Using systems techniques to make CNC fabrication more fluent

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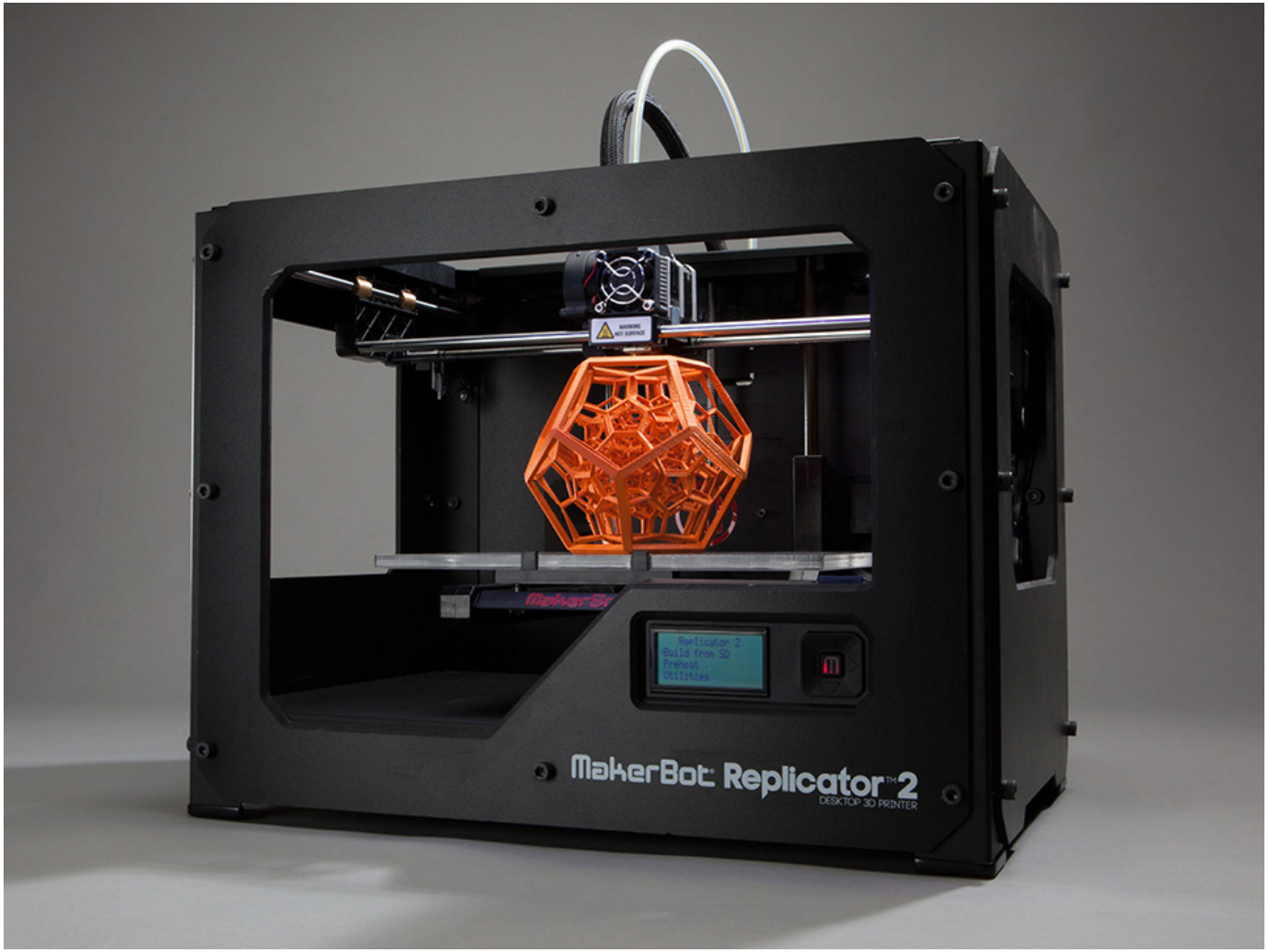
Secure Internet of Things Project Retreat
Santa Cruz
June 7, 2018

Computer-controlled fabrication

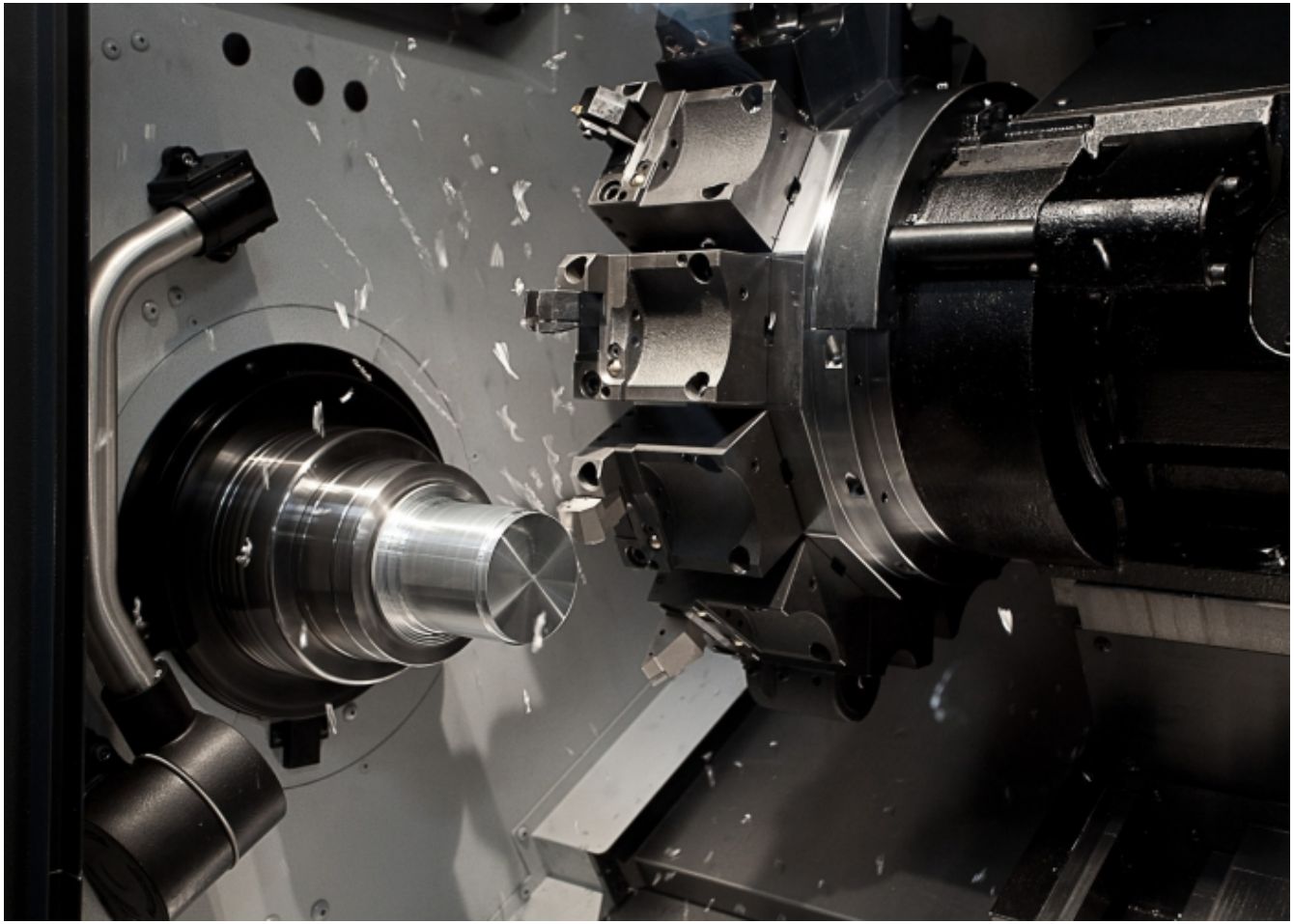
- ``CNC''
  - Started in 1960s.
  - Now is everywhere.
  - Generally: use computer control to turn a ballscrew by a specific amount, thus moving tool by a precise, deterministic distance along axis.
- Almost any object you touch contains some-to-all pieces:
  - Made by a CNC machine directly.
  - Or made by machines that were made by a CNC machine.

3d printing.



CNC mill.

CNC lathe



CNC router

CNC water-jet

Rules of thumb

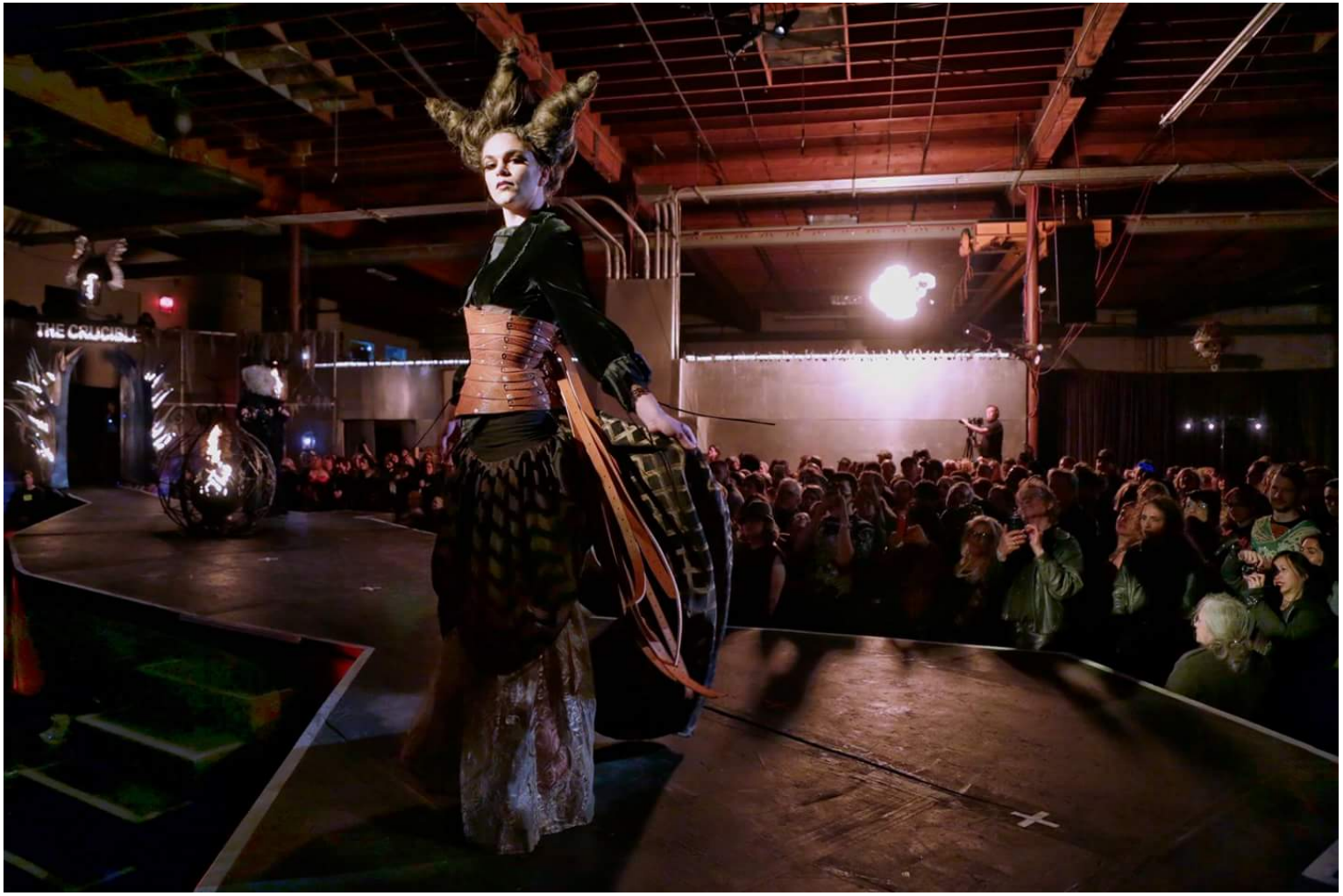
- Machines:
  - heavy (thousands of lbs)
  - precise (thousandths of inch),
  - very very dangerous,
  - easy to wreck. (designed for this!)
  - Expensive.
- Their software, generally:
  - Black box. Expensive. Complex. Problematic.
  - Designed for people who don't know how to program.
  - Labor intensive
    - Usually many mouse clicks to get something done.
    - Ephemeral program must re-type in each time.

Relevance to IoT

- CNC machines = meta-Things that make Things.
  - Embedded
  - Real time
  - Heavy users of sensors.
- IoT = significantly higher probability of fabricating a thing.
  - Will use CNC.
  - Faster prototyping and more accurate, safer fabrication is important.

Motivation: leather+metal for fashion shows.

Motivation: Non-embarrassment. Secret weapons



Reasonable test

- Failure is super embarrassing. Keeps honest.
- Need expressive:
  - Free form designs
  - Different materials
  - Lots of regularity, lots of difference.
- The rule:
  - Assembly can be manual (hammer, sewing)
  - All cutting is by machine. No exceptions.

- More than 10 shows
  - Last four can type “make” and get all programs emitted for 14 models.

This talk

- Improve all CAM systems through PL techniques
  - Low level analysis + rewriting = lift all boats.
  - .
- .

Low hanging fruit

- Almost all controlled by primitive language, Gcode
  - Origin, 1960s.
  - Ignored by programming language community.

```
T3 [ GET TOOL NUMBER 3 ]
 S16000 [ SET SPINDLE SPEED RPM ]
 M3 [SPINDLE ON]
 G53 Z0 [LIFT Z TO TOP]

 [TOOLPATH NAME: Drill 1]
 F5 XY [SET FEEDRATE FOR X AND Y]
 F50 Z [SET FEEDRATE FOR Z]

 G0 X0.000000 Y0.000000
 G0 Z0.800
 G1 X0.000000 Y0.000000 Z0.000000
 G0 X0.000000 Y0.000000 Z0.315000
```

- Many problems have easy PL solutions.
  - Retargetting.
  - Optimization.
  - Error detection.

Tenths: gcode rewriting system

- simple, extensible g rewriting system.
  - Reads in gcode, user-written extensions transform/check, re-emit.

  - Rewriting code = can work with output from anything. Lift all boats.
  - (~ Similar to link-level optimization for machine code.)

Optimization (speed, accuracy)

- CAM software has to produce results quickly.
  - Toolpaths, optimization deal with NP complete problems
  - Also deal with variables the CAM software may not know about.
  - Gcode optimization lets us do extreme and/or more insightful opts.
- Is written by a software company.
  - You will often understand how to machine your materials with your tools on your machines better than a software (CAM) house.
  - They can write the optimization passes you use.
- Often you figure out how to fabricate better over time.
  - Gcode rewriting lets you slip these tricks back into old code en masse.

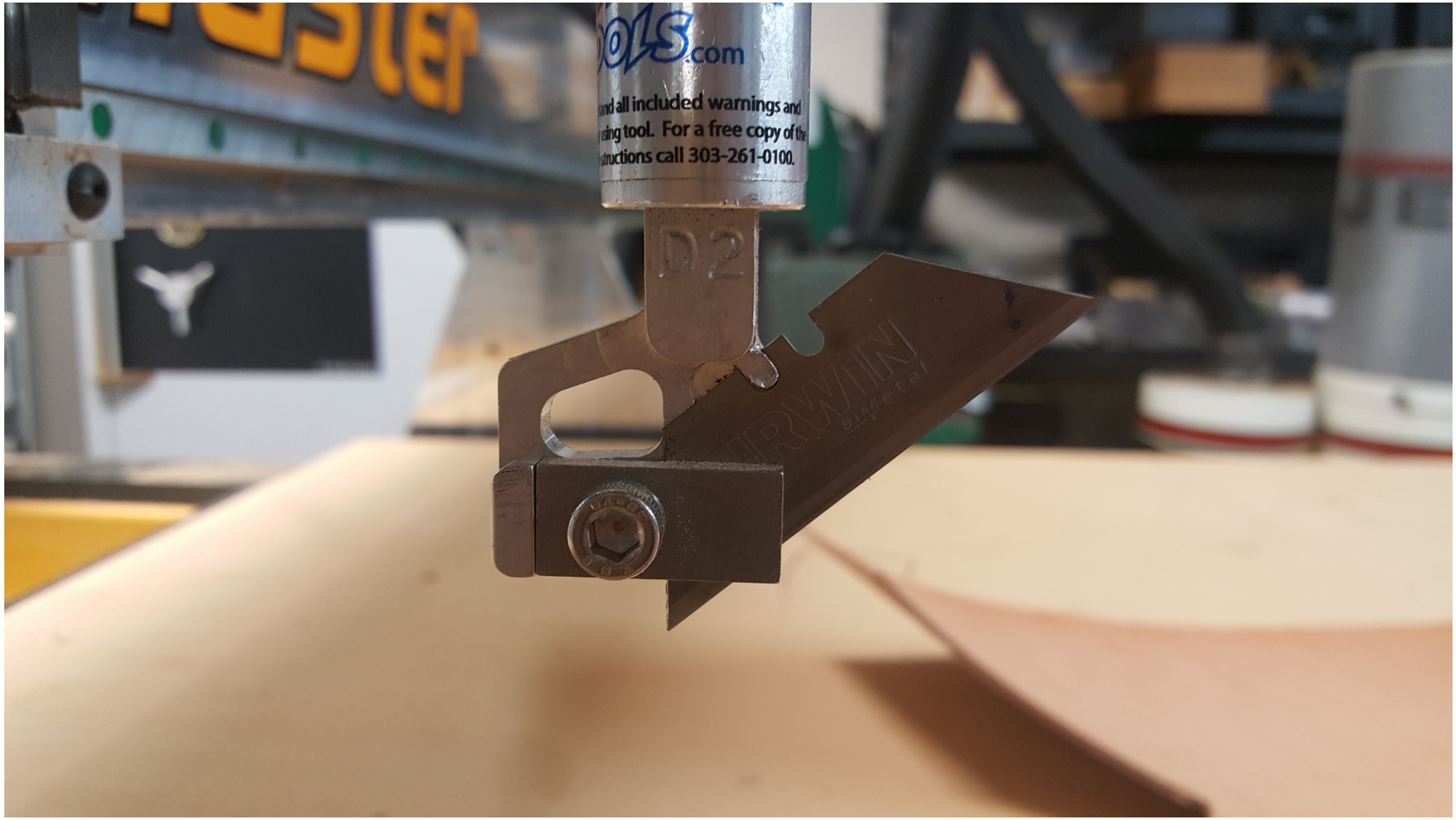
Router

Fabrication pipeline

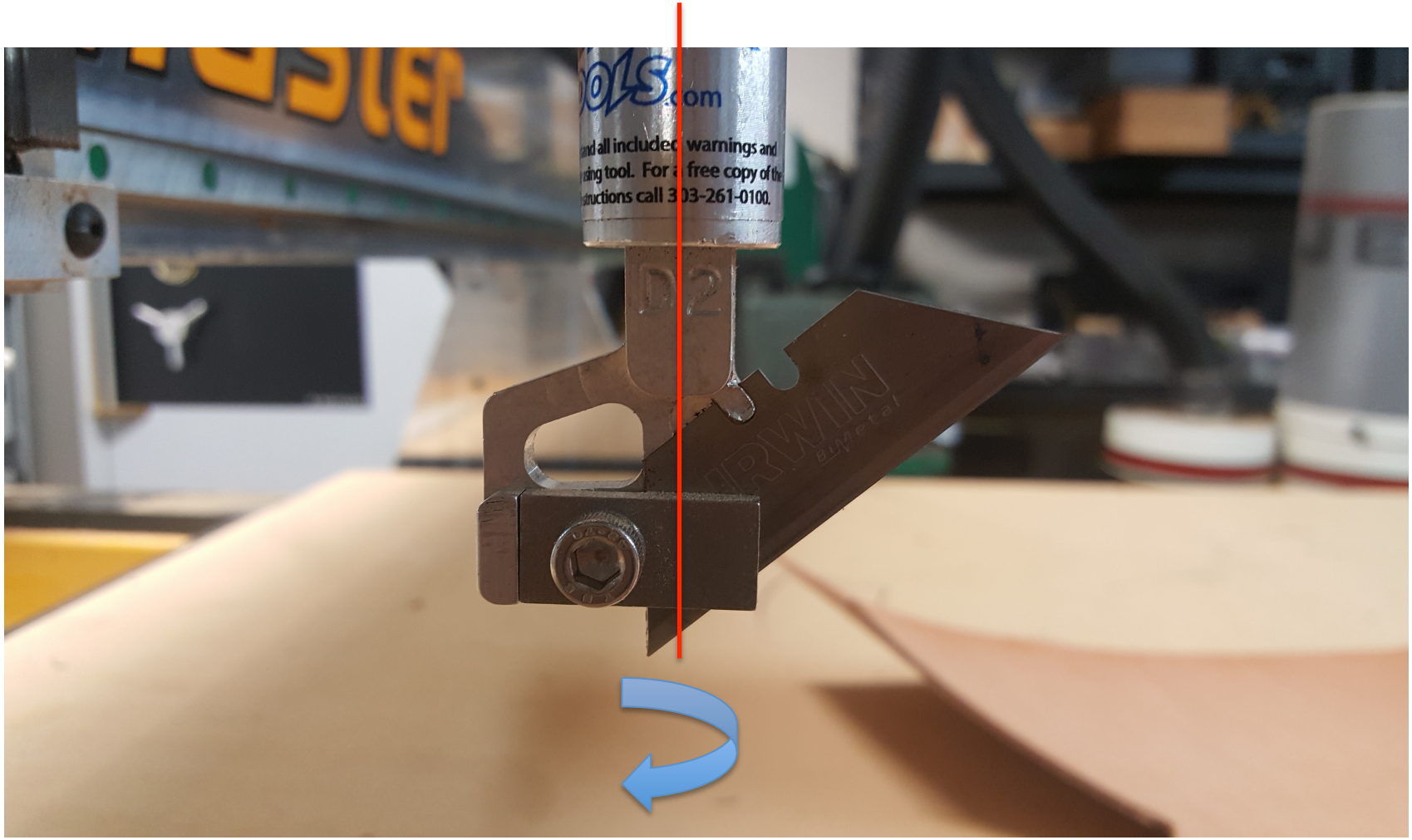
- Fabricate using a common pipeline:

  - The software it ships with (vcarvepro) has many problems.
  - Closed system. Can't do anything to fix.
  - From bitter experience: Working around manually = difficult, dangerous.
  - Using gcode rewriting makes it easy.
    - Problems that can be solved similarly show up everywhere.
    - Picked these b/c easy to explain and make video.

Cutting tool: dragknife



3rd party cutting tool: dragknife

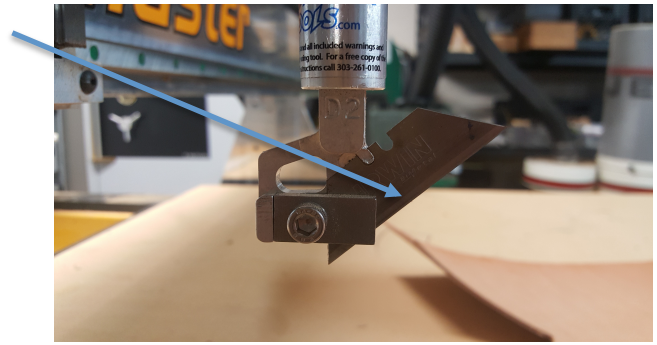


CISC vs RISC

Fixed bugs. Now fix quality

Post-processing to optimize cutting

- The commercial system isn't very accurate.
  - Overcuts b/c razor has a 45 degree angle.
  - Doesn't have option for accurate pivots
  - Seems to have some math issues.



- Solution:
  - Implement our own accurate dragknife tool path generation.
  - Use rewriter to rip out old toolpath and insert our more accurate version in.
  - Communicate to the rewriter by using a fake tool with special name
- Common pattern:
  - optimize drilling, or cutting speeds, etc by post processing
  - Similar to object-code optimization. (OM, etc)

Real use

Real use

Real use

Final product

Rewrite old code with new tricks

- Common: Work with material / tool / machine more?
  - The more tricks you come up with.
  - But old code stays in the old way.
  - Use gcode rewriting to rewrite it with the brave new way.
- Examples:
  - Stress relief
  - Strap cutting tricks

Stress relief cuts

- Obvious in retrospect, not so much at the time.

Works much better (accordion)

Strap cutting is tricky.

- Multiple errors in vid
  - Cutting strategy waste
  - Holes = sieve.
  - …

Can this program destroy the machine?

- Have done bug finding for almost 20 years.
- Can import these techniques, with interesting twists.
- Makes a bunch of problems much easier.

- Currently: have to completely trust the code you run.
  - Did you bump the keyboard? Stray mouse click? Machine can destroy itself.
  - Many properties can verified right before
  - Mechanically reduce trust dramatically.

- Obvious: just do static checks.
  - E.g., make sure don't cut outside window.
  - Would have prevented a near destruction from solidworks!
  - Many of these. They work as you expect.

- Less obvious: cross checking (simple, but serious win).

Cross-checking in one slide

- From regular checking: is this code correct?
  - Typical: no spec.
  - Also typical: other code exists that implements the same interface.
  - So: Cross check (symbolically, statically, dynamically)
  - Any difference = an error. If one is correct, you've shown (sometimes proven) the other is correct too.

  - Works here too!
  - Main game: to see if program is safe, try to link it to others.

Can program crash machine?

- Old program:
  - no idea if it uses the same tools on the machine
  - If it fits within the current work envelop.
  - Look at gcode? (Ha)
  - Re-cam? (easy to make even worse mistakes).
- Simple finesse:

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  - You know the last few programs you have run.
  - They have (apparently) not crashed the machine.
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  - If it uses the same tools, and fits within the same envelop = safe. (Fairly typical) Otherwise extract the delta.
  - Very easy (50 lines) to do on 3-axis machine.
  - Will scale to 5-axis very soon.
- Has been a serious nagging problem in shop.
  - Once you look at the right way is pretty easy.

Other patterns: previous version versus this one

- After crude geometry cut, then start tweaking:
  - Tool depth of cut and feedrate
  - Tool type
  - Order of cuts
  - Adding a single feature.
- A stray mouse click / keyboard can destroy everything.
  - Have to run at 1%, get ready to hit the stop.
- However, is easy to “delta verify” that only that single part changed.
  - --only-doc tool=1
  - --only-feed tool = 3
  - --only-tool-swap tool = 3
  - ….
- Can verify the rest was untouched. Much much improved.

Summary

- Gcode:
  - From the 60s.
  - Controls almost all CNC machines.
  - Entirely ignored by the programming language community.
  - Machinists have many problems b/c have a passive relationship with code.

- Automatically post-process it to:
  - optimize, retarget, correct.
  - Even trivial passes make big different for real people.
  - We use it all the time in our studio.

Fluent: flexible, freeform fabrication

- Programmatic, parametric modeling and fabrication:
  - Model geometry in 3d or input from files (DXF or even gcode)
  - Robust, simple flatten to 2D.
  - Programmatically add features (rivet holes, seam lines, grooves.)
  - Automatically emit gcode to cut.
- Nice-to-killer features:
  - “One touch”
  - Turing completeness = have to anticipate much less
  - Robust.
  - Easy to do novel CNC tricks: have control, have all semantics.
  - “Delta design”: import geometry from different sources, quickly easy modify / combine / remix.
  - “Constraint-based naming”: robust feature naming even with parametric changes

Example: corset

Make corset from thick leather from four annuli

Did this kind of pattern for ~ 1.5 years with solidworks.

Arguably best 3d->2d CAD.

Very

Very

Very

Painful. (google: “solidworks” “sucks”)

Constantly broke.

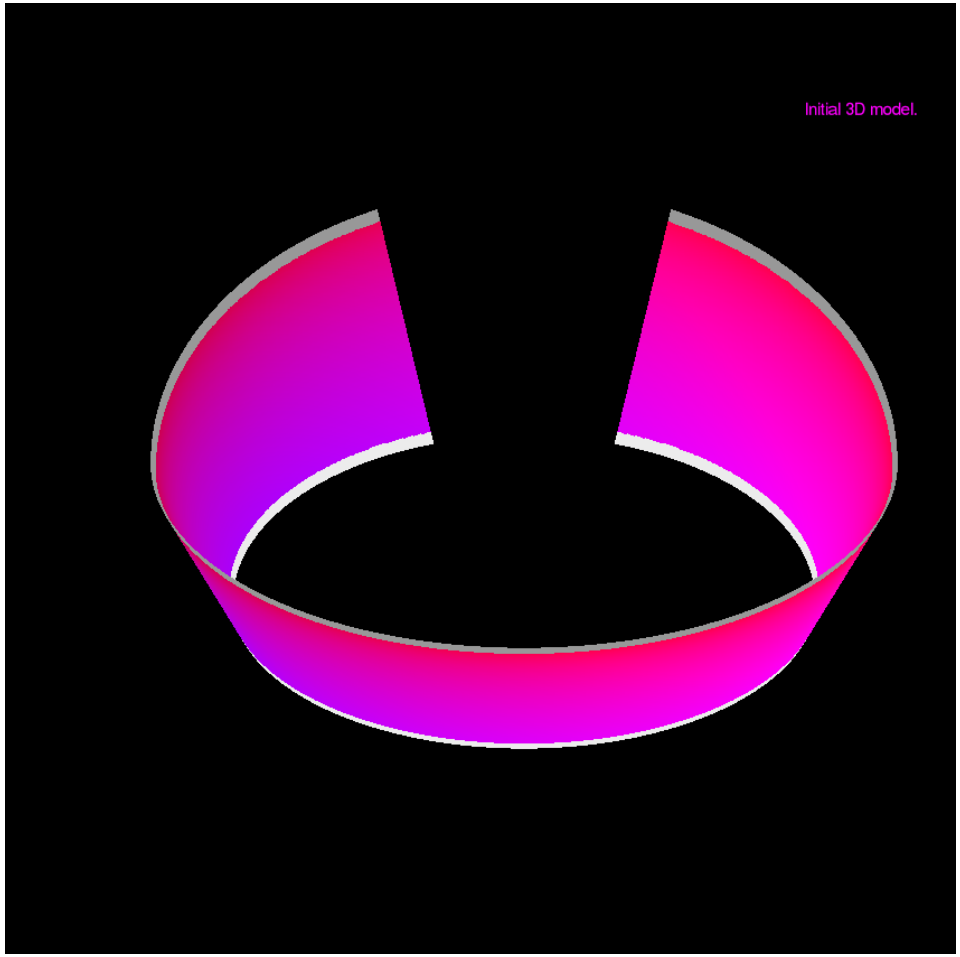
Wearisome amount of manual effort to convert to gcode.

At best: 20-30 minutes / iteration

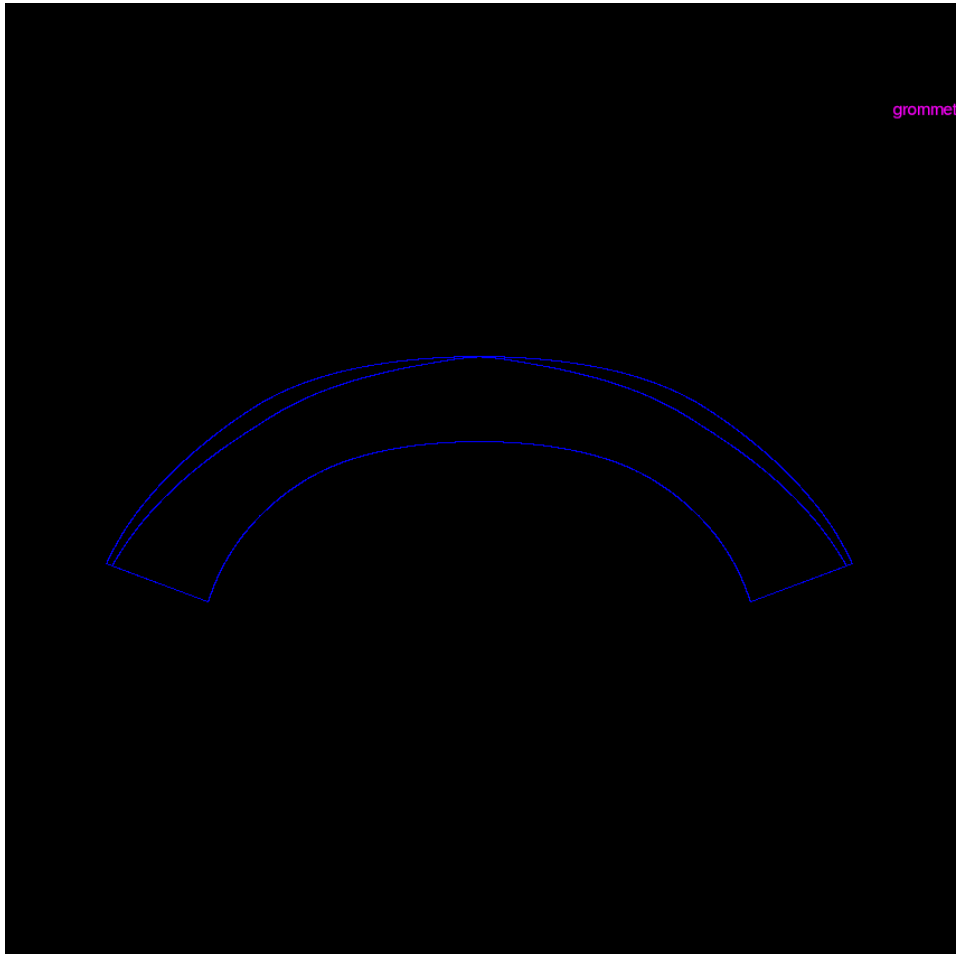
Worst: Forget steps, make mistake

Fluent makes much easier.

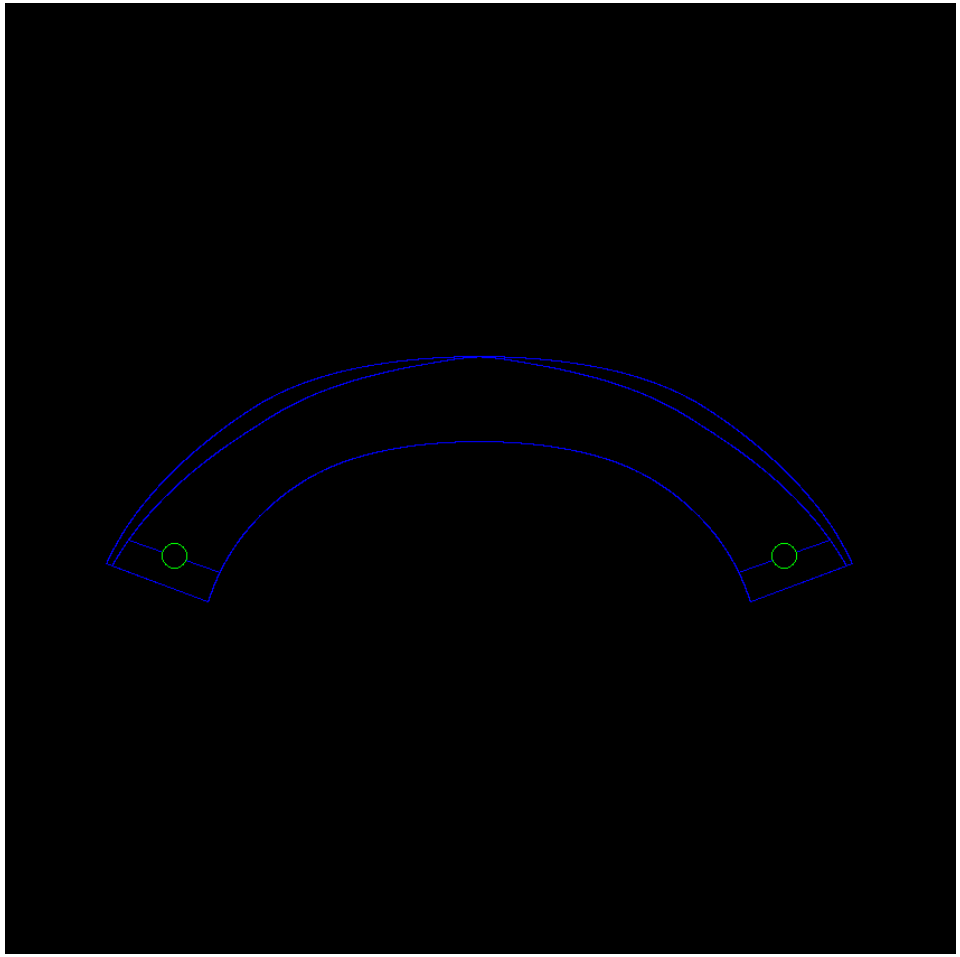
3D bottom corset strip



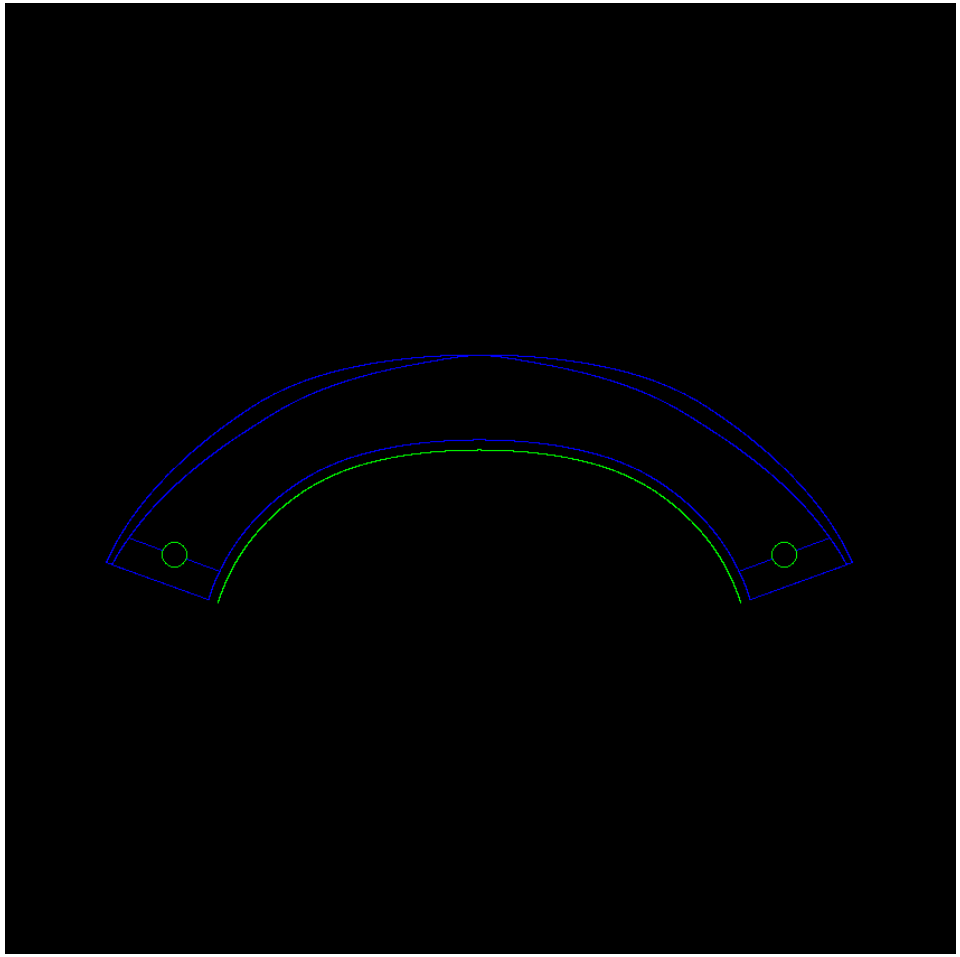
Shape hemline, flatten to 2d



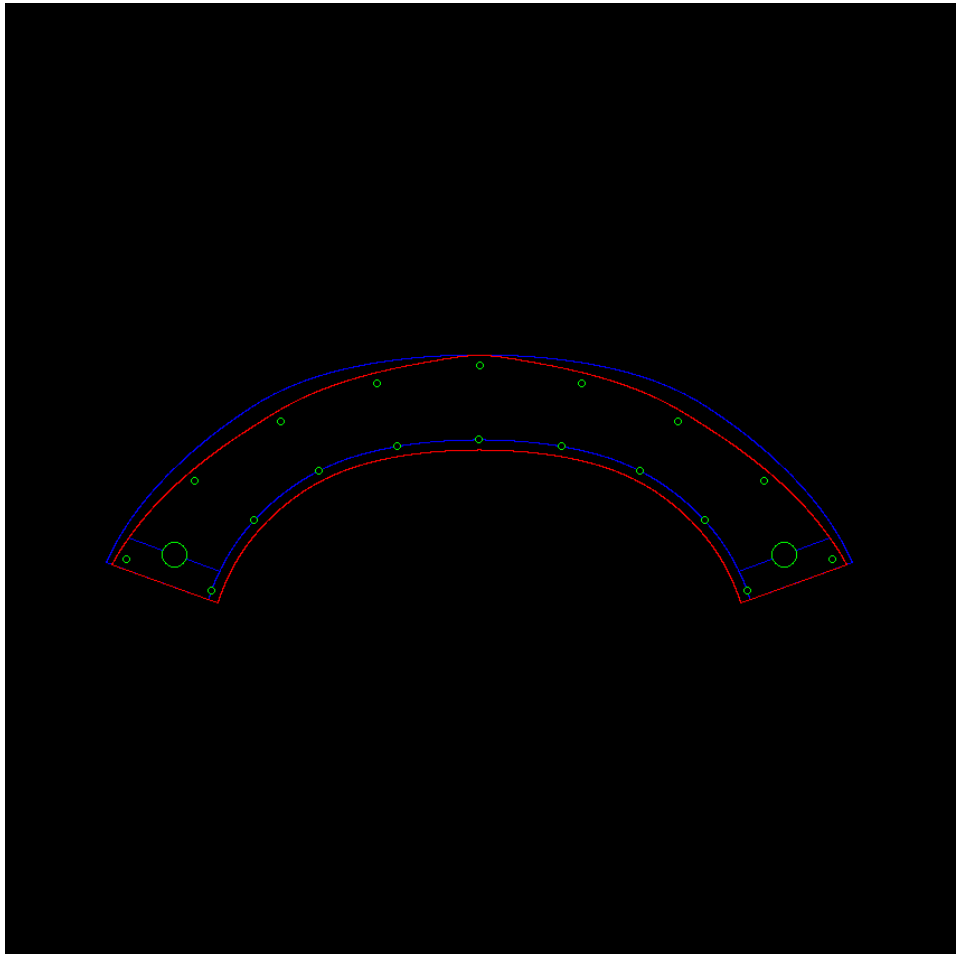
Add grommet holes



Add seam allowance



Add rivet holes



Auto-gen and cut from leather

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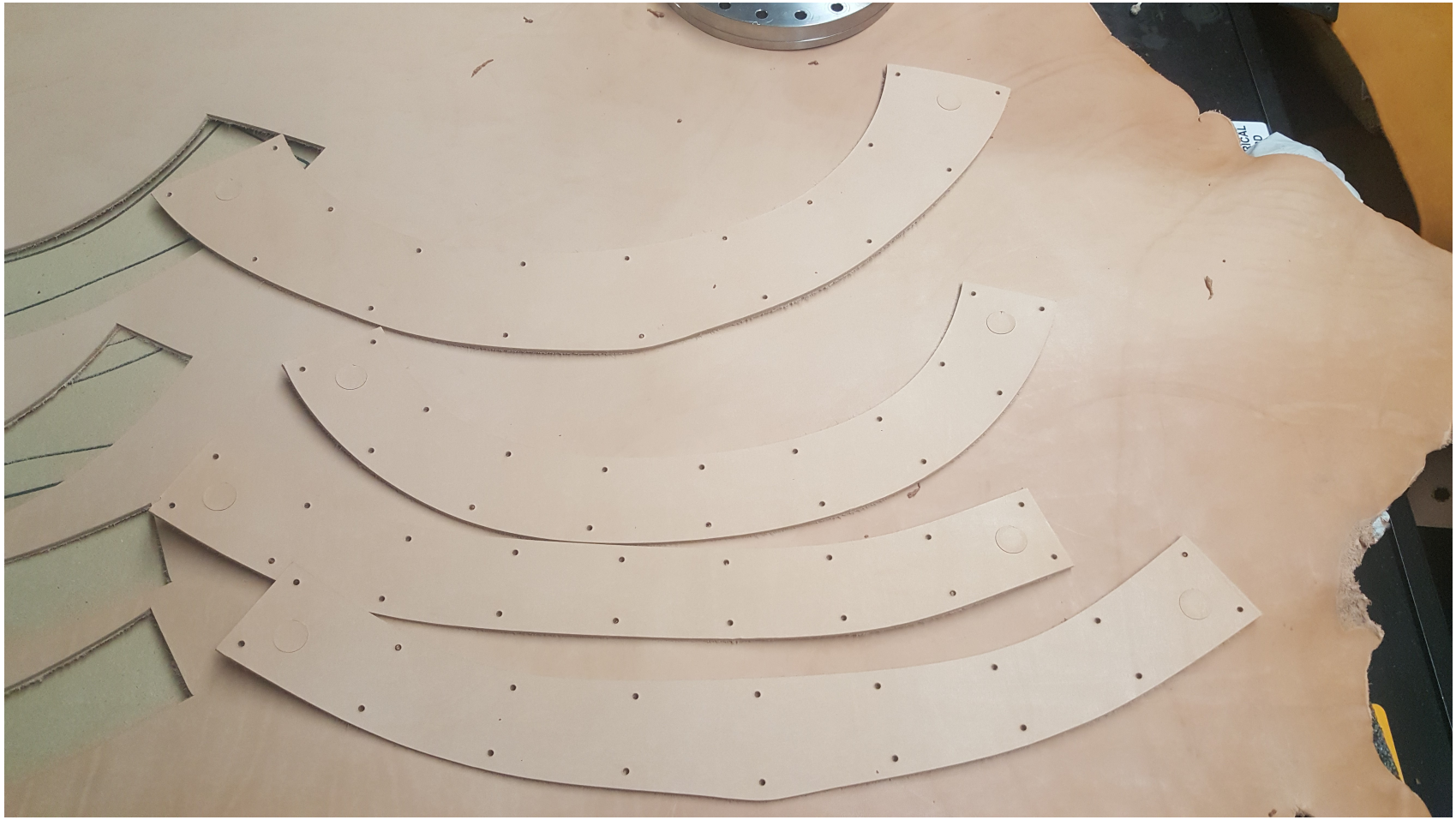

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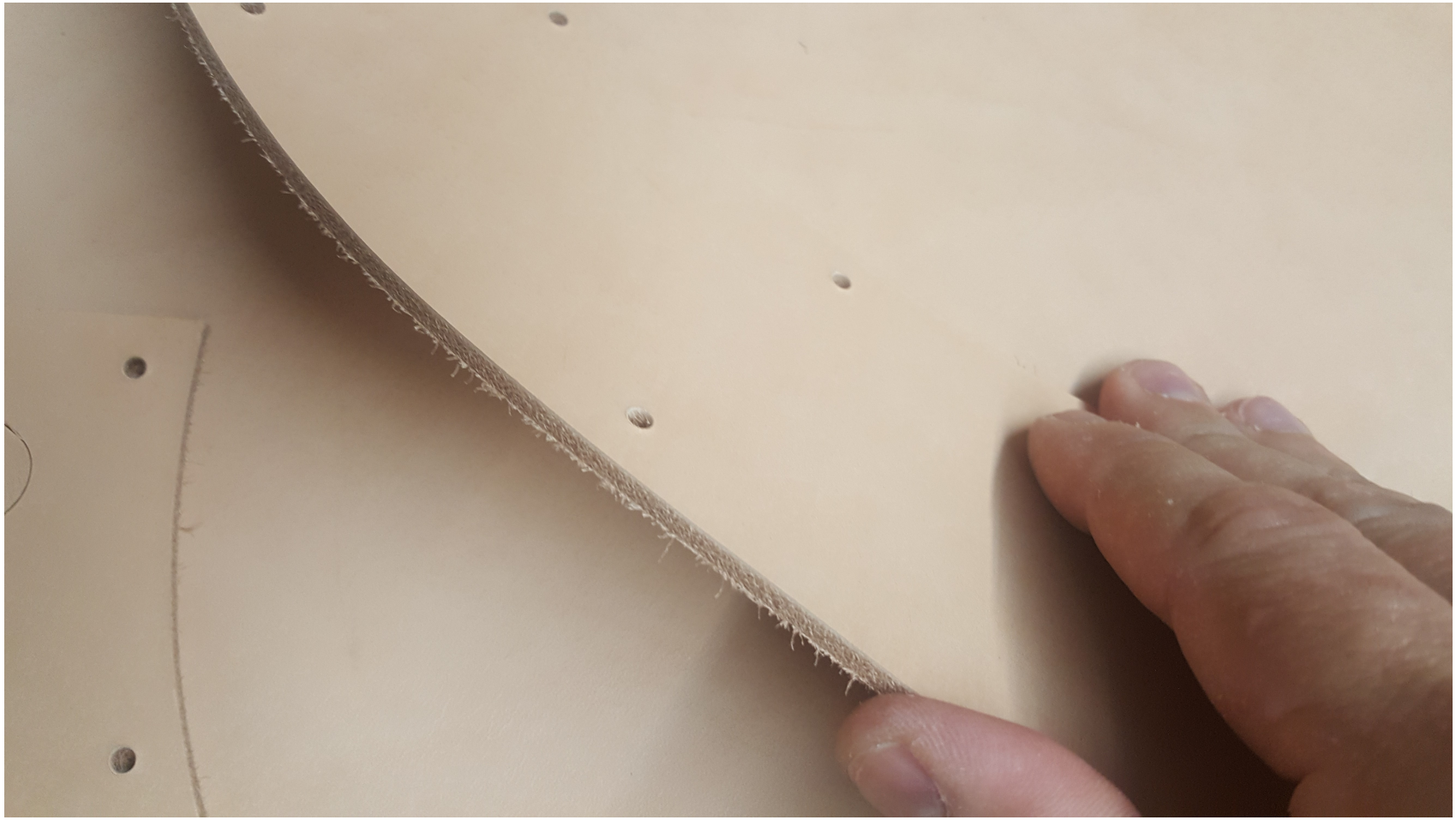
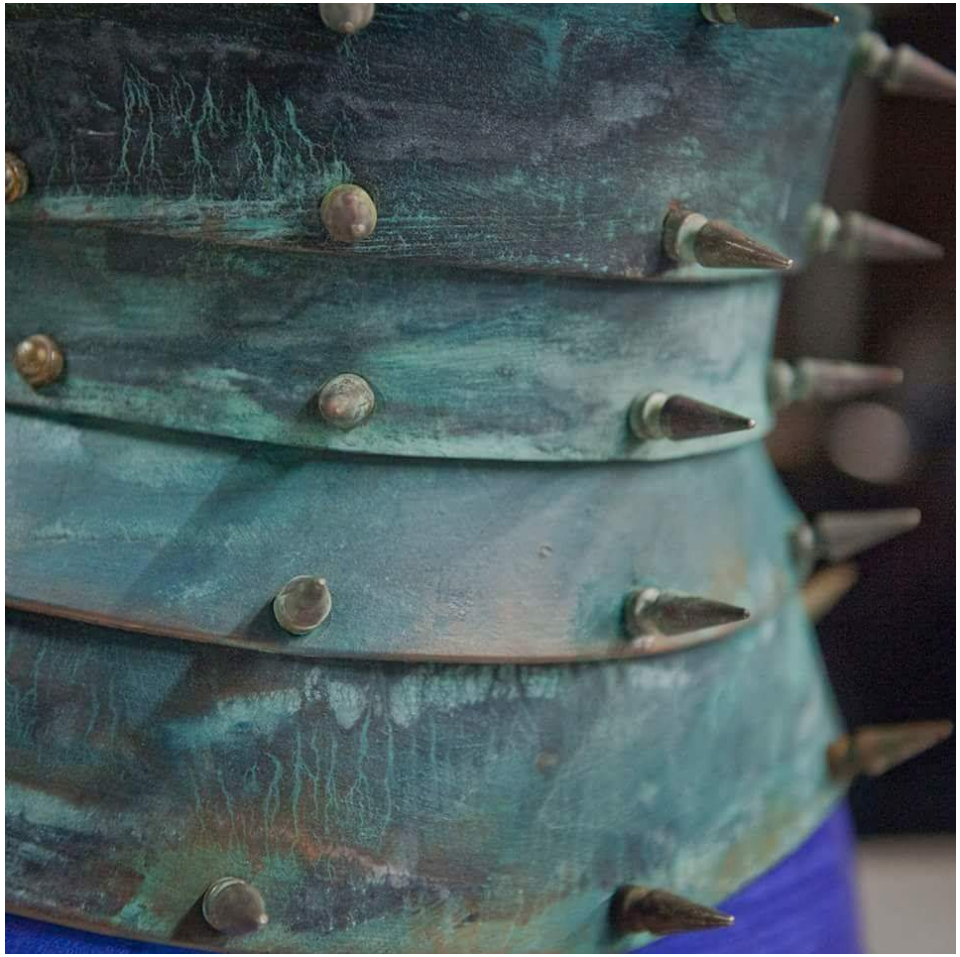


Assembled

Assembled

CNC = quick, easy variations



Show

Show

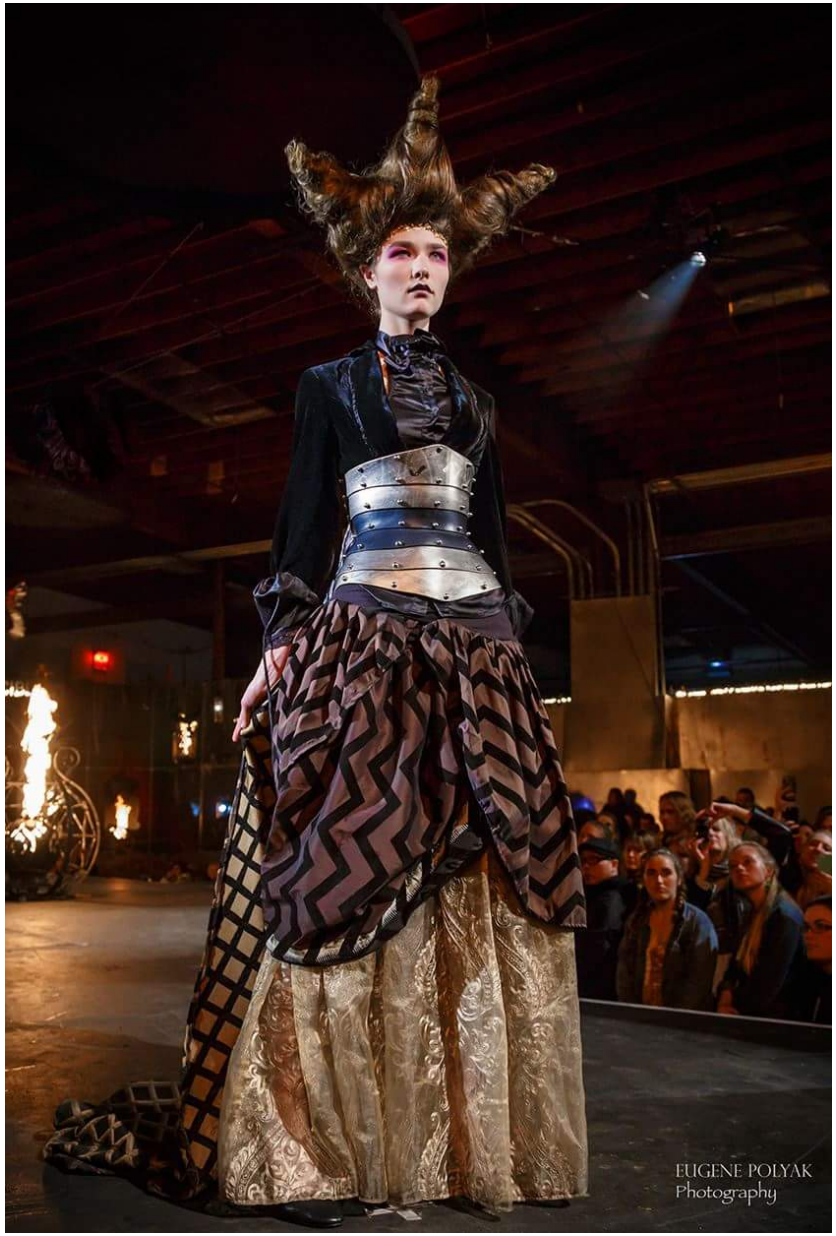
Show

Programmatic = power

Easy to add a new strip with a few lines of code change to interpolate.

Re-compute holes, etc seamlessly

Was tedious enough with CAD that never did.



Few lines = many variants

Programmatic = power

Add a new closure method with a few lines.

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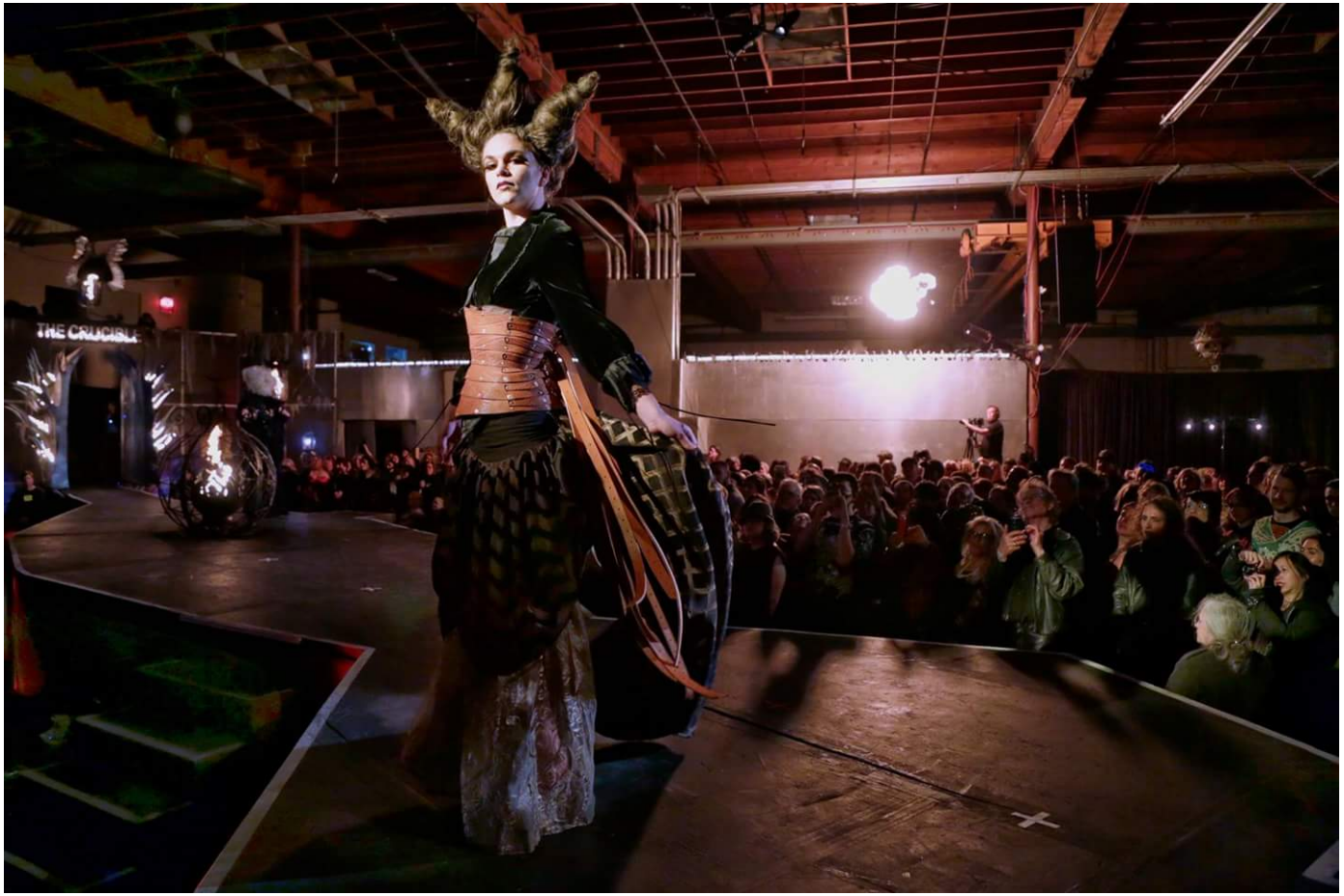

Programmatic = power

Compute holes for ¼ inch thick strips.

Non-trivial. Hole spacing of top strip is a function of curvature in 3d.

AFAIK no CAD system can do this (and would be tricky with a GUI even if they could).

Fluent makes this simple: can match holes up on each strip with a small amount of code.

Programmatic = power

Spatial pun: take lower strip of corset, recut as a scaled down neckpiece from brass.

Because we can write code to manipulate, trivial to rescale this way.

Switch from cutting leather to cutting brass with a single line change.

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Computational to visual

Encode new cutting techniques: makes it easy to have complete control over cutting and still keep gcode genereation automatic.

one person figures out, adds library, everyone can use.

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Co-fabrication: metal and leather

Co-fabrication

Fluent

- 3d modeling with integrated code generation
- Makes simple things simple, fancy things possible.
  - Easily add novel cutting techniques
  - Easily add novel geometric calculations.
  - A lot of control for optimizing cutting.
  - One touch fabrication.
- Last show:
  - one key press ~ all cutting programs for all outfits.
- Changing measurements?
  - few numbers, then press key again.
  - Major win.

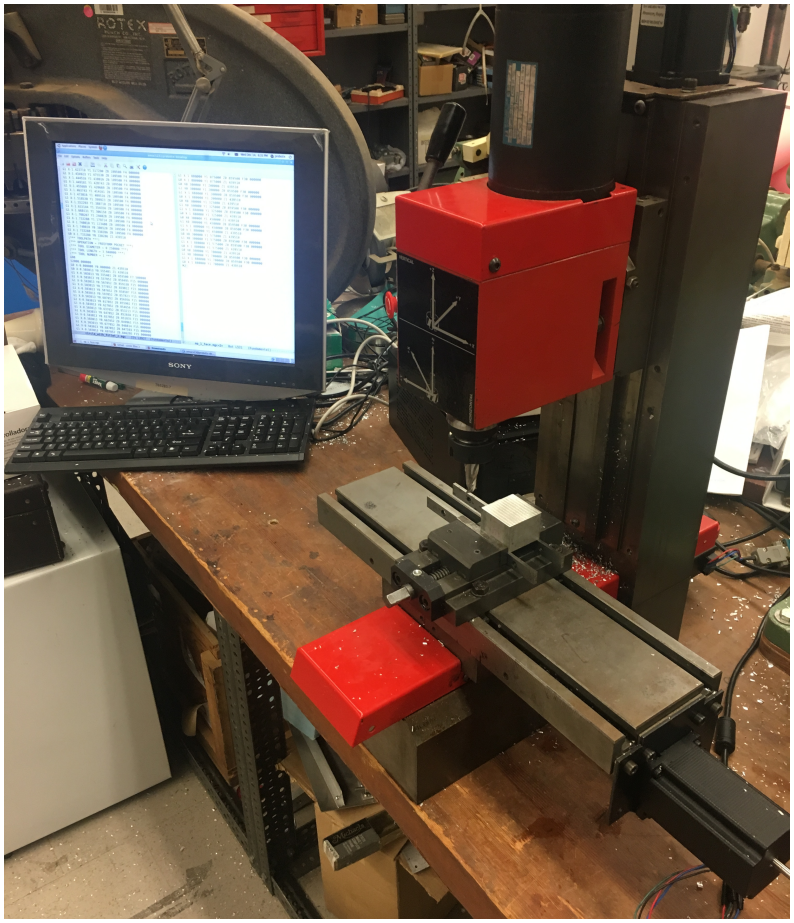
Thanks!

Thanks!

Synthesizing CNC Mill Programs

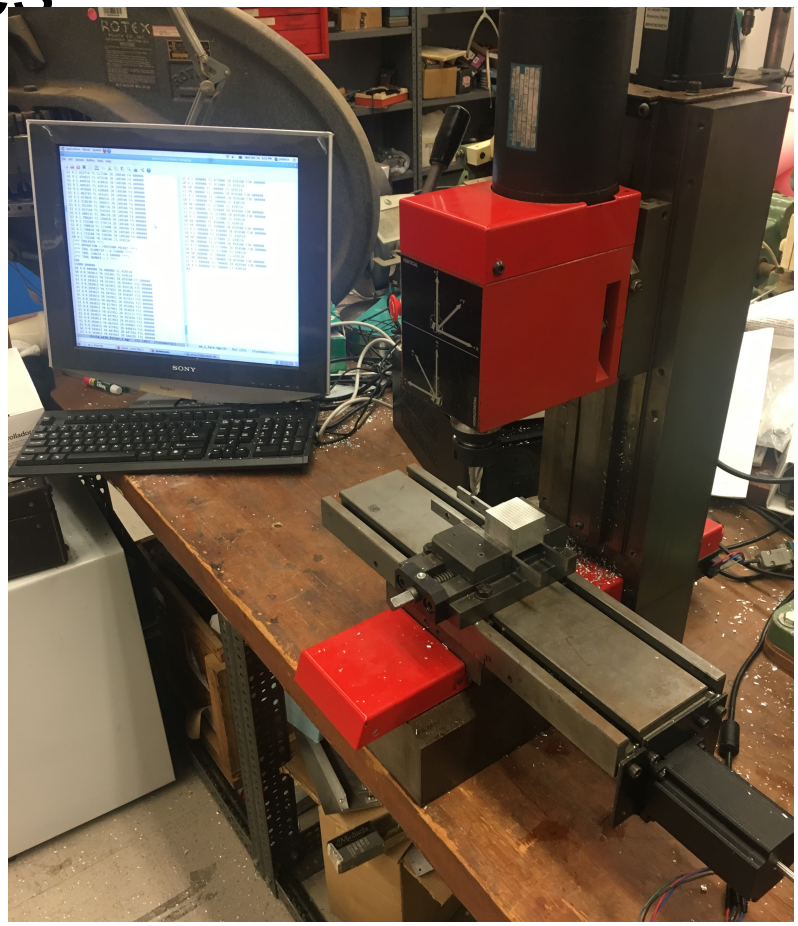
What is a CNC Mill?

- Computer controlled metal cutting machine
- Ubiquitous: Almost every modern machine shop has at least one
- Expensive: Thousands to hundreds of thousands of dollars
- Programmed in G-code, simple control language invented in the 1950s



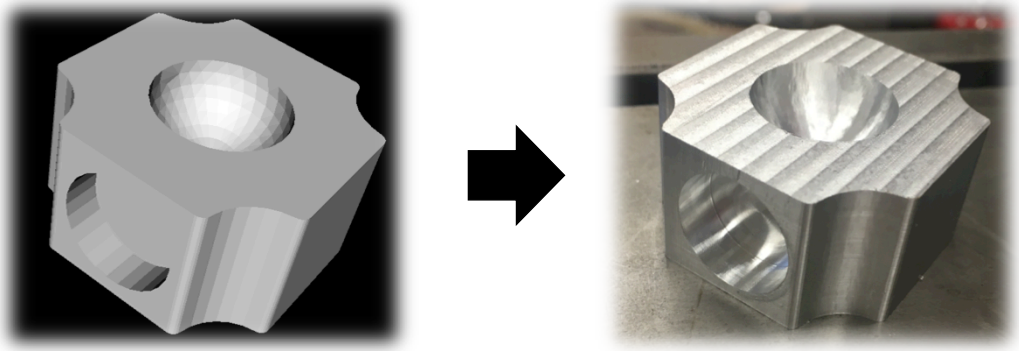
Programming Challenges

- Expensive -> Want high utilization
- Made out of metal -> Any programming bug is expensive, maybe tragic
- Requires a machinist to make tricky geometry / physics decisions

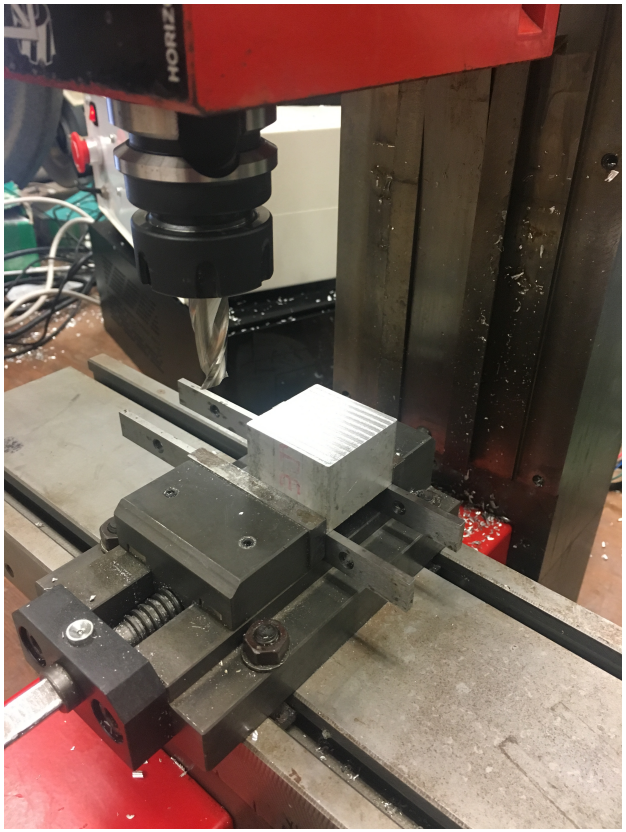


Milling Program Synthesis

- Inputs:
  - CAD model of the part
  - List of cutting tools
  - Size of the initial stock
  - Dimensions of the vice
- Output: A crash free plan to cut the part



Setup 1



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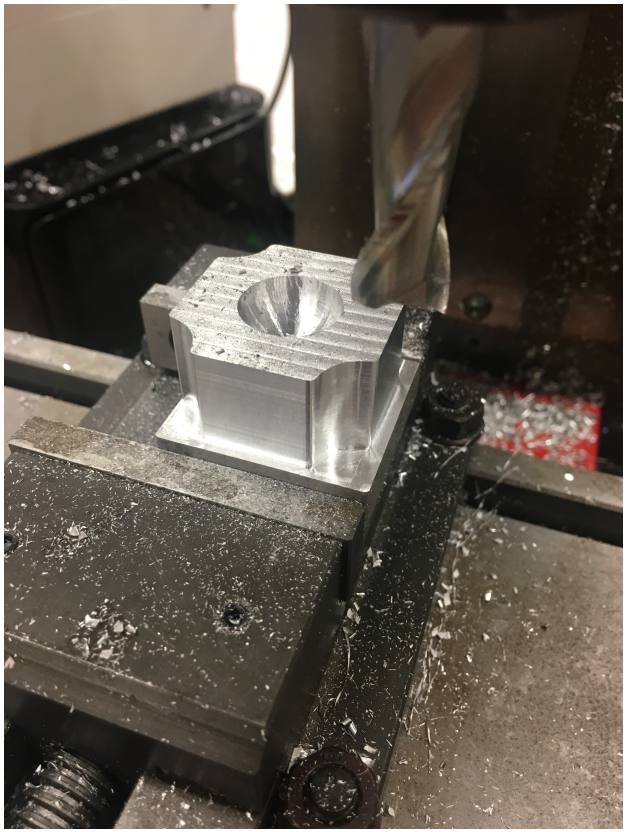

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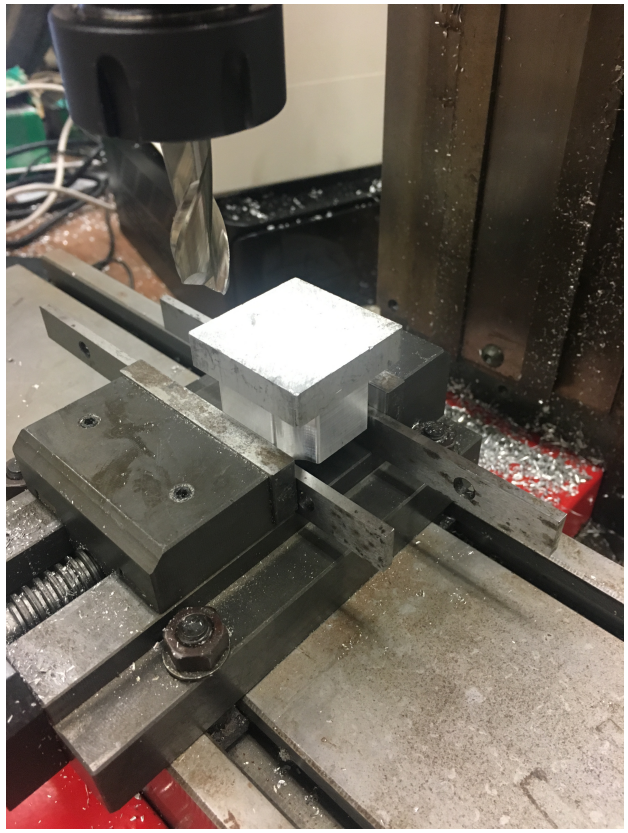
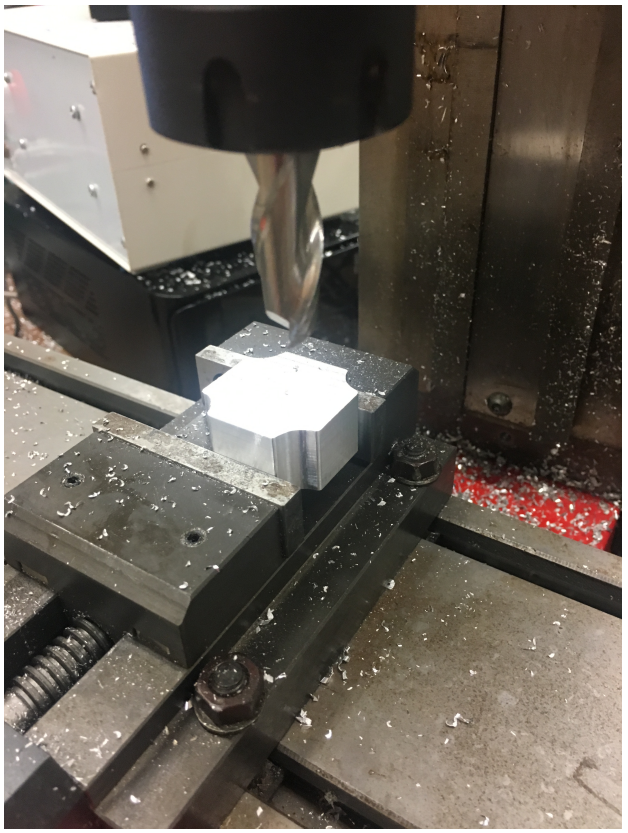
Setup 2



Start



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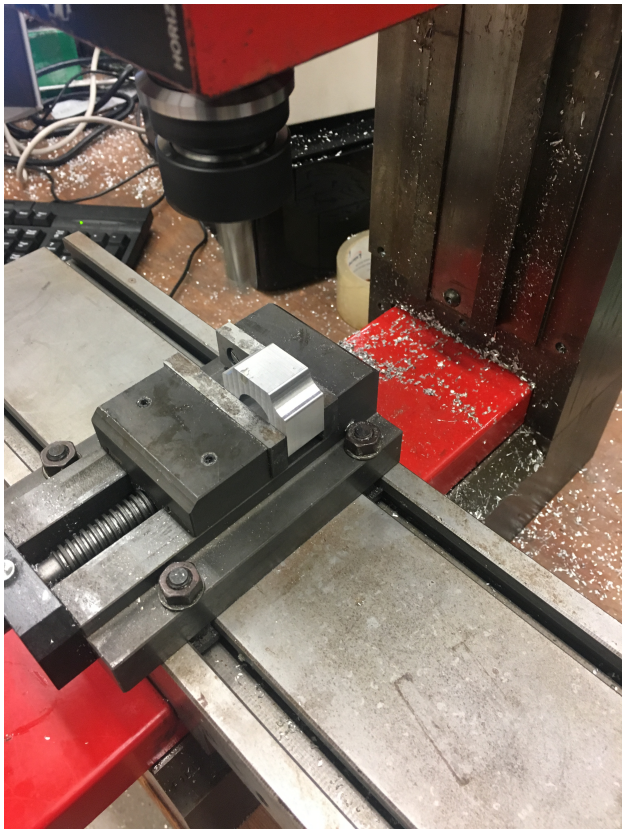
Setup 3



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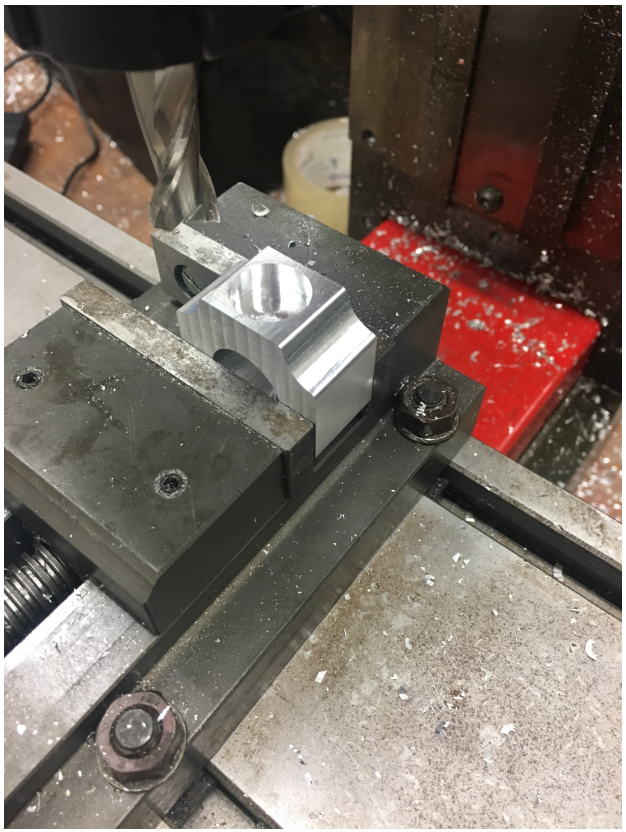

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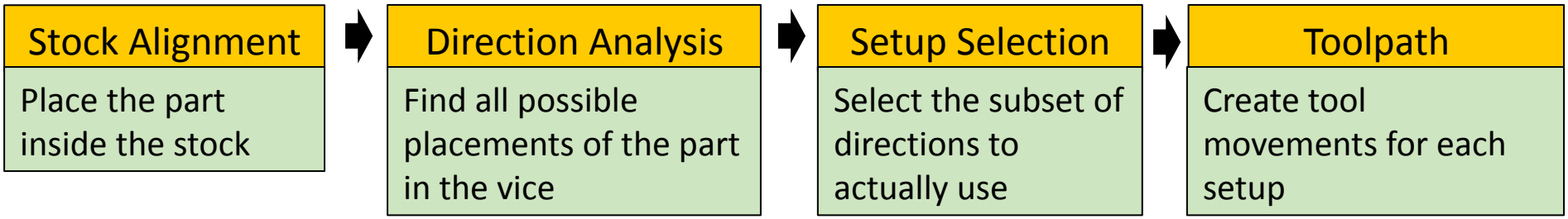
Planning Pipeline



Conclusion

- To our knowledge this is the first fully automatic, end to end process planner for 3 axis mills that has been tested on real parts
- Plans are crash free by construction
- Plans are toolpath overlap free by construction

Future Challenges

- Extend to more advanced machine tools, 4, 5 axis mills, mill turns
- Handle more tool types
- Support automatic design of custom fixtures for more irregular shapes
- Manufacturability feedback

Dawson Engler

- Associate Professor, Stanford
  - MIT PhD (exokernel operating system)
  - Co-founded Coverity
    - Commercialized static checking work
    - 1000s of customers, bought by Synopsis
- Research: find real bugs in real code
  - Agnostic on method, main religion = results.
  - Static, Model checking, Symbolic execution
- These days:
  - Design and CNC fabrication (this talk).