
- Formal verification:
  - Toolpaths, GCode, different machines
  - CNC simulation
  - Editing GCode
  - Retargeting
- Toolpath generation for additive/subtractive manufacturing
  - Novel materials and machines, e.g., chocolate sprayer
- Integrated design and machining