Industrial Automation

(Automação de Processos Industriais)

CAD/CAM and CNC

http://users.isr.ist.utl.pt/~jag/courses/api1617/api1617.html

Prof. Paulo Jorge Oliveira, original slides
Prof. José Gaspar, rev. 2016/2017

Syllabus:

Chap. 4 - GRAFCET *(Sequential Function Chart)* [1 weeks]

…

Chap. 5 – CAD/CAM and CNC [1 week]

Methodology CAD/CAM. Types of CNC machines.

Interpolation for trajectory generation.

Integration in Flexible Fabrication Cells.

…

Chap. 6 – Discrete Event Systems [2 weeks]

Some pointers to CAD/CAM and CNC

History: http://users.bergen.org/jdefalco/CNC/history.html

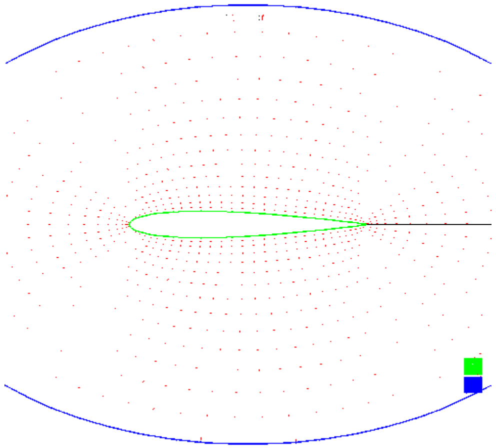
Tutorial: http://users.bergen.org/jdefalco/CNC/index.html
http://www-me.mit.edu/Lectures/MachineTools/outline.html
http://www.tarleton.edu/~gmollick/3503/lectures.htm

Editors (CAD): http://www.cncezpro.com/
http://www.cadstd.com/
http://www.turbocad.com
http://www.deskam.com/
http://www.cadopia.com/

Bibliography:

* **Computer Control of Manufacturing Systems**, Yoram Koren, McGraw Hill, 1986.
* **The CNC Workbook : An Introduction to Computer Numerical Control** by Frank Nanfarra, et al.

CAD/CAM and CNC



Concept

Tool / Methodology

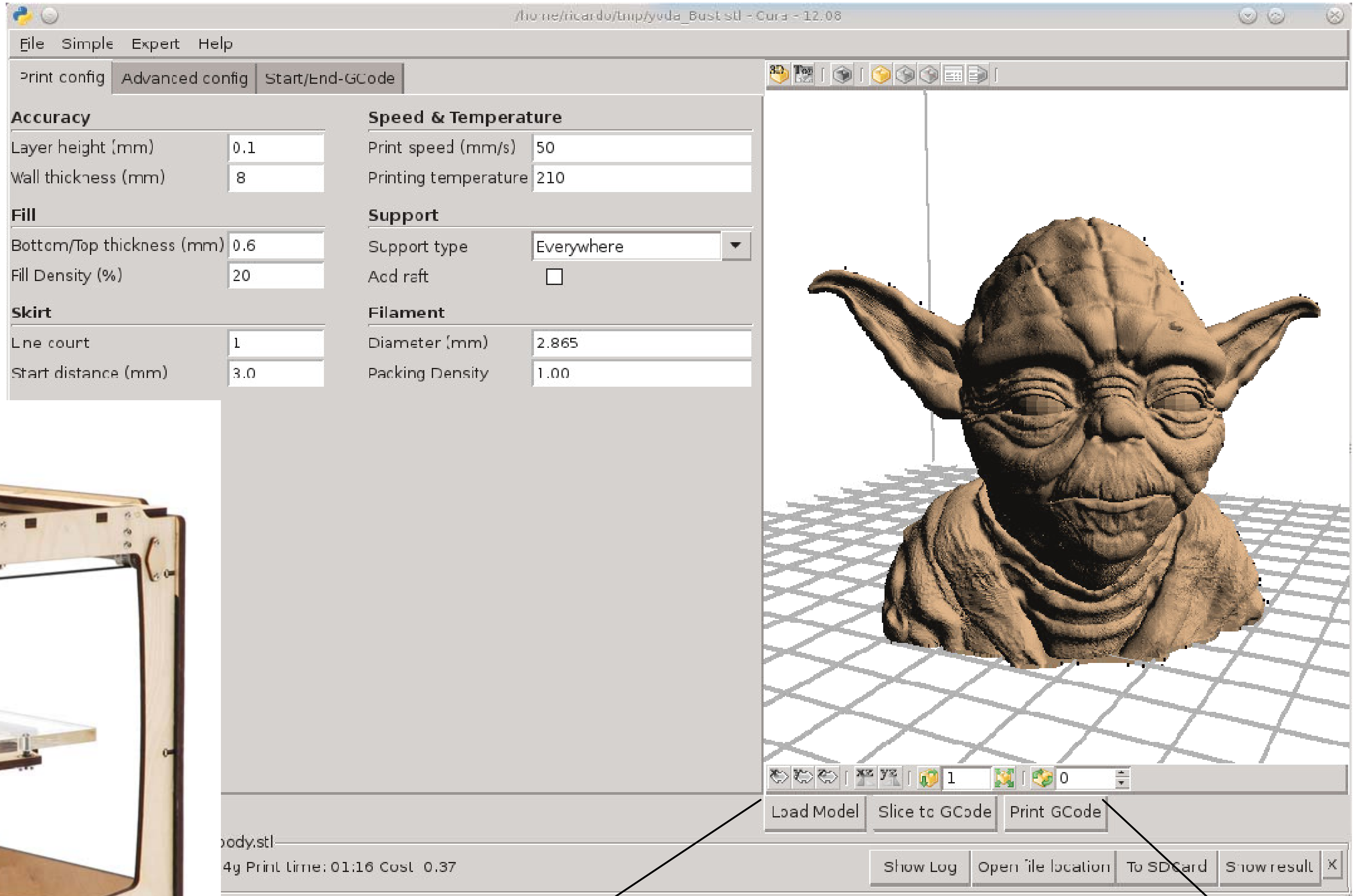
Prototype

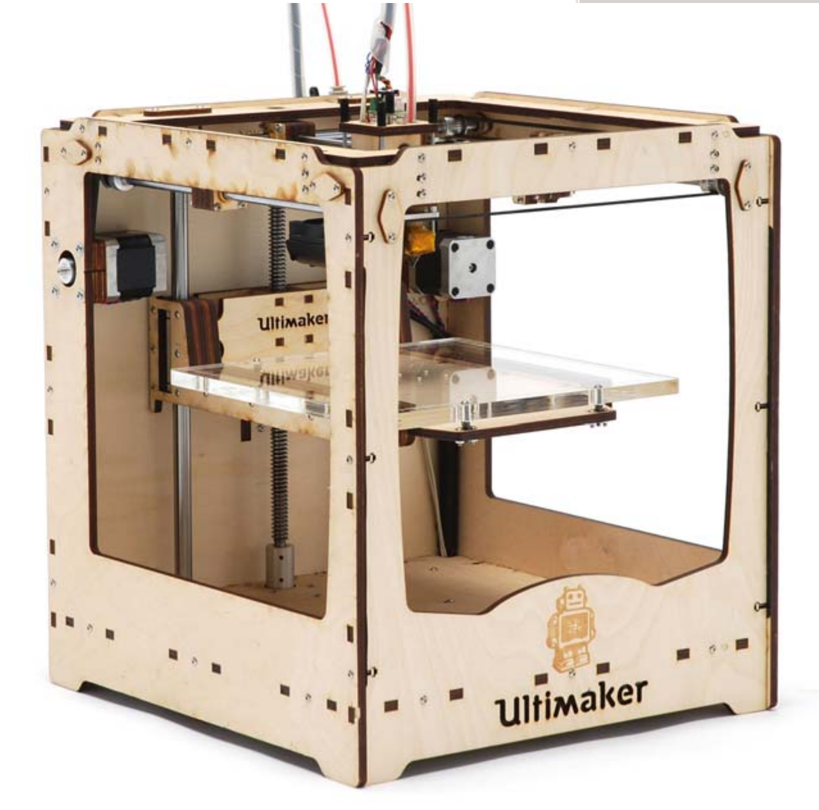
Nowadays, machines are almost perfect! the technological question is mostly about ***integration.***

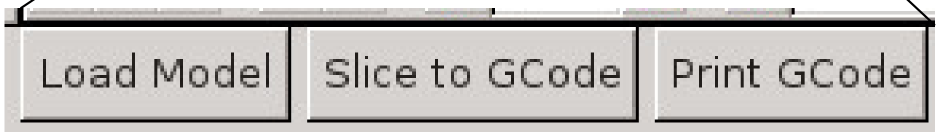
CAD/CAM and CNC at home!

http://daid.github.com/Cura/

Order in the internet, receive by mail and assemble yourself!
http://www.ultimaker.com/







Brief relevant history NC

1947 – US Air Force needs lead John *Parsons* to develop a machine able to produce parts described in 3D.

1949 – Contract with *Parsons Corporation* to implement to proposed method.

1952 – Demonstration at MIT of a working machine tool (NC), able to produce parts resorting to simultaneous interpolation on several axes.

1955 – First NC machine tools reach the market.

1957 - NC starts to be accepted as a solution in industrial applications , with first machines starting to produce.

197x – Profiting from the microprocessor invention appears the CNC.

Footnotes:

1939-1945 – Second World War, 1947-1991 – Cold war;
1946 – ENIAC first electronic general purpose computer
1968 – Bedford/GM PLC, 1975-1979 – GRAFCET

Evolution in brief

CAD/CAM and CNC

Modification of existing machine tools with **motion sensors** and **automatic advance** systems.

Closed-loop control systems for **axis control**.

Incorporation of the **computational advances** in the CNC machines.

Development of **high accuracy interpolation** algorithms to trajectory interpolation.

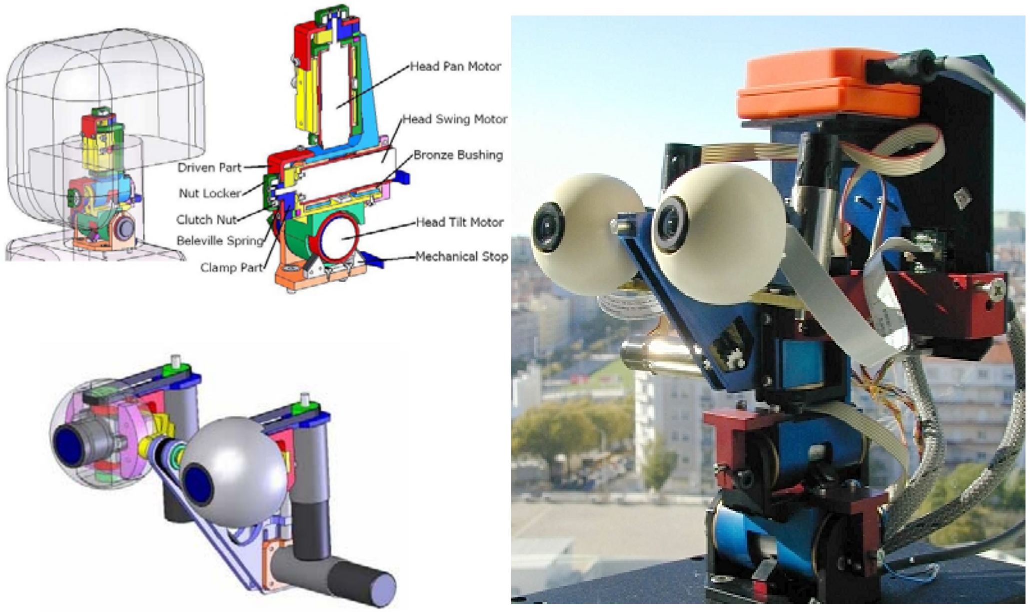
Resort to **CAD systems to design parts** and to manage the use of CNC machines.

CAD/CAM and CNC

Industrial areas of application:

- *Aerospace* — *e.g. designing and testing wing and blade profiles*
- *Automobiles* — *e.g. concept car design*
- *Moulds/Dies* — *e.g. bottle caps, gears, hard shell luggage*
- *Electronics* — *e.g. mounting components on PCBs*
- *Machinery* — *e.g. iCub*

WorkNC CAD/CAM software by Sescoi



iCub head design at IST

CAD/CAM and CNC

Methodology CAD/CAM

Use technical data from a ***database*** in the design and production stages.
Information on parts, materials, tools, and machines are ***integrated***.

CAD (Computer Aided Design)

Allows the design in a computer environment.

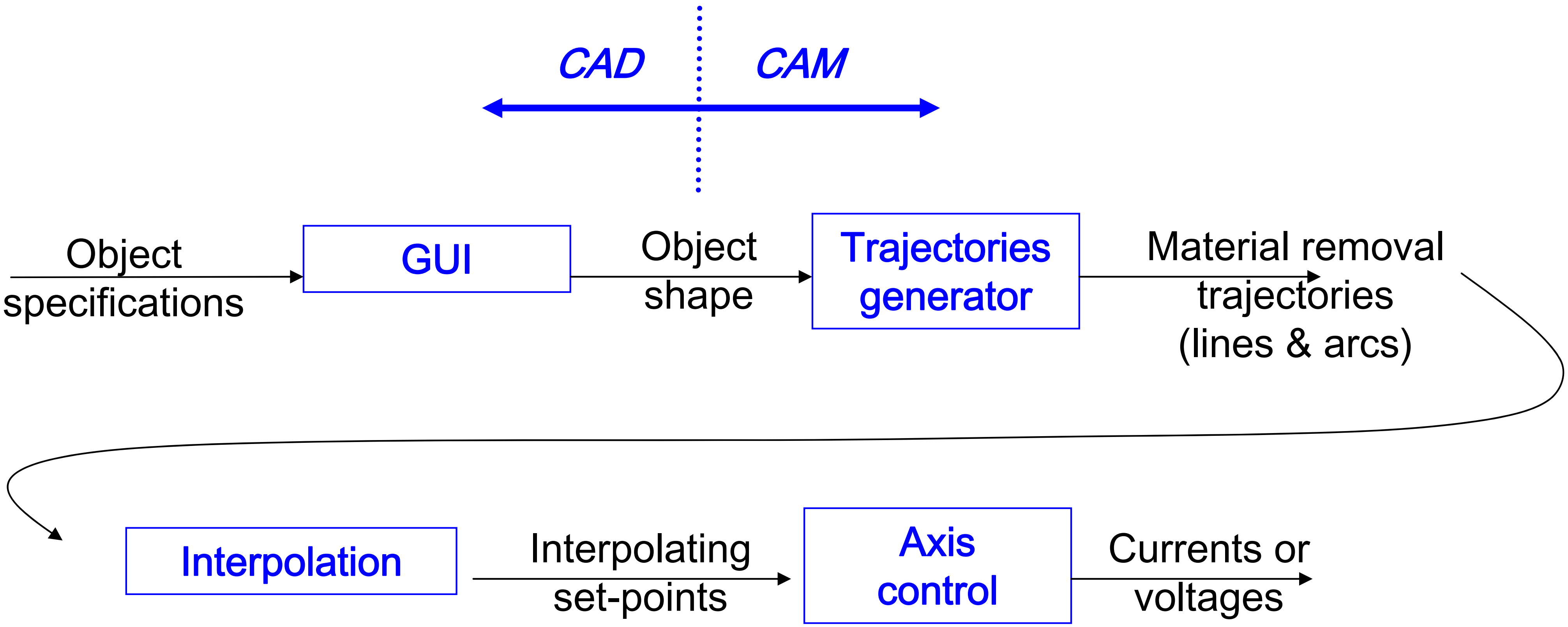
Ideas → ***Design***

CAM (Computer Aided Manufacturing)

To manage programs and production stages on a computer.

Design → ***Product***

CAD/CAM and CNC Methodology CAD/CAM



CAD/CAM and CNC

Objectives

- Increase accuracy, reliability, and ability to introduce changes/**new designs**
- Increase workload
- Reduce production costs
- Reduce waste due to errors and other human factors
- Carry out **complex tasks** (e.g. Simultaneous 3D interpolation)
- Increase precision of the produced parts.

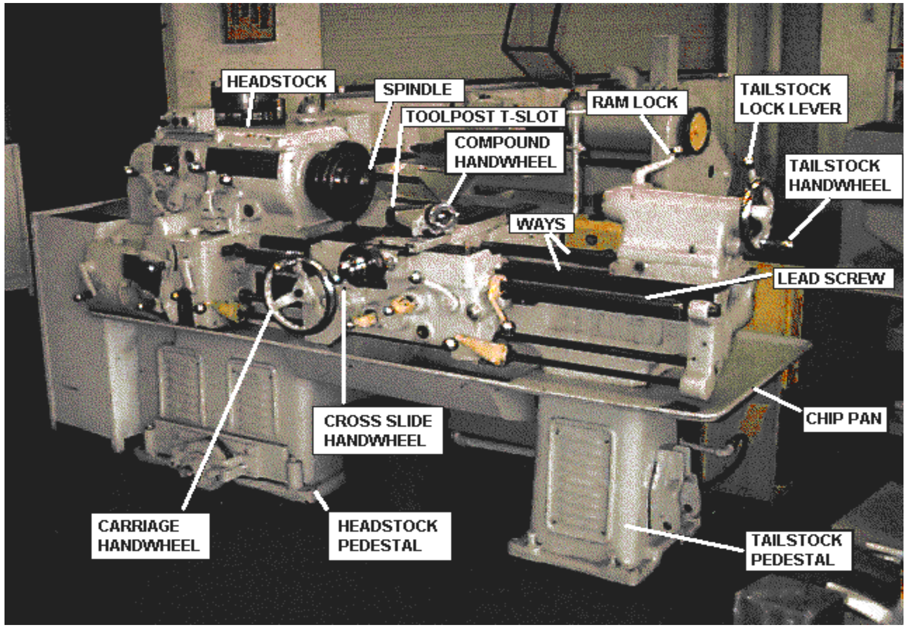
Advantages

- Reduce the production/delivery **time**
- Reduce **costs** associated to parts and other auxiliary
- Reduce storage space
- Reduce time to start production
- Reduce machining time
- Reduce **time to market** (on the design/redesign and production).

Limitations

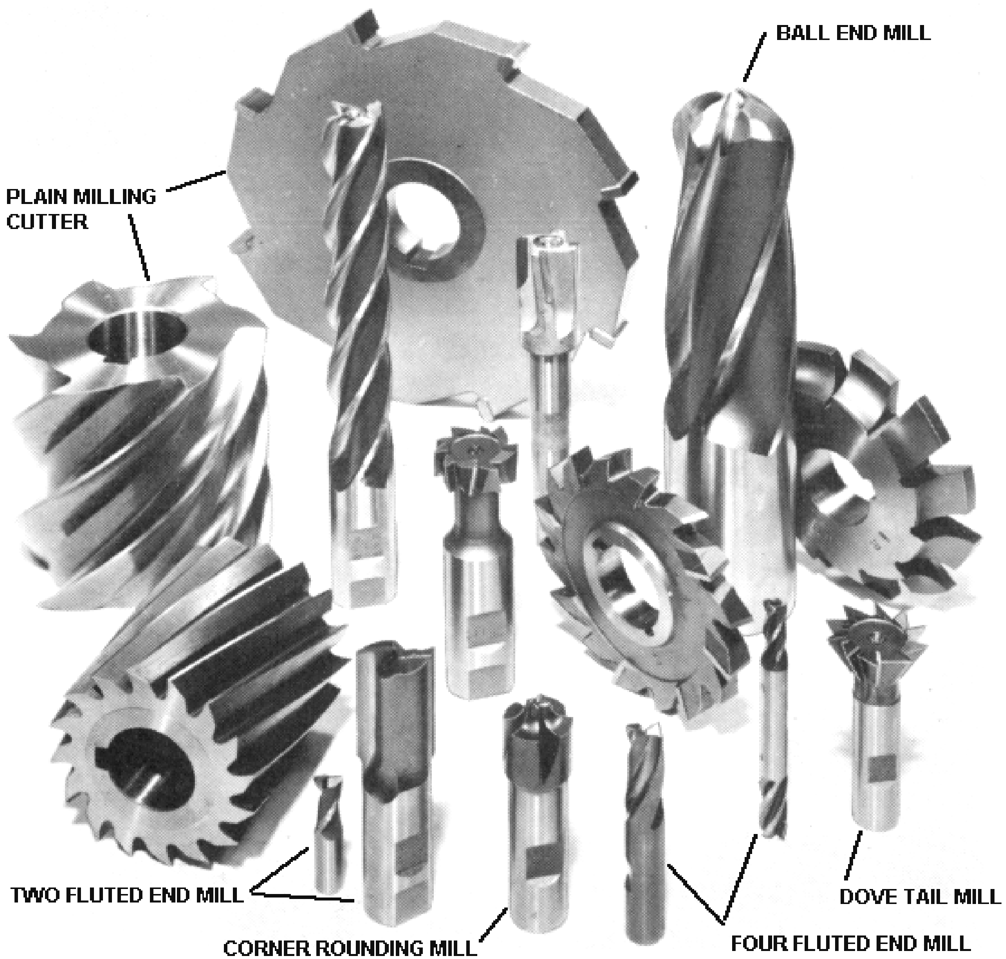
- High initial **investment** (30k€ to 1500k€)
- Specialized **maintenance** required
- Does not eliminate the human errors completely
- Requires more specialized **operators**
- Not so relevant the advantages on the production of small or very small series.

CAD/CAM and CNC Tools

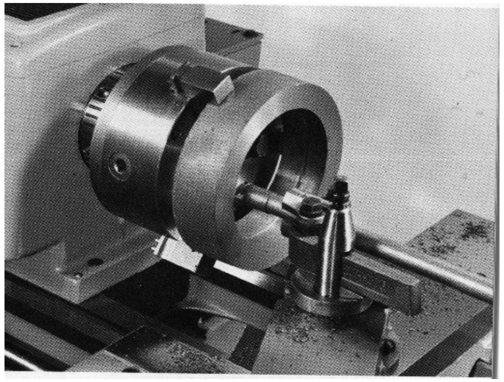


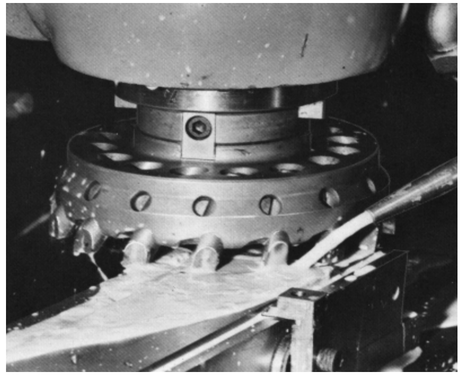
http://www.schaublinmachines.co.uk/machining-centres/160 CNC Fanuc.html

CAD/CAM and CNC **Tools :**

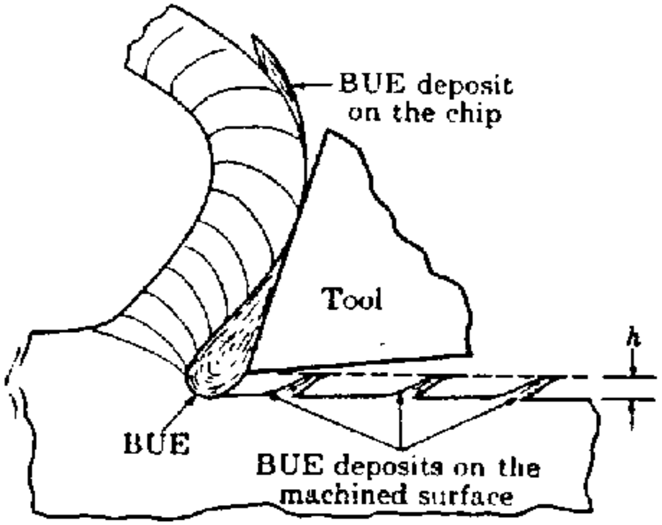


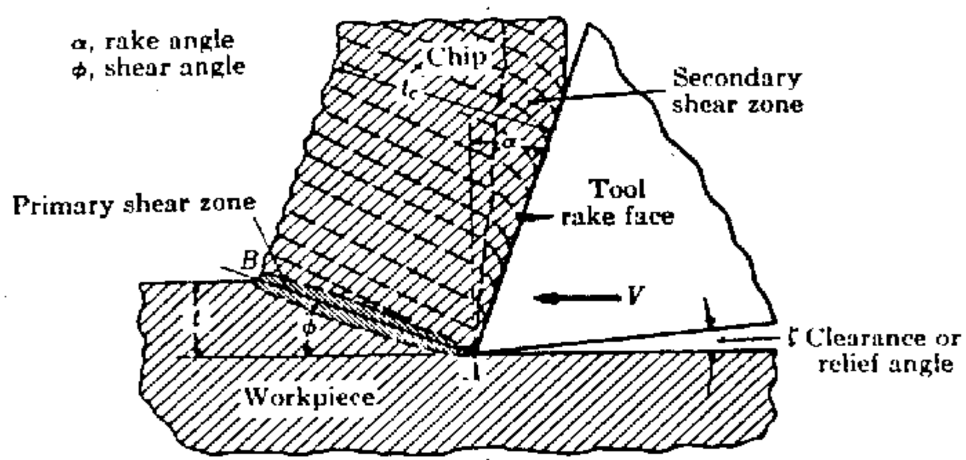
CAD/CAM and CNC Tools :





Attention to the constraints
on the materials used ...

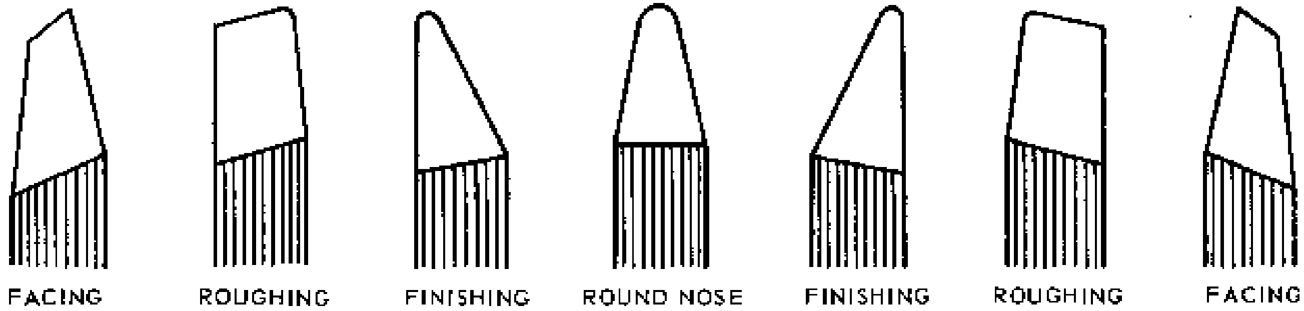




• **Speed of advance** • **Speed of rotation** • **Type of tool**

CAD/CAM and CNC

Tools :



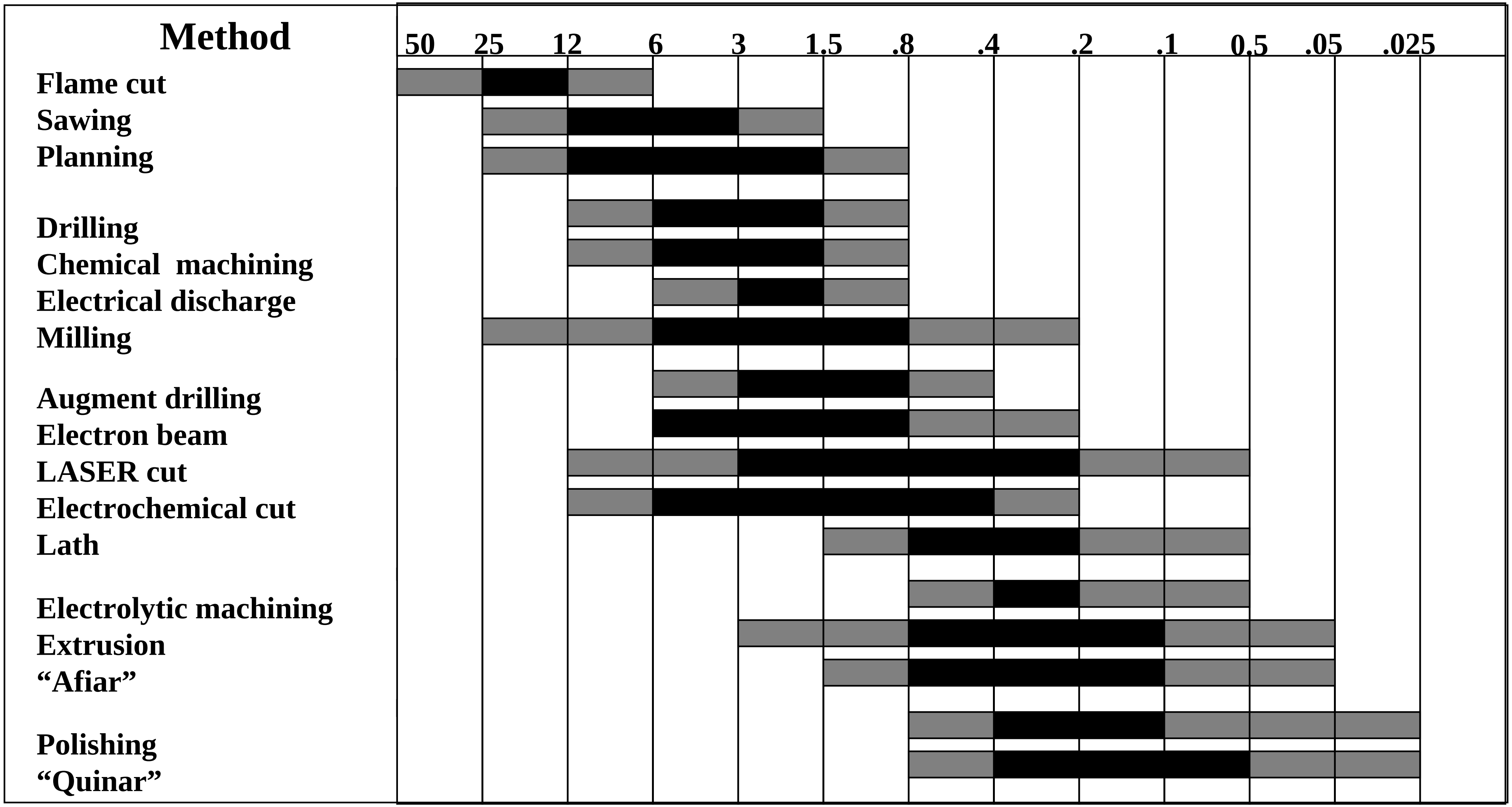
LEFT-CUT tools *RIGHT-CUT tools*

Specific tools to perform different operations.

Micro-machined mirror, camera mounting, acquired images [IST/Portugal, USP/Brazil].

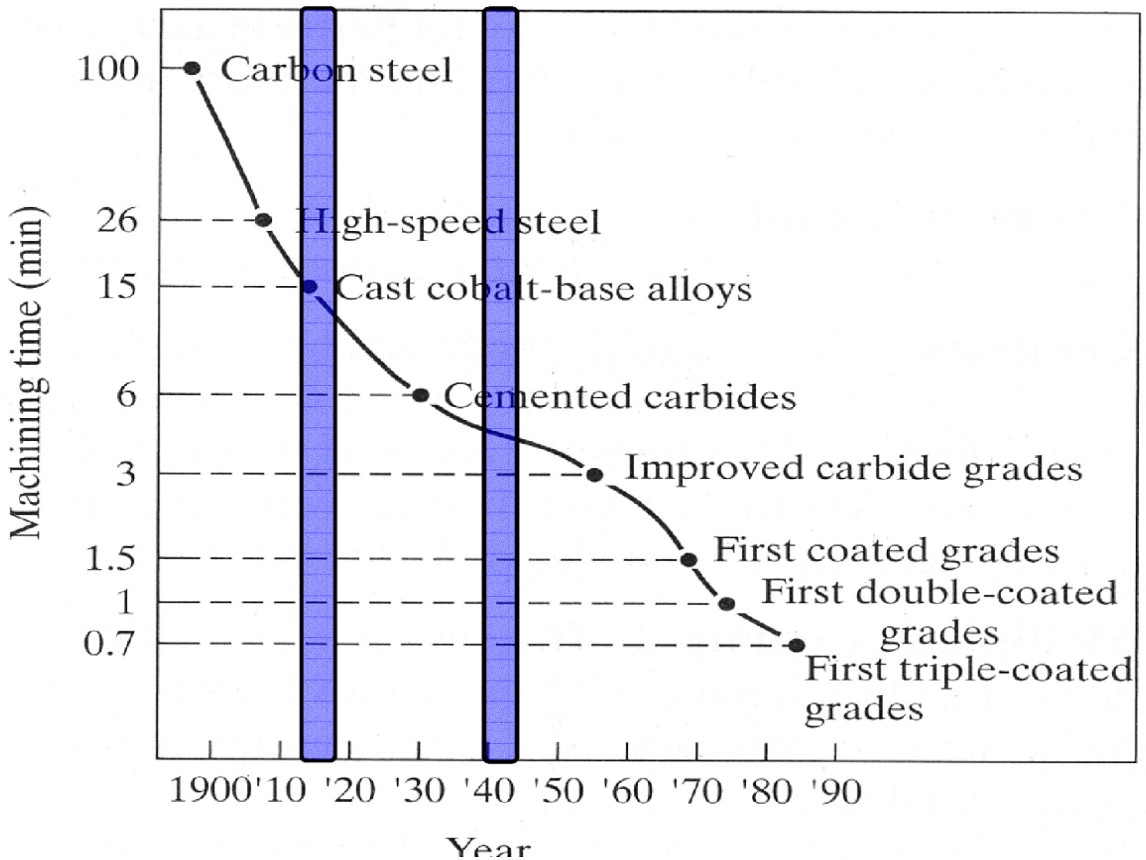
CAD/CAM and CNC

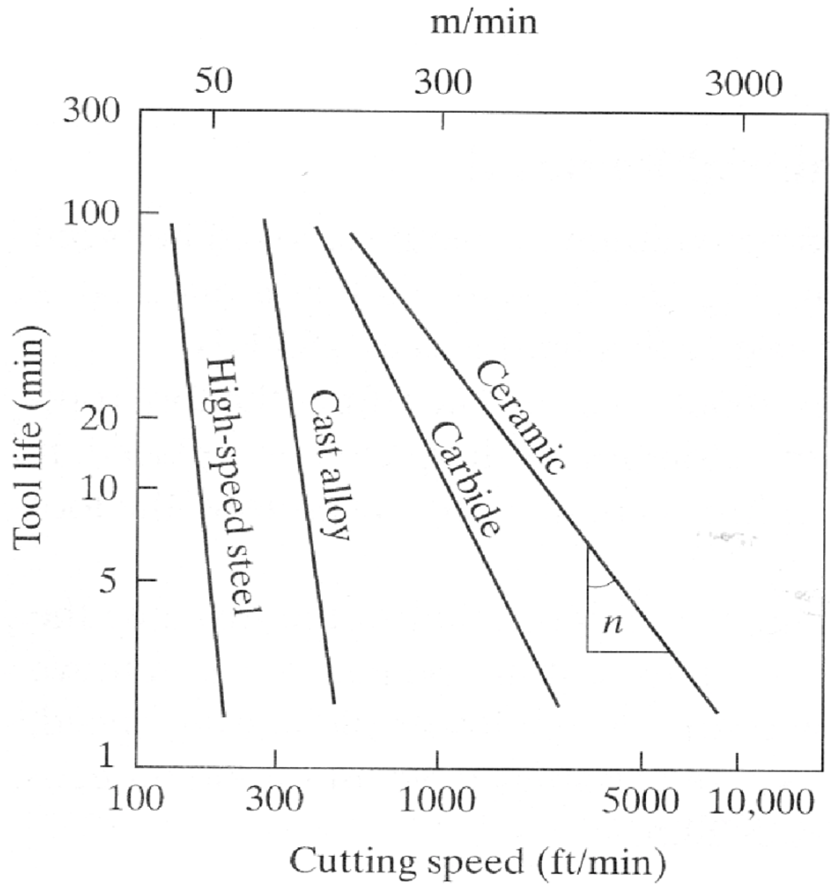
Tools: impact on the quality of finishing (μm)



CAD/CAM and CNC

Evolution of tools performance:





CAD/CAM and CNC

Tools: Energy Requirements

Approximate Energy Requirements in Cutting Operations (at drive motor, corrected for 80% efficiency; multiply by 1.25 for dull tools).

	Specific energy	
Material	$W \cdot s/mm^3$	$hp \cdot min/in.^3$
Aluminum alloys	0.4–1.1	0.15–0.4
Cast irons	1.6–5.5	0.6–2.0
Copper alloys	1.4–3.3	0.5–1.2
High-temperature alloys	3.3–8.5	1.2–3.1
Magnesium alloys	0.4–0.6	0.15–0.2
Nickel alloys	4.9–6.8	1.8–2.5
Refractory alloys	3.8–9.6	1.1–3.5
Stainless steels	3.0–5.2	1.1–1.9
Steels	2.7–9.3	1.0–3.4

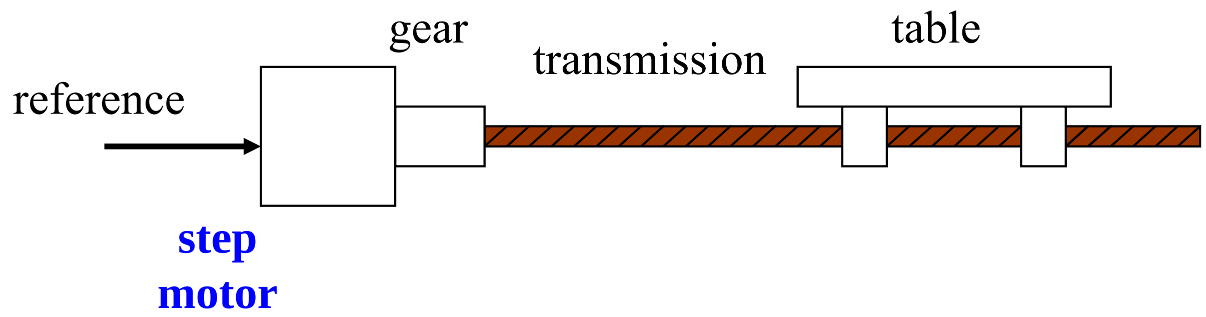
CAD/CAM and CNC Evolution of Numerical Control

- Numerical Control (NC)
  - Data on paper or received in serial port
  - NC machine unable to perform computations
  - Hardware interpolation
- Direct Numerical Control (DNC)
  - Central computer control a number of machines DNC or CNC
- Computer Numerical control (CNC)
  - A computer is on the core of each machine tool
  - Computation and interpolation algorithms run on the machine
- Distributive numerical control
  - Scheduling
  - Quality control
  - Remote monitoring

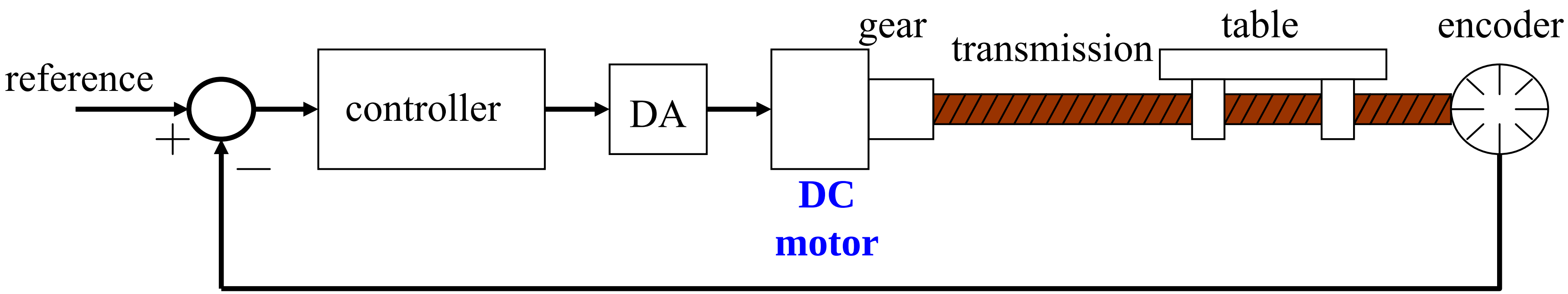
CAD/CAM and CNC Numeric Control

Architecture of a NC system: 1 axis

Open-loop

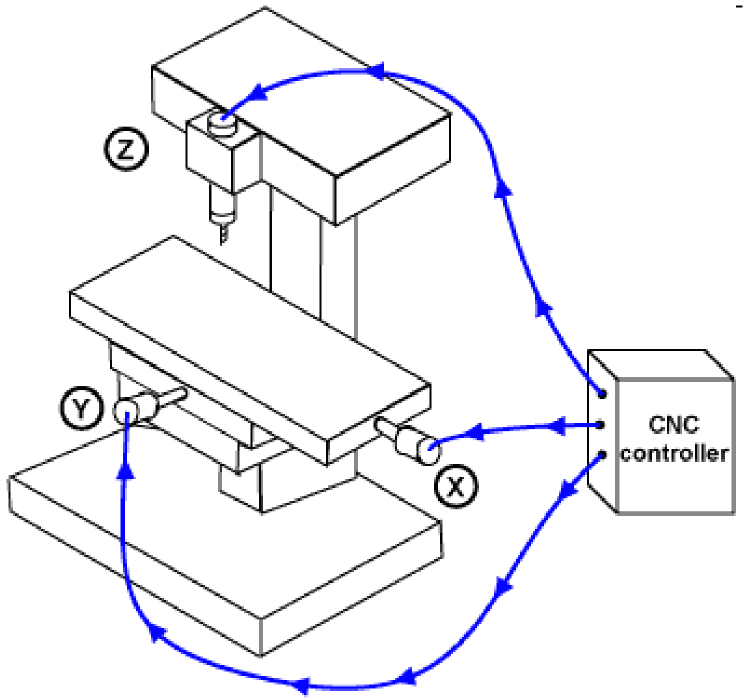


Closed-loop

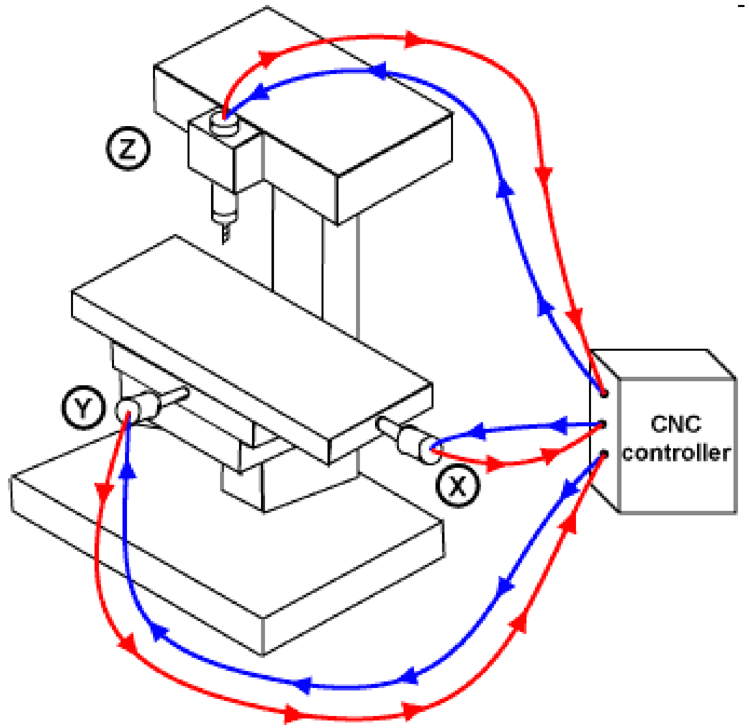


CAD/CAM and CNC Numeric Control

Architecture of a NC system: 3 axis



Open-Loop-System

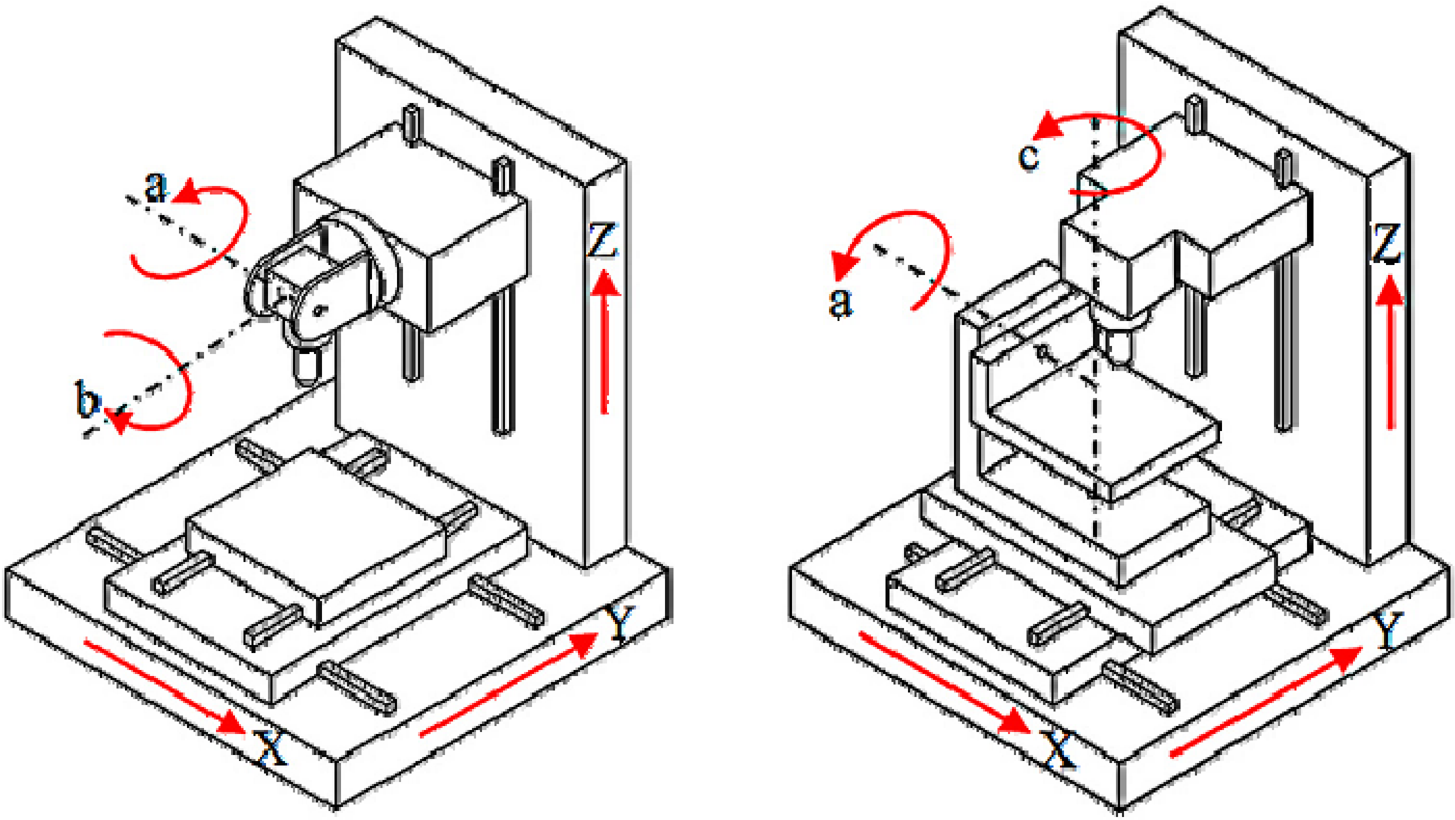


Closed-Loop-System

[http://www.kanabco.com/vms/cnc_control/cnc_control_03.html]

CAD/CAM and CNC Numeric Control

Architecture of a NC system: 5 axis

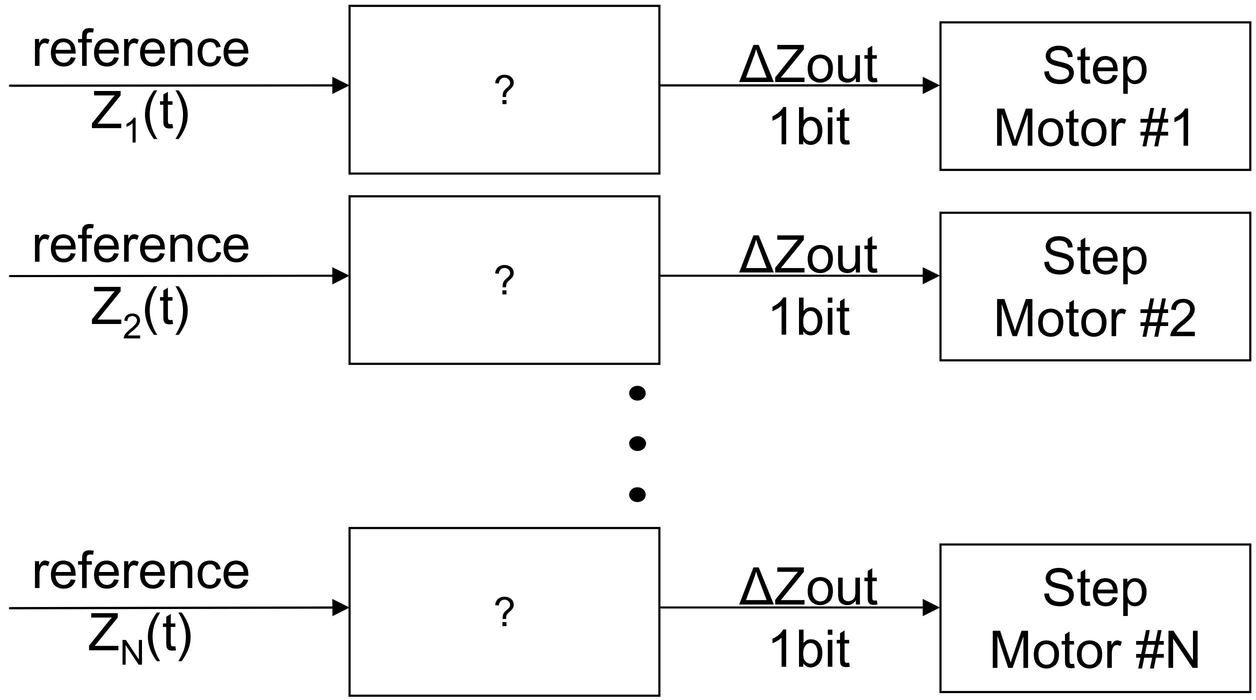


Standard configurations of the rotary axes on 5–axis CNC machines,
an ***orientable-spindle*** machine (left) and ***orientable-table*** machine (right) [Faroukia’14].

[Faroukia'14] "Inverse kinematics for optimal tool orientation control in 5-axis CNC machining", Rida T. Faroukia, Chang Yong Hanb, Shiqiao Lia, Computer Aided Geometric Design, v31n1 pp13-26 2014

CAD/CAM and CNC

Interpolation Motivation



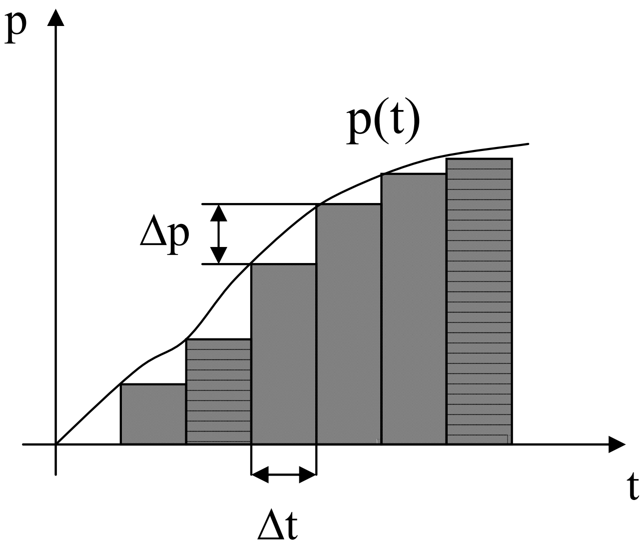
*Note1: The references are usually very **simple**, e.g.* $Z_i(t)=a_i t+b_i$

*Note2: Step motors count steps, i.e. are **numerical integrators** hence we have to convert Z(t) to an **incremental representation*** p_k

CAD/CAM and CNC

Interpolation: use incremental representation

Motivation from numerical integration



Area of a function

$$z(t) = \int_0^t p(\tau)d\tau \cong \sum_{i=1}^{k} p_i \Delta t$$

Introducing z_k, as the value of z at t=kΔt

$$z_k = \sum_{i=1}^{k-1} p_i \Delta t + p_k \Delta t = z_{k-1} + \Delta z_k, \qquad \Delta z_k = p_k \Delta t \qquad \Rightarrow \quad p_k = \Delta z_k / \Delta t$$

The integrator works at a rhythm of f=1/Δt and the function p is given app. by:

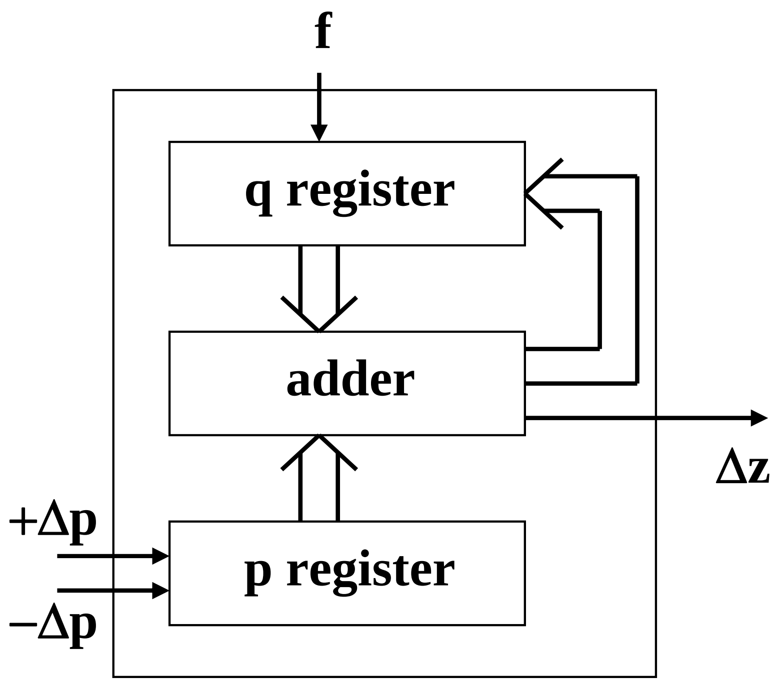
$$p_k = p_{k-1} \pm \Delta p_k$$

To be able to implement the integrator in registers with n bits, p must verify $p_k<2^n$.

In the following we will use p_k and Δp_k instead of z_k or z(t).

CAD/CAM and CNC

Implementation of a Digital Differential Analyzer (DDA)



The p register input is 0, +1= Δp or –1= –Δp.

The q register stores the **area integration** value

$$q_k = q_{k-1} + p_k .$$

If the q register value exceeds (2^n-1) an overflow occurs and Δz=1:

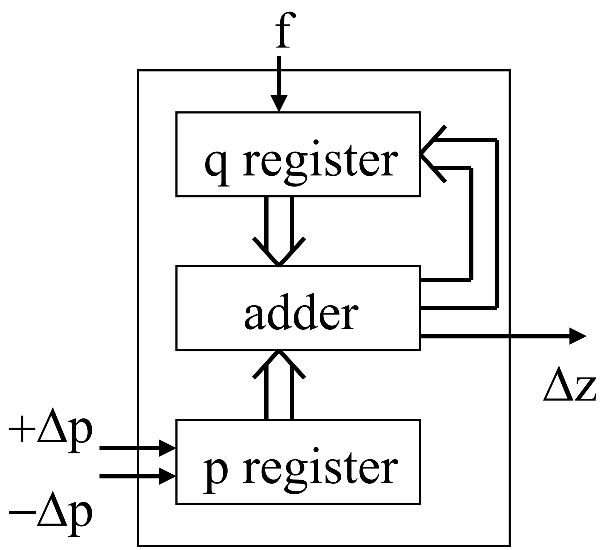
$$\Delta z_k = p_k / 2^n$$

Defining C=f/2^n, and given that f=1/Δt, one has a scale factor from p_k to Δz_k:

$$\Delta z_k = p_k \, C \, \Delta t$$

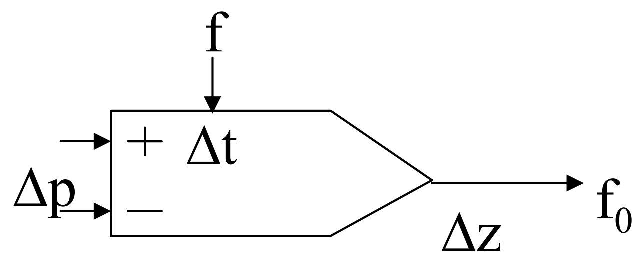
CAD/CAM and CNC

DDA for Linear Interpolation (1 axis):

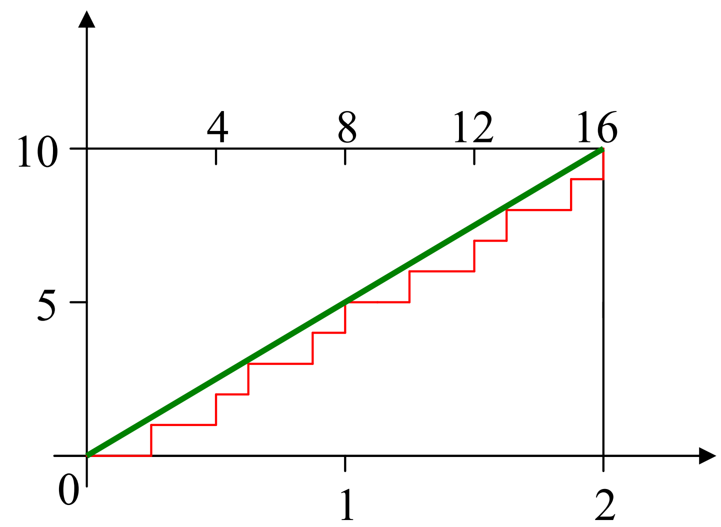


Example: let p=5, Δ p=0 and assume q is a 3 bits register

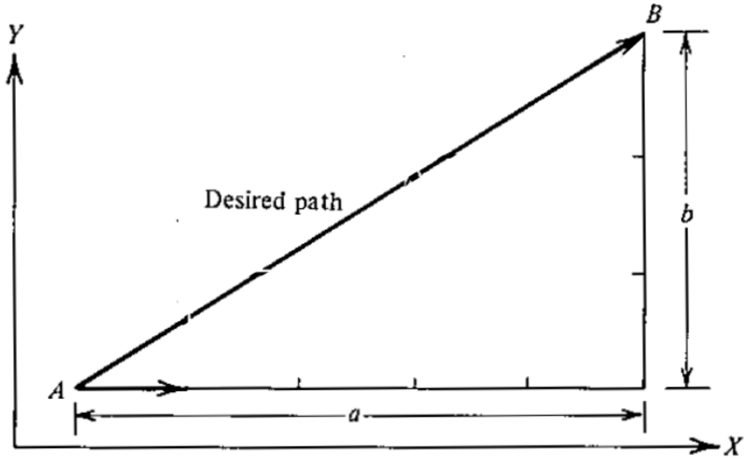
Step	q	Δz	Σ Δz
1	5		0
2	2	1	1
3	7		1
4	4	1	2
5	1	1	3
6	6		3
7	3	1	4
8	0	1	5
9	5		5
		...	



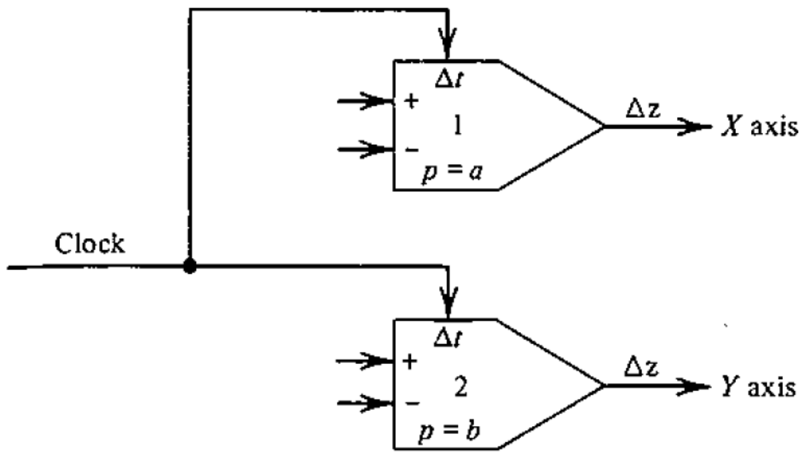
$$f_0 = \left(\frac{\Delta z}{\Delta t}\right)_k = C p_k, \quad \text{where} \quad C = \frac{f}{2^n}$$



CAD/CAM and CNC DDA for Linear Interpolation (2 axis):

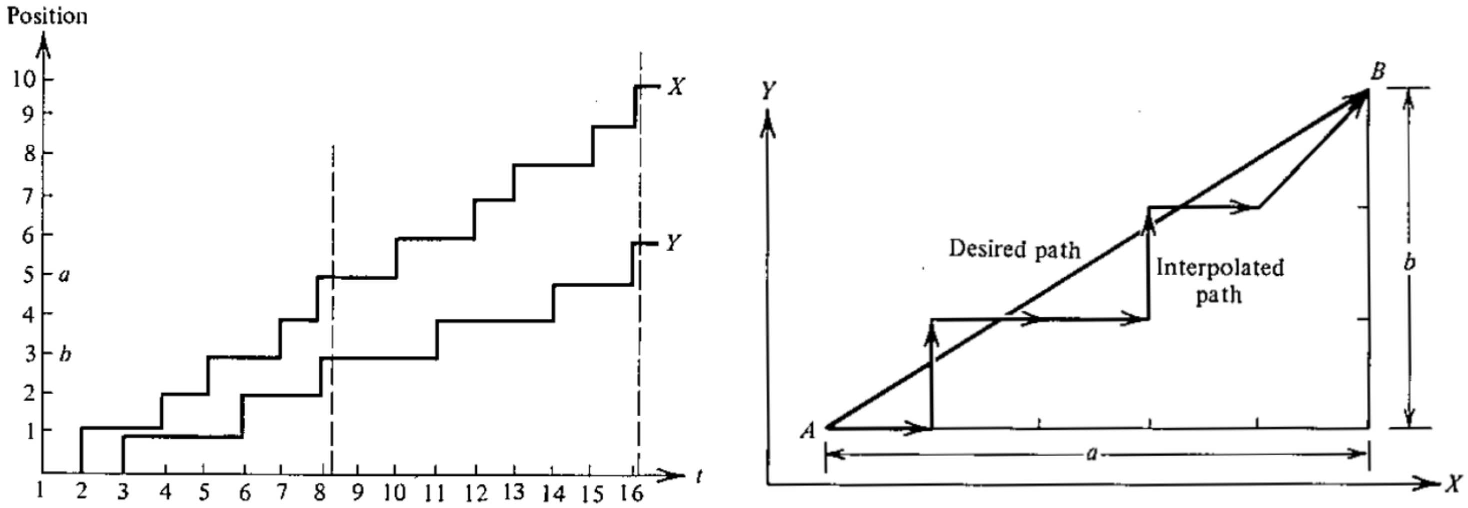


(a) Specifications



(b) DDA solution

(c) Results for a=5 b=3



CAD/CAM and CNC **Exponential Deceleration:**

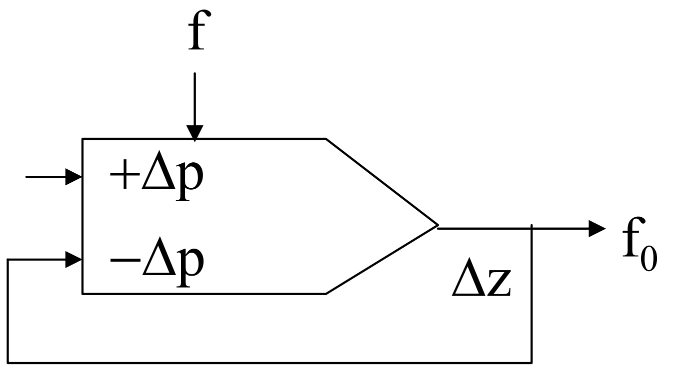
Let $p(t) = p_0 e^{-\alpha t} \Rightarrow dp = -\alpha p_0 e^{-\alpha t} dt$ and $\frac{\Delta z}{\Delta t} = Cp_k = Cp_0 e^{-\alpha t}$.

The differential of p(t) is approximately

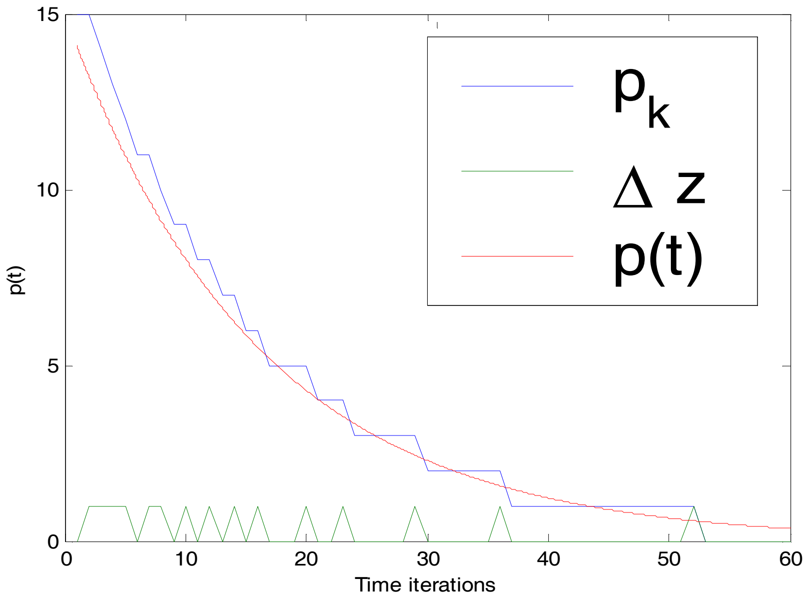
$$-\Delta p = \alpha p_k \Delta t$$

Setting C=α, i.e. $f=2^n\alpha$, one has

$$-\Delta p = \Delta z$$



Example: $p(t)=15e^{-t}$



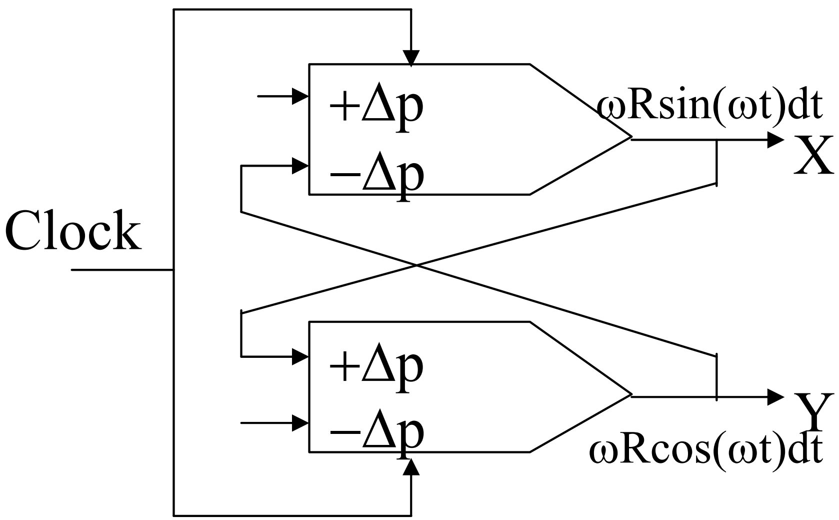
CAD/CAM and CNC **Circular Interpolation:**

Let $(X-R)^2 + Y^2 = R^2$ or

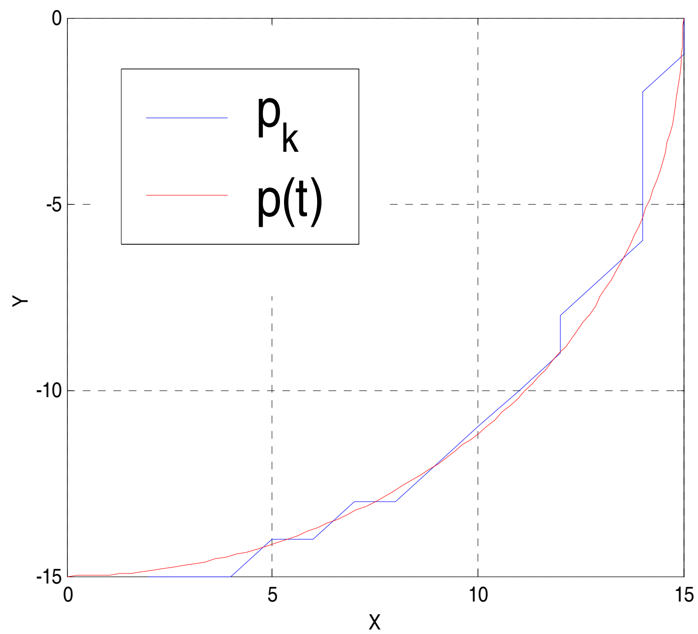
$$X = R(1-\cos(\omega t))$$
$$Y = R\sin(\omega t)$$

The differential is

$$dX = \omega R\sin(\omega t)dt = d(-R\cos(\omega t))$$
$$dY = \omega R\cos(\omega t)dt = d(R\sin(\omega t))$$

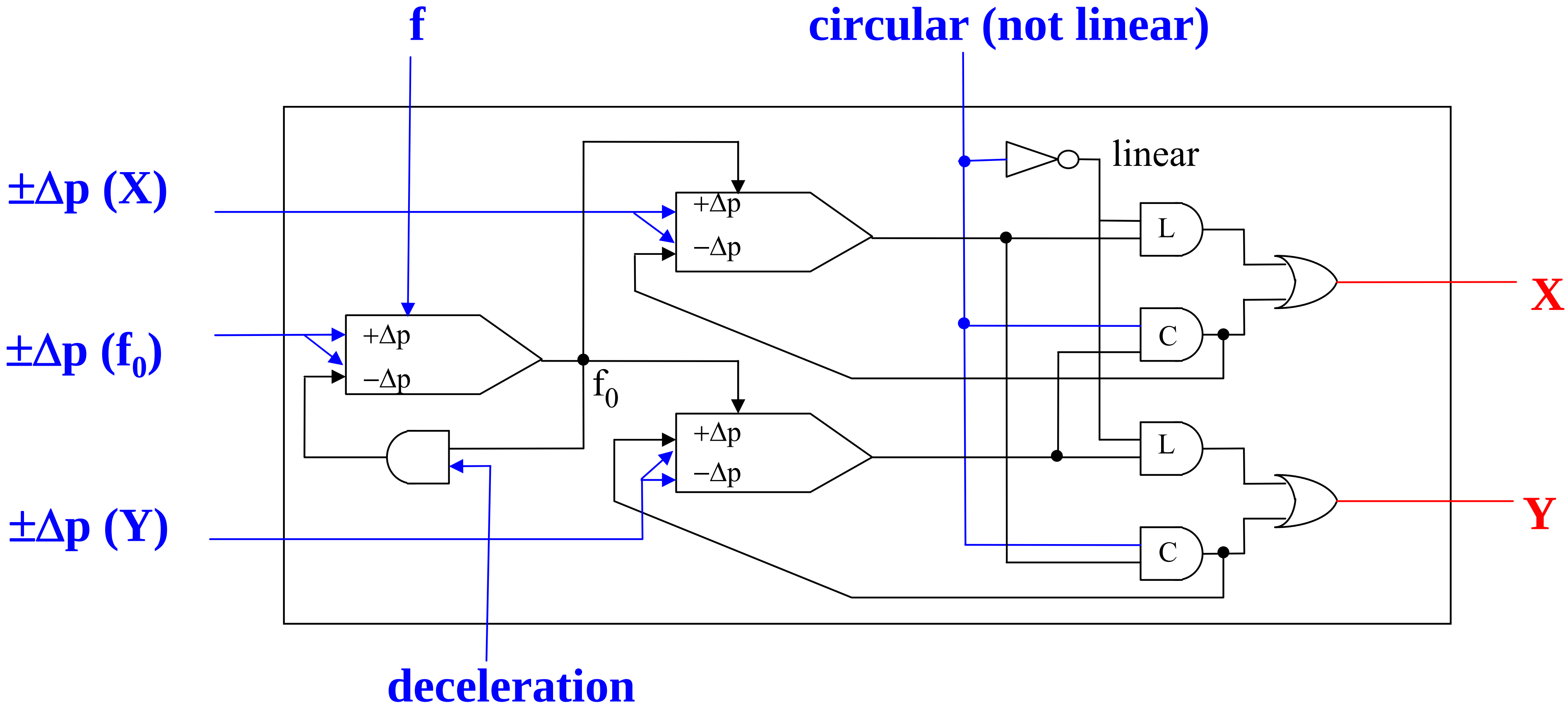


Example: Circumference of radius 15, centered at the origin.



CAD/CAM and CNC **Full DDA**

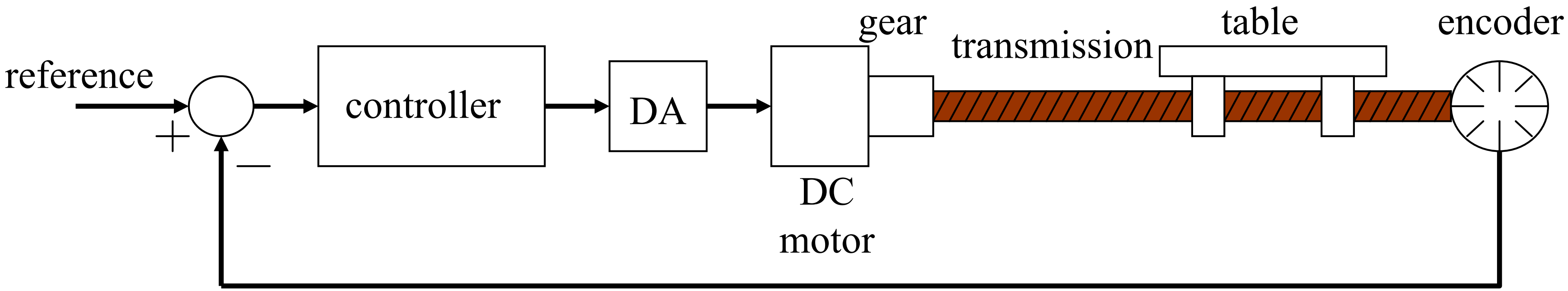
2D Line, 2D Arc, Acceleration / Deceleration



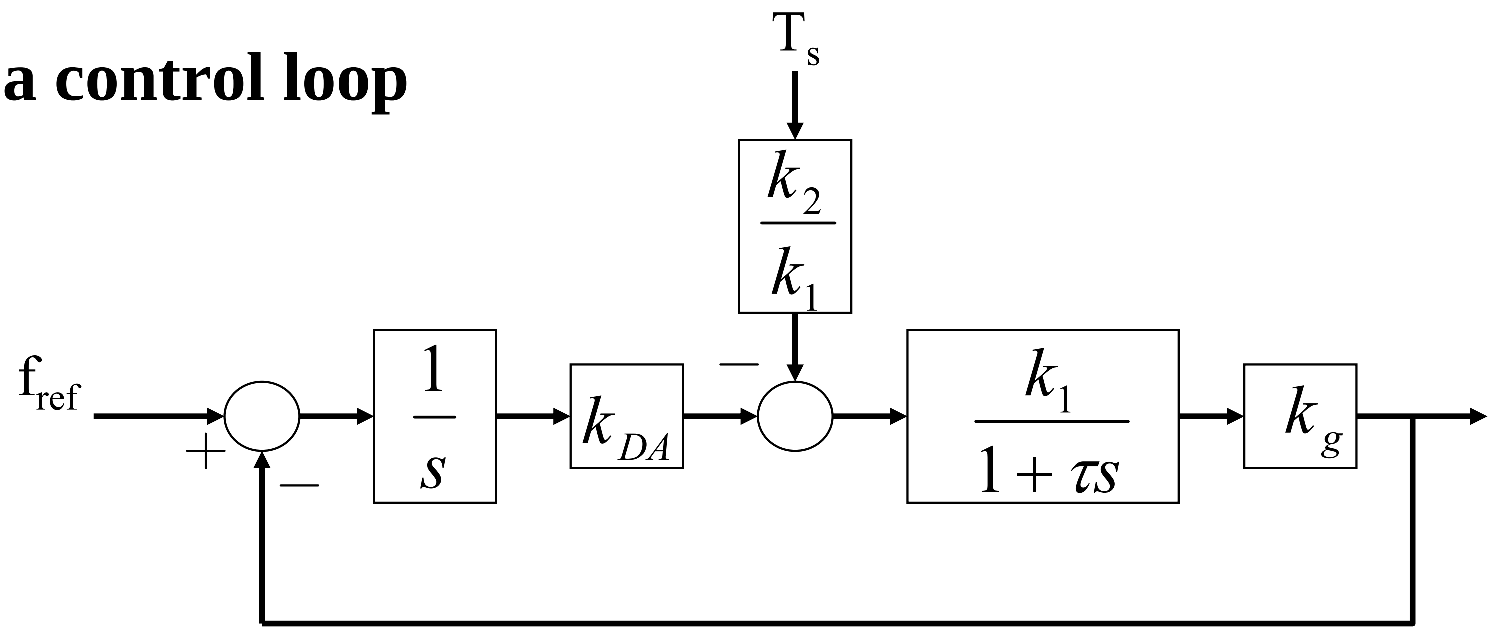
[Koran86] **Computer Control of Manufacturing Systems**, Yoram Koren,,McGraw Hill, 1986

CAD/CAM and CNC

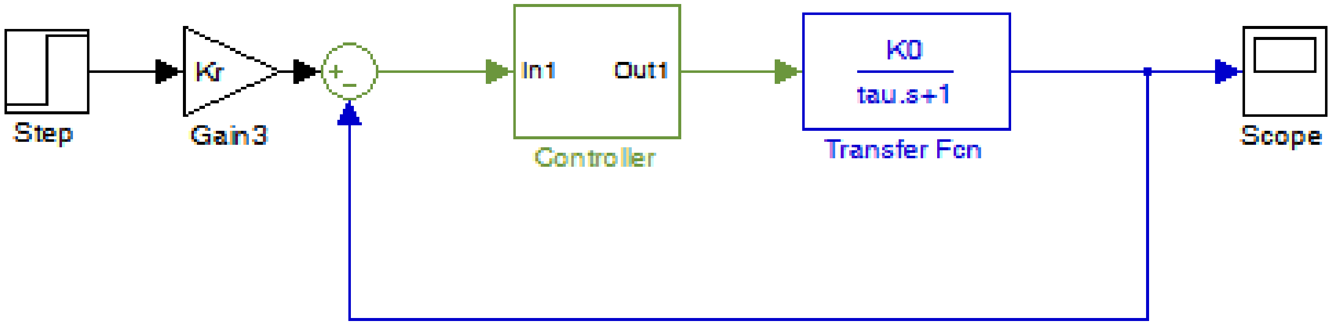
CNC Axes Control



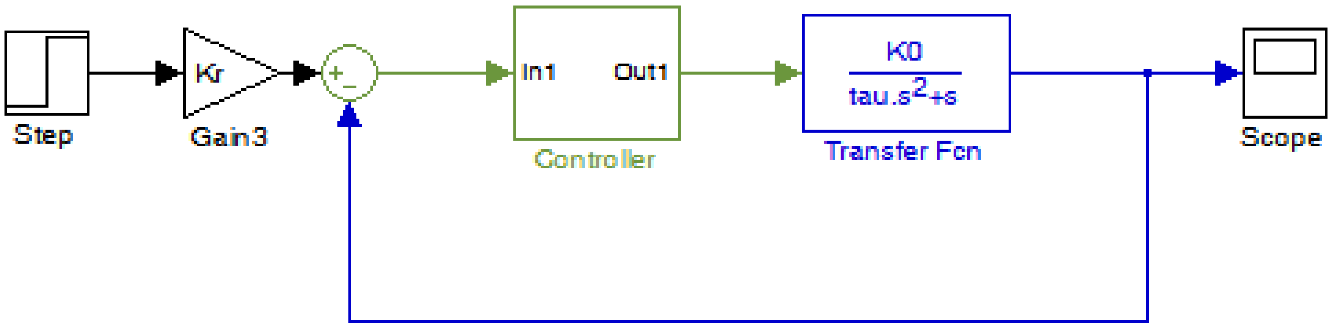
Dynamics of a control loop



DC motor - speed control



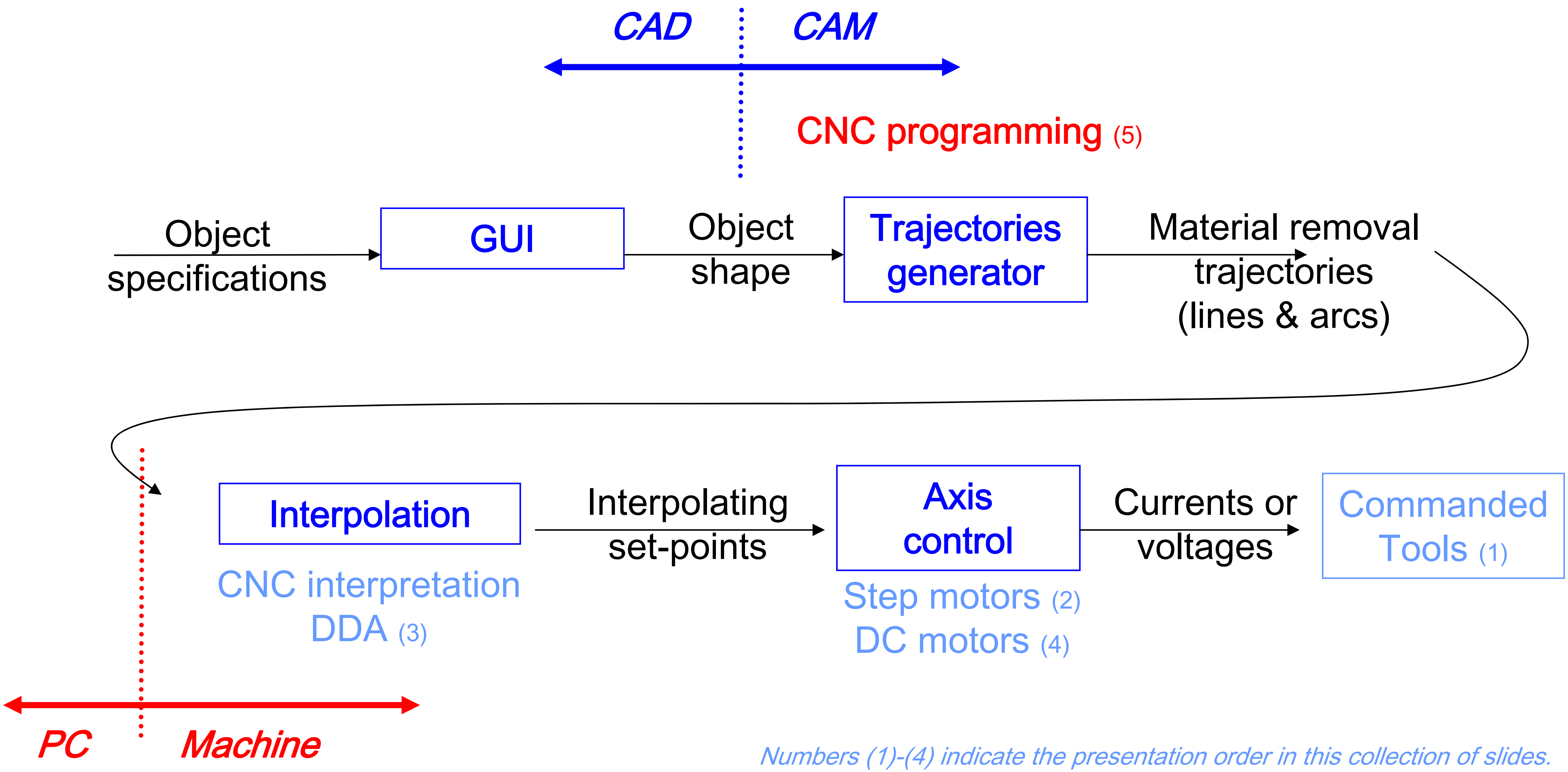
DC motor - position control



In the position control example, a proportional controller is enough to obtain ***zero steady state error*** *in the position, i.e. steady state output is Kr times a constant input. Why?*

Speed control is preferred. Position based control tends to produce ***not so smooth trajectories****. Note however that speed can be estimated from position sensors.*

CAD/CAM and CNC Methodology CAD/CAM



Numbers (1)-(4) indicate the presentation order in this collection of slides. In the following we introduce (5).

CAD/CAM and CNC - **CNC Programming**

Summary of the previous slide:

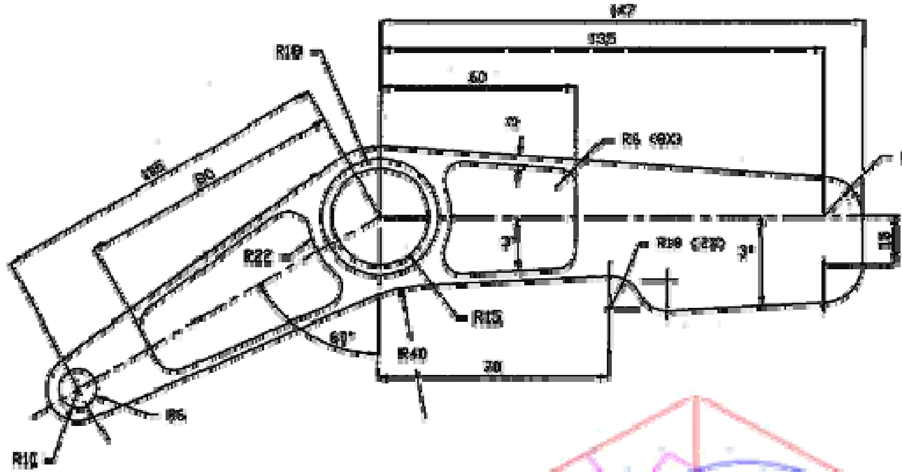
CNC machines know how to do **interpolation**, but not how to machine a complete part.

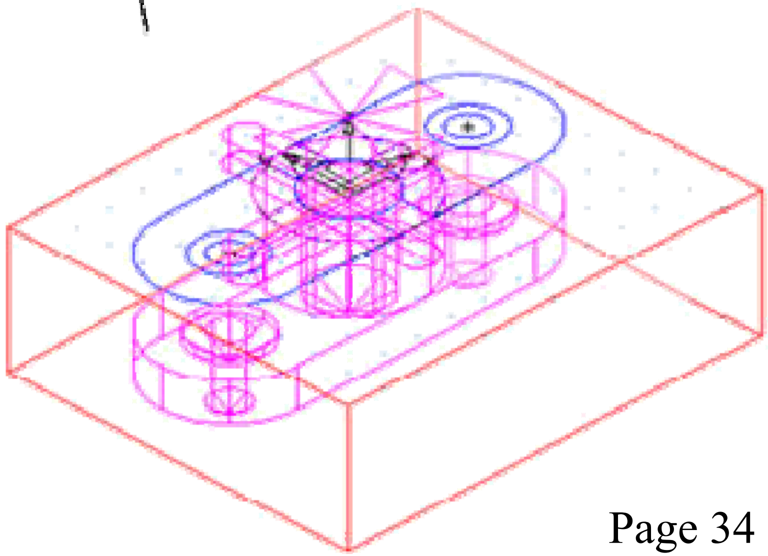
CAM helps to bridge the gap between **object shapes** and making **material removal trajectories** (to be interpolated).

In other words, one needs to do **CNC programming**.

Steps 1, 2, ... 6, to execute a part

1. Read and **interpret** the technical drawings





In the following: **G-code** (also RS-274), which has many variants, is the common name for the most widely used numerical control (NC) programming language.

CAD/CAM and CNC - CNC Programming

2. Choose the most adequate **machine** for the several stages of machining

Relevant features:

- The workspace of a machine versus the part to be produced
- The options available on each machine
- The tools that can be used
- The mounting and the part handling
- The operations that each machine can perform

3. Choose of the most adequate **tools**

Relevant features:

- The material to be machined and its characteristics
- Standard tools cost less
- The quality of the mounting part is function of the number of parts to produce
- Use the right tool for the job
- Verify if there are backup tools and/or stored available
- Take into account tool aging

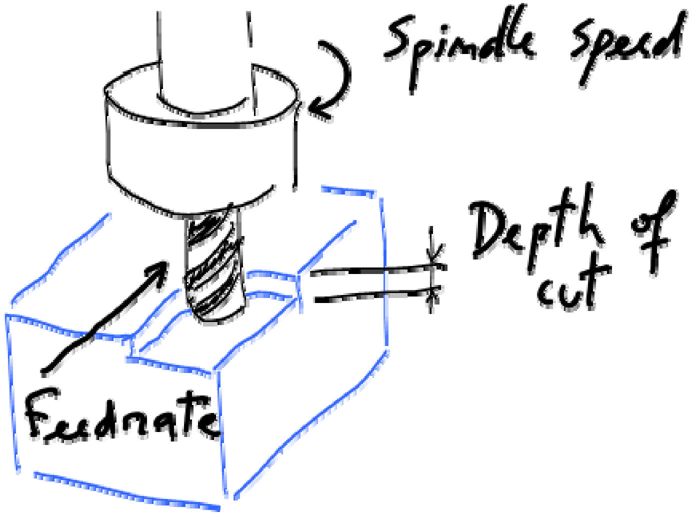
CAD/CAM and CNC - CNC Programming

4. Cutting data

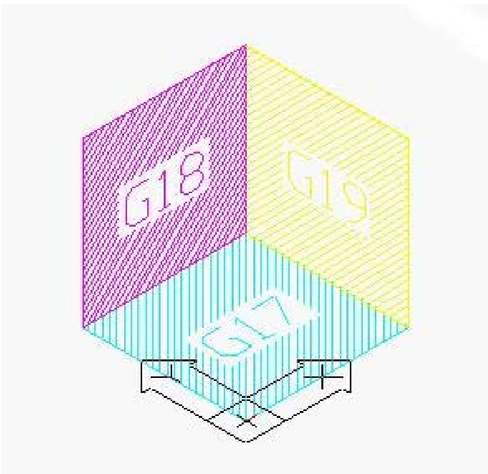
• Spindle Speed – speed of rotation of the cutting tool (rpm)

• Feedrate – linear velocity of advance to machine the part (mm/minute)

• Depth of Cut – depth of machining in z (mm)



5. Choice of the interpolation plane, in 2D ½ machines



5.1. Unit system
imperial / inches (G70) or
international millimeters (G71).

5.2. Command mode*
Absolute = use world coordinate system (G90)
Relative = move w.r.t. the current position (G91)

* There are other command modes, e.g. helicoidal.

CAD/CAM and CNC - CNC Programming

6. Data Input

N	Sequence Number
G	Preparatory Functions
X	X Axis Command
Y	Y Axis Command
Z	Z Axis Command
R	Radius from specified center
A	Angle ccw from +X vector
I	X axis arc center offset
J	Y axis arc center offset
K	Z axis arc center offset
F	Feed rate
S	Spindle speed
T	Tool number
M	Miscellaneous function

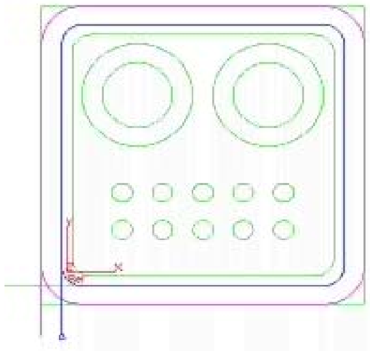
Example of a CNC program:

```
N30 G0 T1 M6
N35 S2037 M3
N40 G0 G2 X6.32 Y-0.9267 M8
N45 Z1.1
N50 Z0.12
N55 G1 Z0. F91.7
N60 X-2.82
N65 Y0.9467
N70 X6.32
N75 Y2.82
N80 X-2.82
N85 G0 Z1.1
...
```

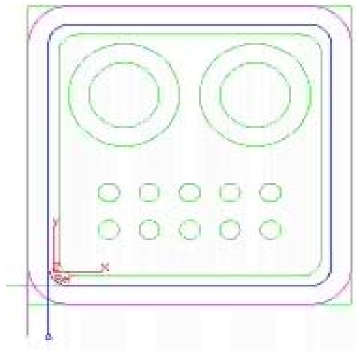
CAD/CAM and CNC - CNC Programming

Preparatory functions (inc.)

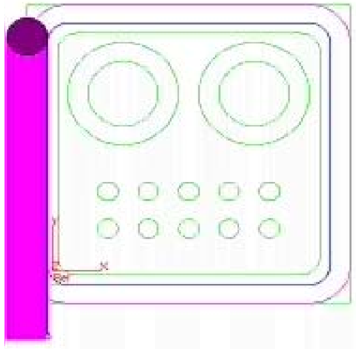
G00 – GO



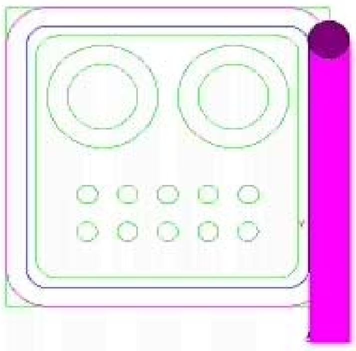
G01 – Linear Interpolation



G02 – Circular Interpolation (CW)



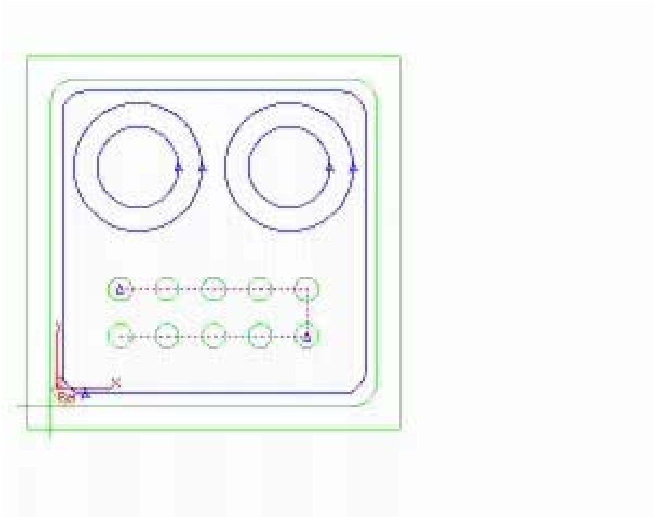
G03 – Circular Interpolation (CCW)



CAD/CAM and CNC - CNC Programming

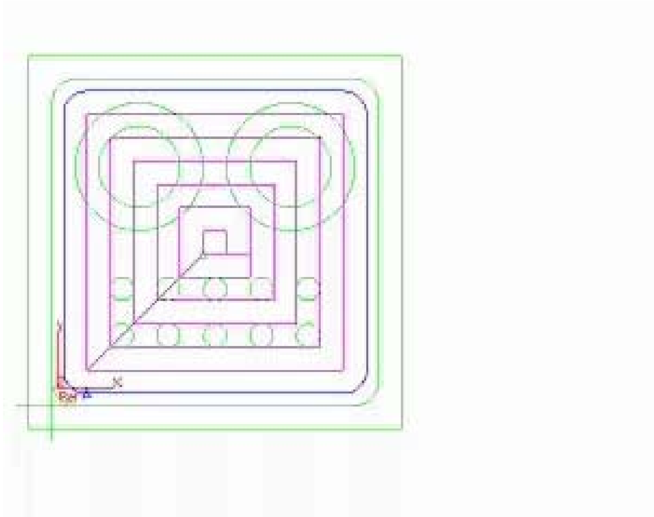
Canned Cycles

G81 – Drilling cycle with multiple holes



Special Cycles or Canned Cycles

G78 – Rectangular pocket cycle, used to clean a square shaped area



CAD/CAM and CNC - CNC Programming

Other preparatory functions

G04 - A temporary dwell, or **delay** in tool motion.
G05 - A permanent hold, or **stopping** of tool motion. It is canceled by the machine operator.
G22 - Activation of the stored **axis travel limits**, which are used to establish a safety boundary.
G23 - Deactivation of the stored axis travel limits.
G27 - Return to the machine **home** position via a programmed intermediate point
G34 - Thread cutting with an increasing lead.
G35 - Thread cutting with a decreasing lead.
G40 - Cancellation of any previously programmed tool radius compensation
G42 - Application of cutter radius compensation to the right of the workpiece with respect to the direction of tool travel.
G43 - Activation of tool length compensation in the same direction of the offset value
G71 - Canned cycle for multiple-pass turning on a lathe (foreign-made)
…

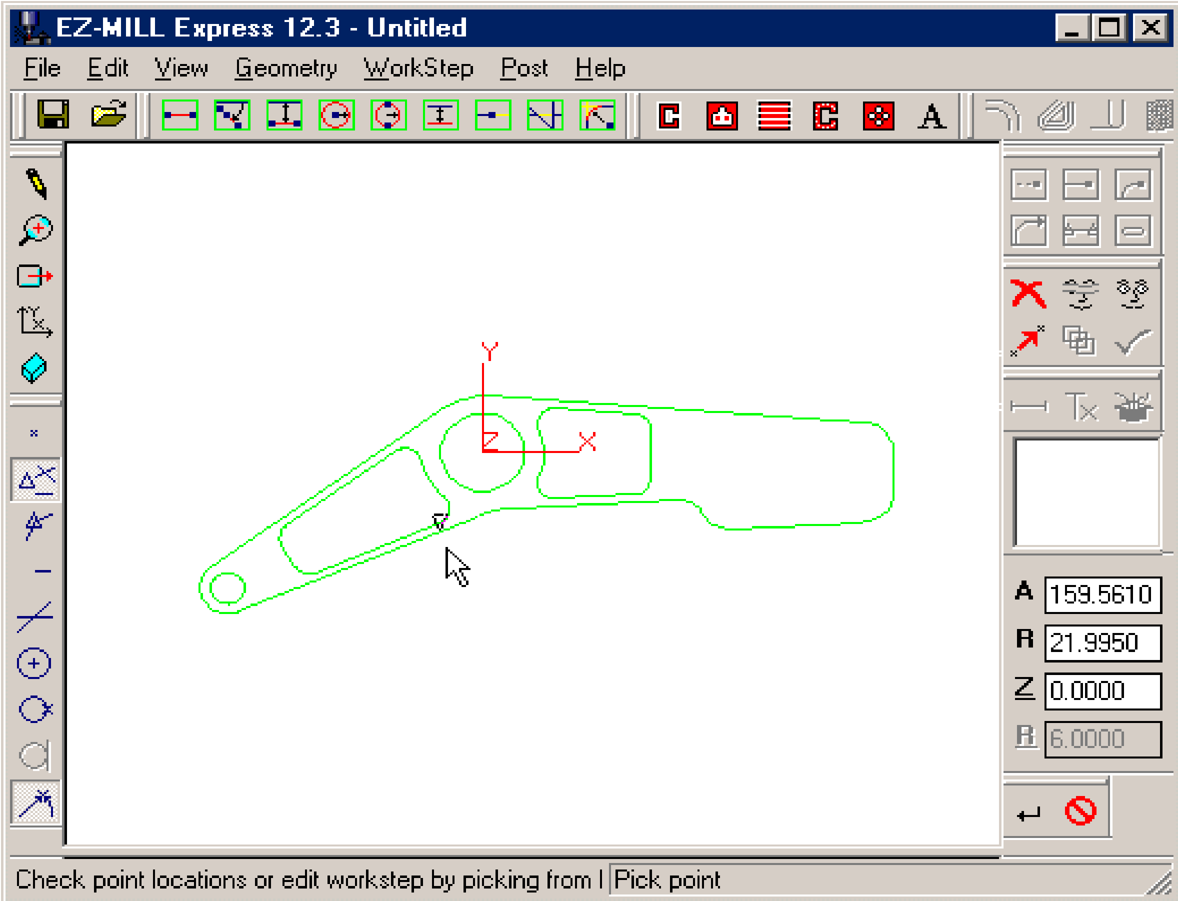
Miscellaneous functions

M02 - Program end
M03 - Start of **spindle rotation clockwise**
M04 - Start of spindle rotation counterclockwise
M07 - Start of **mist coolant** (spray)
M08 - Start of **flood coolant** (e.g. oil)

CAD/CAM and CNC

Examples of CNC programming

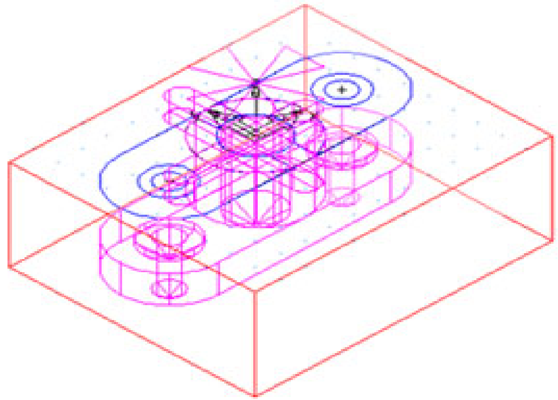
See http://ezcam.com/ez-show/

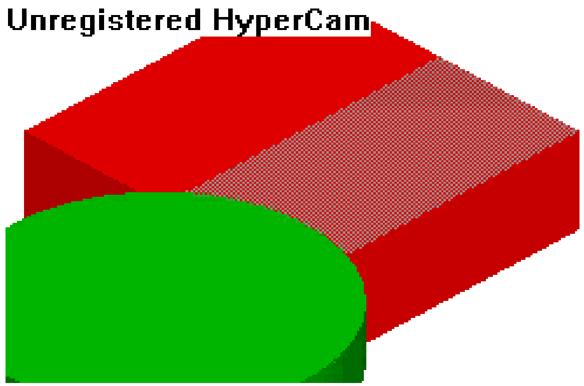


CAD/CAM and CNC - CNC Programming

Example of a CNC program

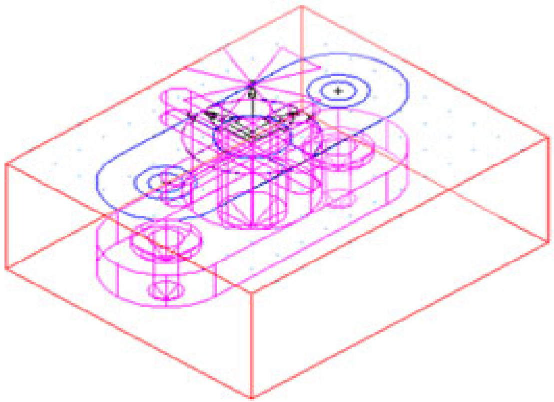
```
N30 G0 T1 M6
N35 S2037 M3
N40 G0 G2 X6.32 Y-0.9267 M8
N45 Z1.1
N50 Z0.12
N55 G1 Z0. F91.7
N60 X-2.82
N65 Y0.9467
N70 X6.32
N75 Y2.82
N80 X-2.82
N85 G0 Z1.1
...
```





CAD/CAM and CNC

Example of CNC programming



CAD/CAM and CNC

Tool change

Tools are usually of easy access when the machines need the tools to be changed manually.

Most recent systems have an automated toolbox that allows tool selection without the need for human intervention.

CAD/CAM and CNC

Advanced CNC programming languages

• Automatically Program Tool (APT), developed at MIT in 1954
• Derived from APT: ADAPT (IBM), IFAPT (France), MINIAPT (Germany)
• More refrences: Compact II, Autospot, SPLIT

Current trend in interpolation

Modern CAD systems have progressively gained the capability to describe a wide variety of complex shaped parts (like dies and molds) through parametric curves or surfaces like the Bezier, B-Spline or ***Non-Uniform Rational B-Spline (NURBS)****. (...) NURBS is one curve interpolator that draws considerable attention owing to the fact that NURBS offers a universal mathematical form for representing both analytical and free-form shapes [9]. In fact, most commercial CNC controller manufacturers (such as* ***Fanuc*** *[15] and* ***Siemens*** *[16]) incorporate such interpolation capabilities to their high-end CNC products.*

In "Direct command generation for CNC machinery based on data compression techniques", U. Yaman, M. Dolen, Robotics and Computer-Integrated Manufacturing 29 (2013) 344–356

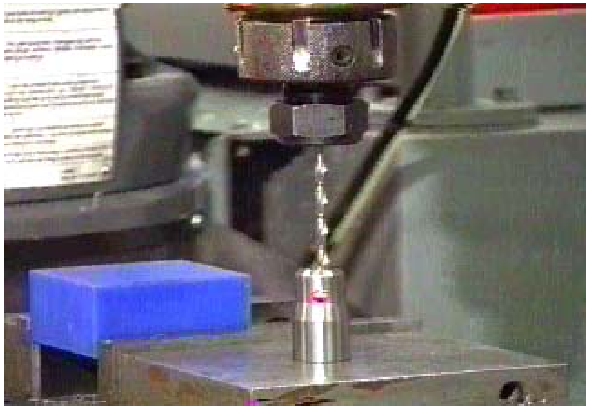
CAD/CAM and CNC Machine operation

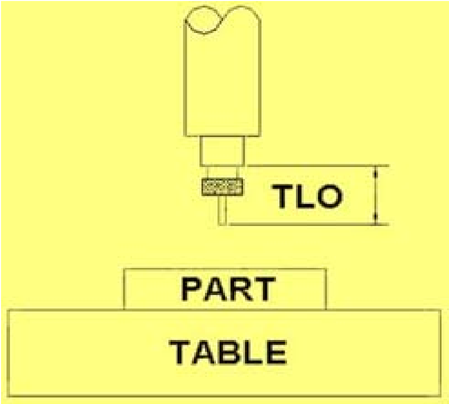
Rules of security

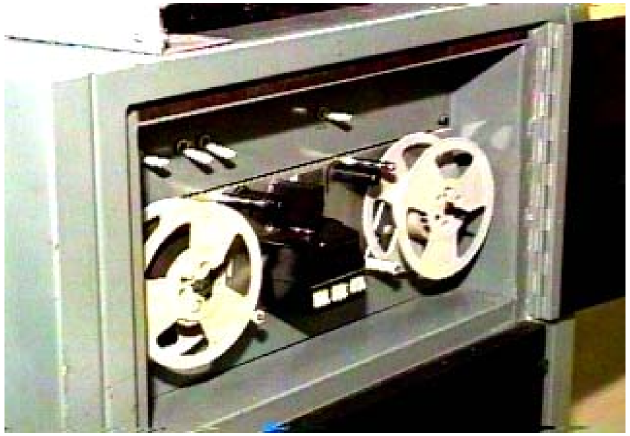
- Security is not facultative
- The eyes must be always protected.
- The tools and parts must be handled and installed properly.
- Avoid the use of large cloths
- Clean the parts with a brush, never with the hands.
- Be careful with you and the others.

Operation rules

Verify tolerances and tools offsets for proper operation







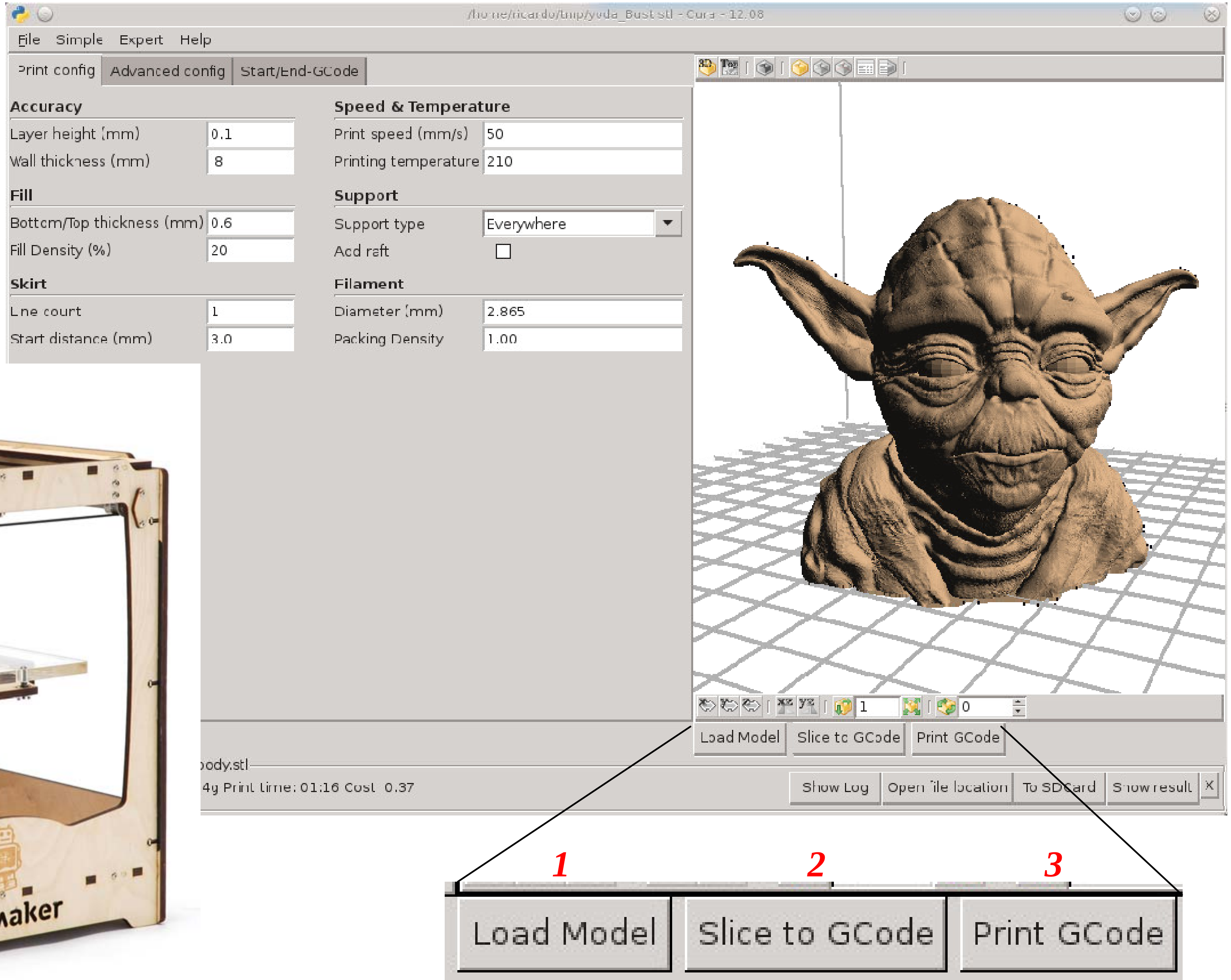
Load program
Follow up machine operation
Verify carefully the produced part.

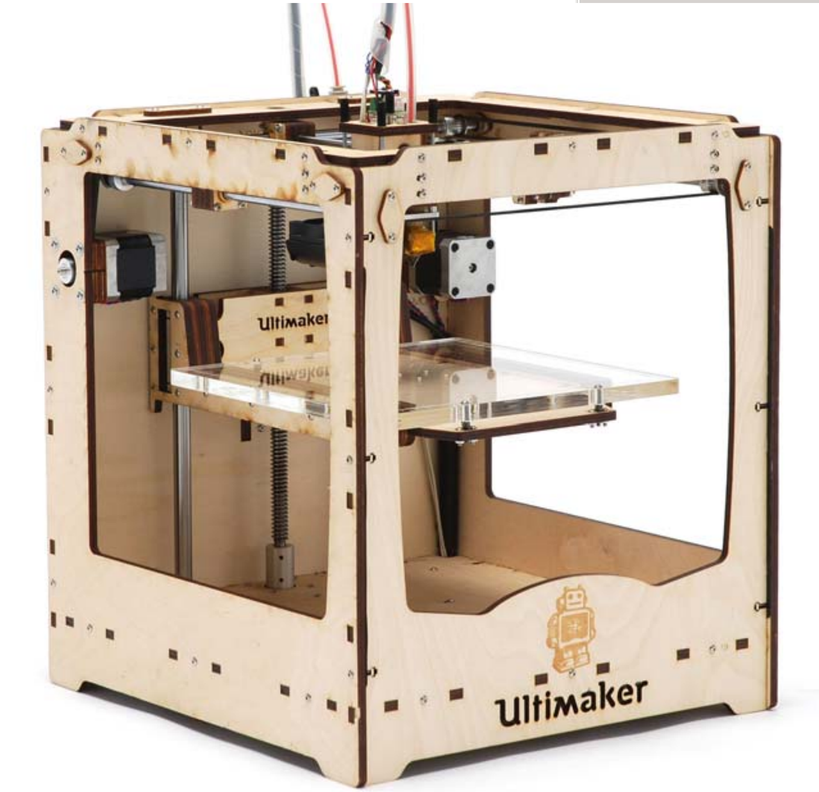
CAD/CAM and CNC at home!

http://daid.github.com/Cura/

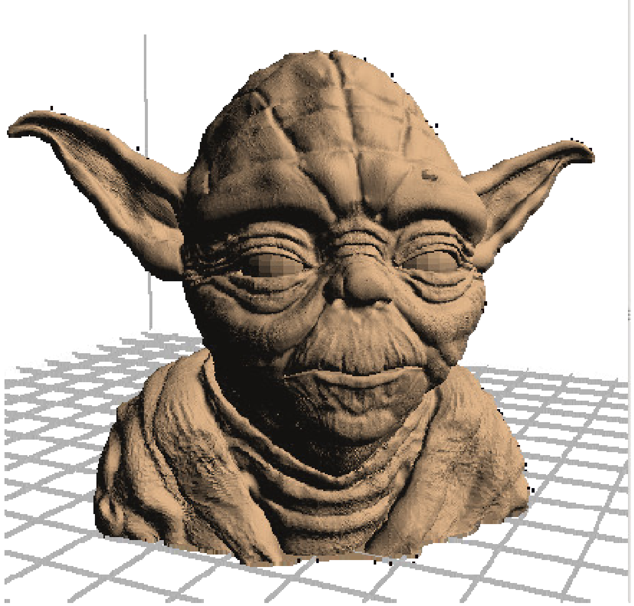
Order in the internet, receive by mail and assemble yourself!

http://www.ultimaker.com/





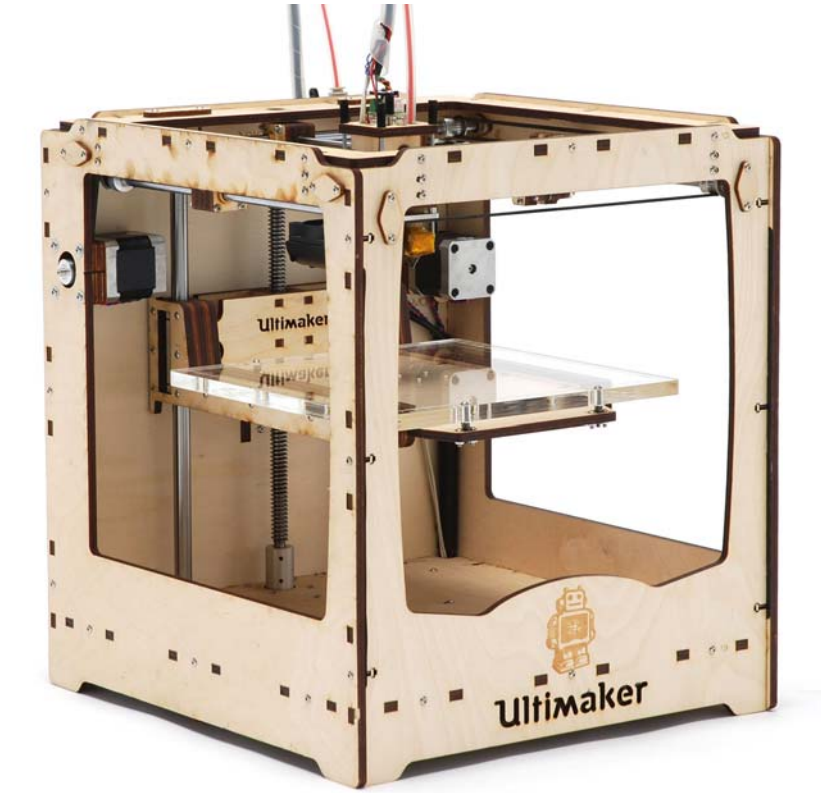
CAD/CAM and CNC at home! - PC side, Slice to GCode

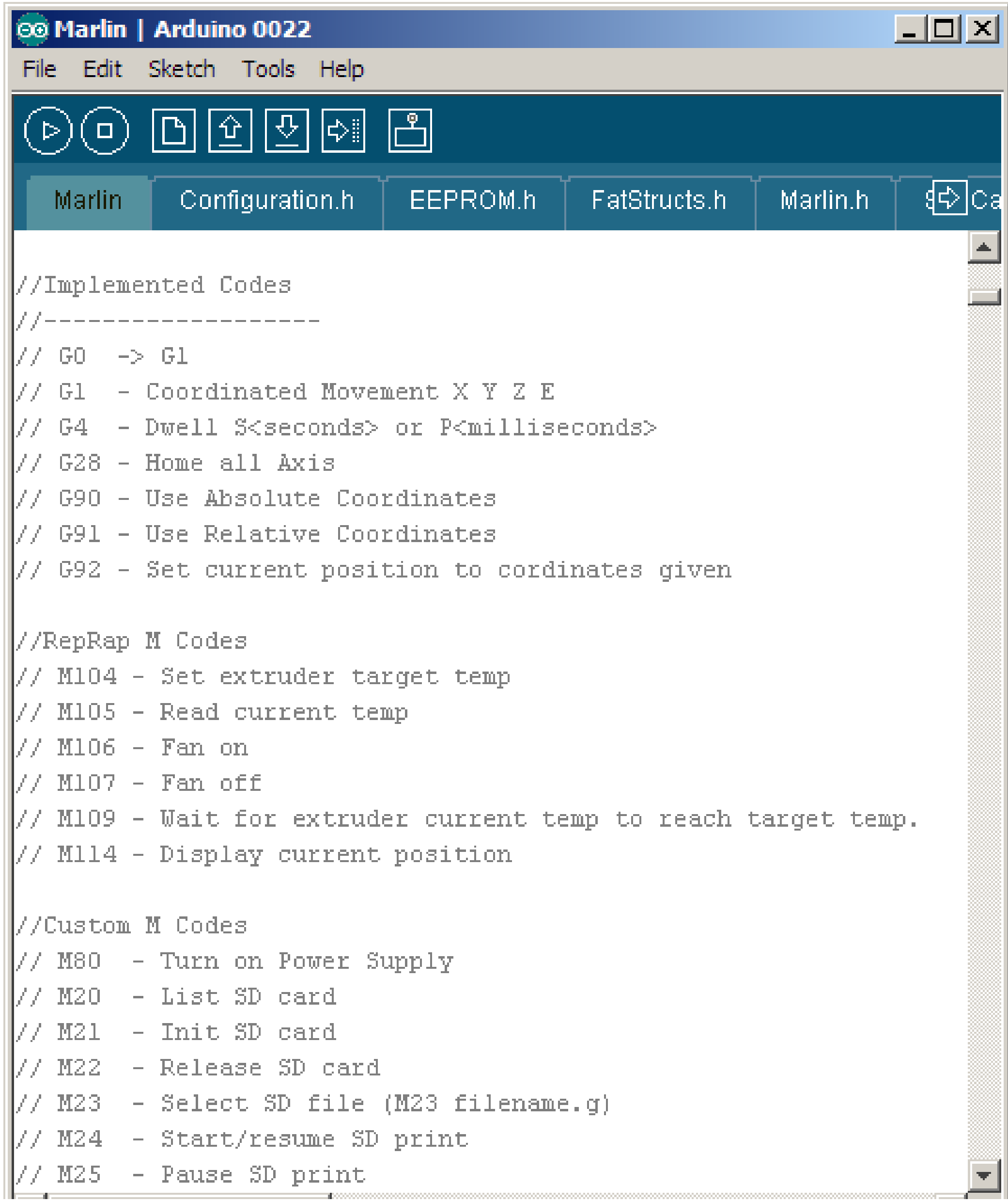


File generated on the PC side, *sliced GCode*, has many MBytes

```
;TYPE:CUSTOM
M92 E865.888000
M109 S210.000000
;Sliced /home/ricardo/tmp/dump_body.stl at: Sun 28 Oct 2012 22:20:23
;Basic settings: Layer height: 0.1 Walls: 0.8 Fill: 20
;Print time:     1:16
;Filament used:     1.10m     9.24g
;Filament cost:     0.37
G21         ;metric values
G90         ;absolute positioning
M107        ;start with the fan off
G28 X0 Y0   ;move X/Y to min endstops
G28 Z0      ;move Z to min endstops
G92 X0 Y0 Z0 E0         ;reset software position to front/left/z=0.0
G1 Z15.0 F180
G92 E0                  ;zero the extruded length
G1 F200 E3
G92 E0                  ;zero the extruded length again
;G1 X100 Y100 F9000
G1 F9000
;LAYER:0
;TYPE:SKIRT
G1 X74.244 Y116.715 Z0.3 F9000.0
G1 F4200.0
G1 E4.525
G1 F9000.0
G1 X75.623 Y120.052 Z0.3 F1200.0 E4.5922
G1 X113.604 Y120.572 E5.2993
```

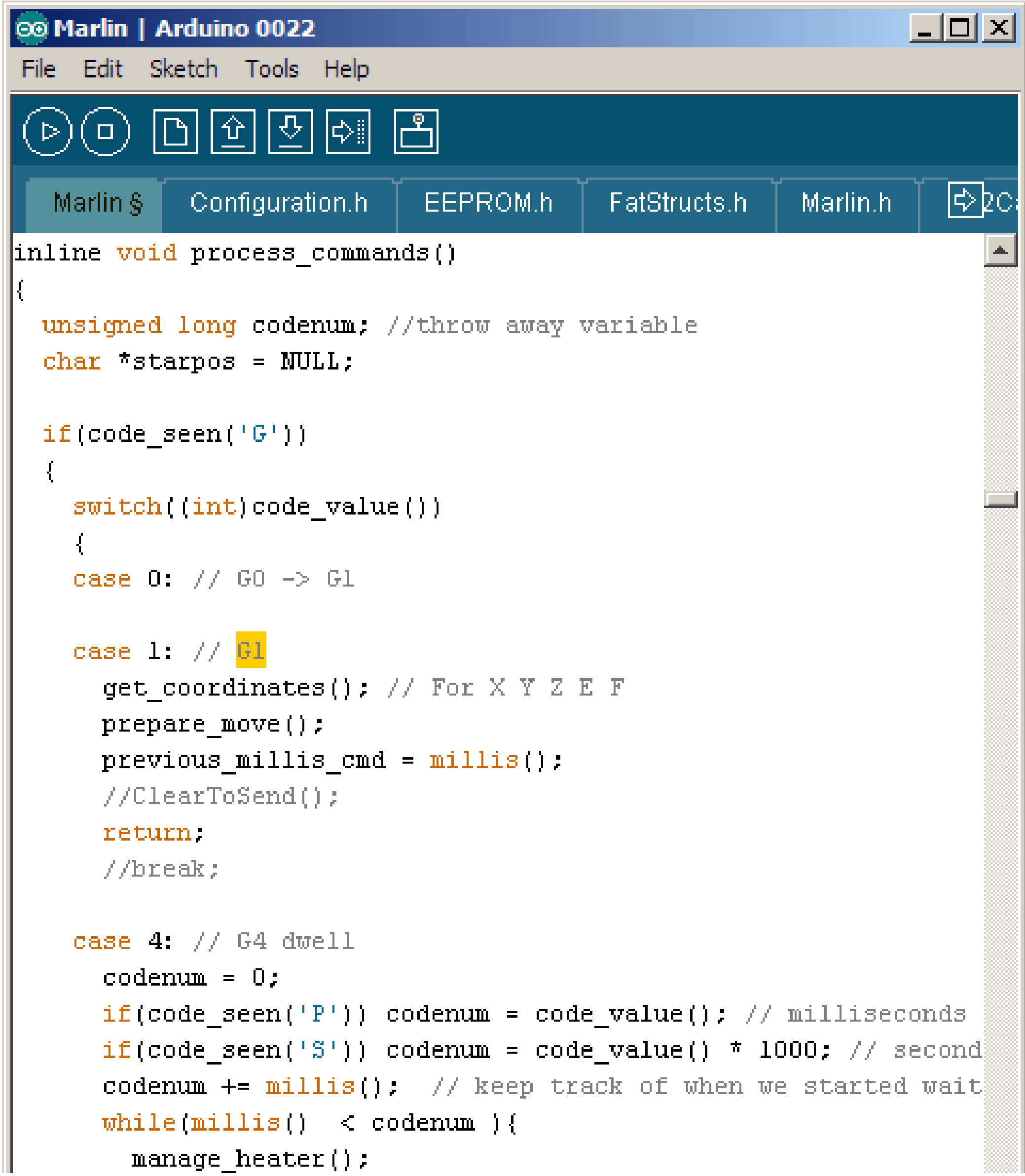
CAD/CAM and CNC at home! - Machine side, GCode interpreter





https://github.com/bkubicek/Marlin
http://wiki.ultimaker.com/How_to_upload_new_firmware_to_the_motherboard

CAD/CAM and CNC at home! - Machine side, GCode interpreter



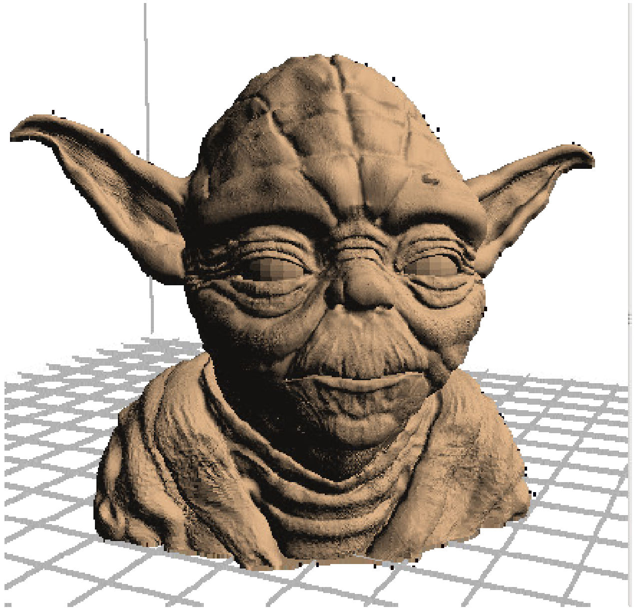
CAD/CAM and CNC at home! - Machine side, GCode interpreter

```
void prepare_move()
{
  plan_buffer_line(destination[X_AXIS], destination[Y_AXIS],
    destination[Z_AXIS], destination[E_AXIS],
    feedrate*feedmultiply/60.0/100.);

  for(int i=0; i < NUM_AXIS; i++) {
    current_position[i] = destination[i];
  }
}
```

```
void plan_buffer_line(float x, float y, float z, float e, floa
// Add a new linear movement to the buffer.
// steps_x, _y and _z is the absolute position in mm.
// Microseconds specify how many microseconds the move should
// calculation the caller must also provide the physical lengt

  // Calculate the buffer head after we push this byte
  int next_buffer_head = (block_buffer_head + 1) %BLOCK_BUFFER

  // If the buffer is full: good! That means we are well ahead
  // Rest here until there is room in the buffer.
  while(block_buffer_tail == next_buffer_head) {
    manage_heater();
    manage_inactivity(1);
  }

  // The target position of the tool in absolute steps
  // Calculate target position in absolute steps
  long target[4];
  target[X_AXIS] = lround(x*axis_steps_per_unit[X_AXIS]);
  target[Y_AXIS] = lround(y*axis_steps_per_unit[Y_AXIS]);
  target[Z_AXIS] = lround(z*axis_steps_per_unit[Z_AXIS]);
```

```
ISR(TIMER1_COMPA_vect)
// "The Stepper Driver Interrupt" - This timer interrupt is the workhorse.
// It pops blocks from the block_buffer and executes them by pulsing the st
{
  if(busy){ /*Serial.println("BUSY")*/;
    return;
  } // The busy-flag is used to avoid reentering this interrupt

  busy = true;
  sei(); // Re enable interrupts (normally disabled while inside an interru
#ifdef ULTIPANEL
  static int breakdown=0;
        if((breakdown++)%100==0)
   buttons_check();
/* [ErikDeBruijn] Perhaps it would be nice to use a piece of code like this
      if(sdactive){
        sprintf("SD printing byte %i%",(int) (sdpos/filesize*100)); // perh
        Serial.print(sdpos);
        Serial.print("/");
        Serial.println(filesize);
      }
*/
#endif
```

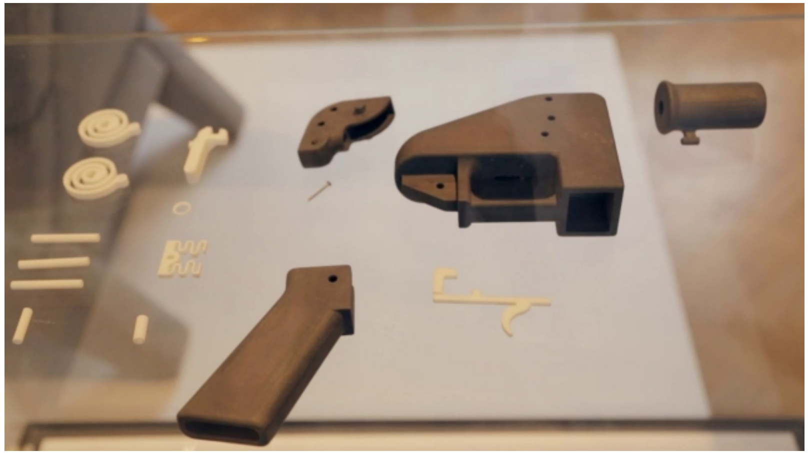
CAD/CAM and CNC at home!



CAD/CAM and CNC at home – a word of caution

3D-printed gun on display at V&A museum

By Sophie Curtis, The Telegraph, 17th Sep 2013



Victoria and Albert Museum (London), acquired, for display in their collection, the world's first 3D-printed gun, named "Liberator", developed and successfully fired by Texan law student Cody Wilson.

http://www.telegraph.co.uk/technology/news/10314763/3D-printed-gun-on-display-at-VandA-museum.html
http://www.dezeen.com/2013/09/26/movie-kieran-long-v-and-a-museum-london-3d-printed-gun/

UK police raise specter of 3-D printer-made guns

By Laura Smith-Spark, CNN, 25th Oct 2013

The U.S. State Department banned the inventor of a plastic handgun, "The Liberator," from distributing its instructions.
Police in England said Friday they have seized what could be the parts for Britain's first firearm made using 3-D printing -- but later said more testing is needed to establish if this is the case.

http://edition.cnn.com/2013/10/25/world/europe/uk-police-3d-printer-gun/