Industrial Automation

(Automação de Processos Industriais)

CAD/CAM and CNC

http://www.isr.tecnico.ulisboa.pt/~jag/courses/api20b/api2021.html

Prof. Paulo Jorge Oliveira, original slides
Prof. José Gaspar, rev. 2020/2021

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

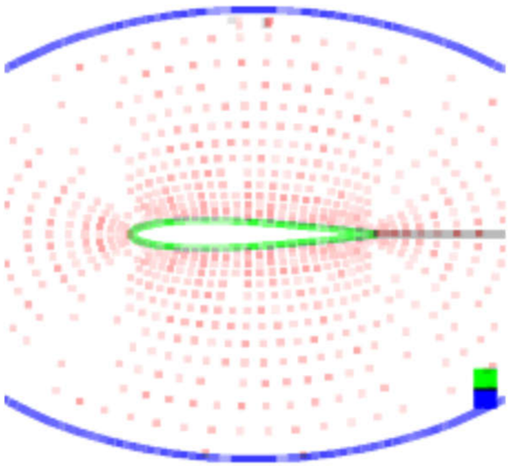
Editors (CAD):
http://www.cncezpro.com/
http://www.cadstd.com/
http://www.turbocad.com
http://www.deskam.com/
http://www.cadopia.com/

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

After the second world war, there were available large design & production facilities. Typically one had to wait a ***long time till a first prototype****:*

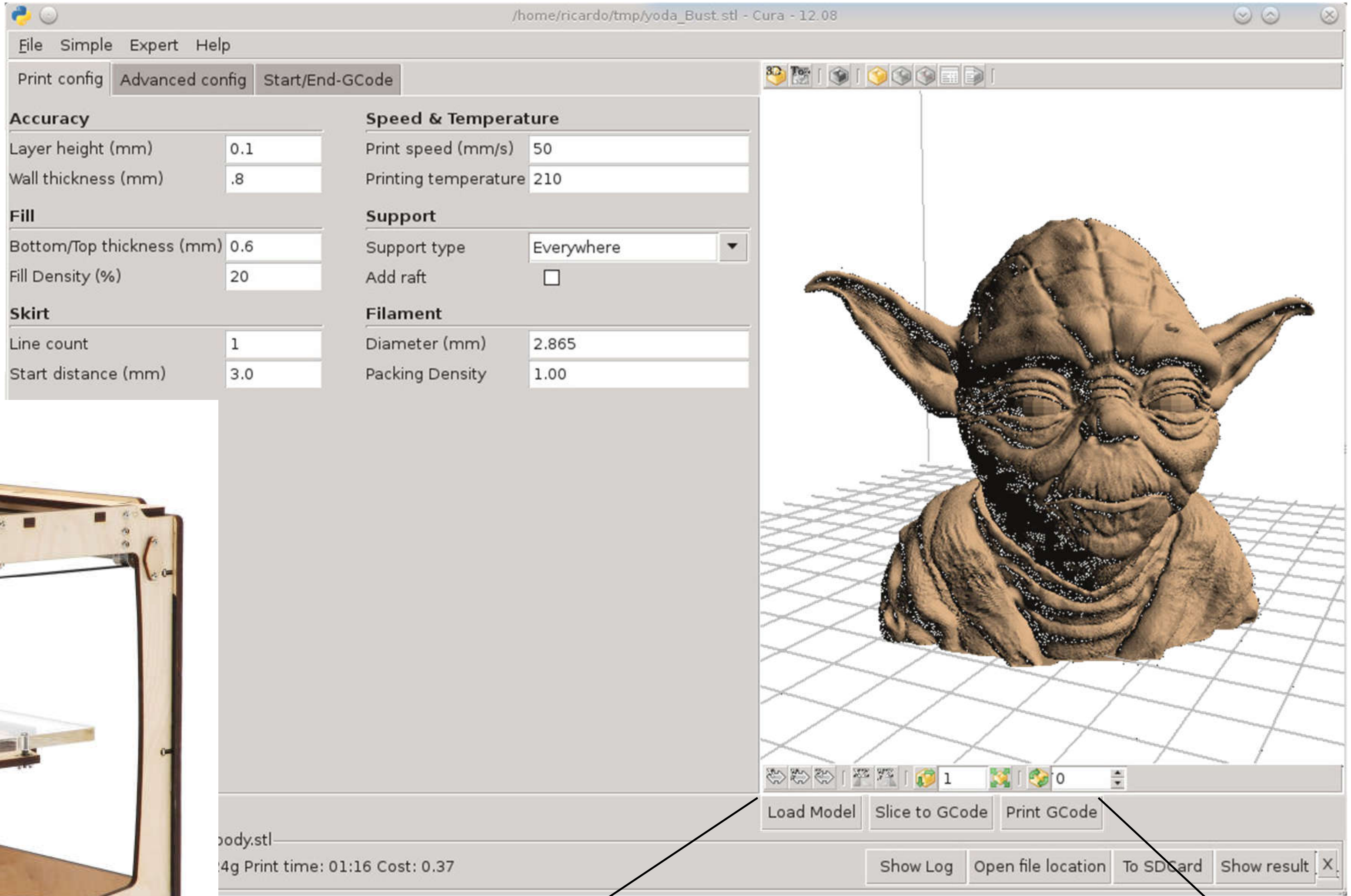


Concept → ***Tool / Methodology*** → ***Prototype***

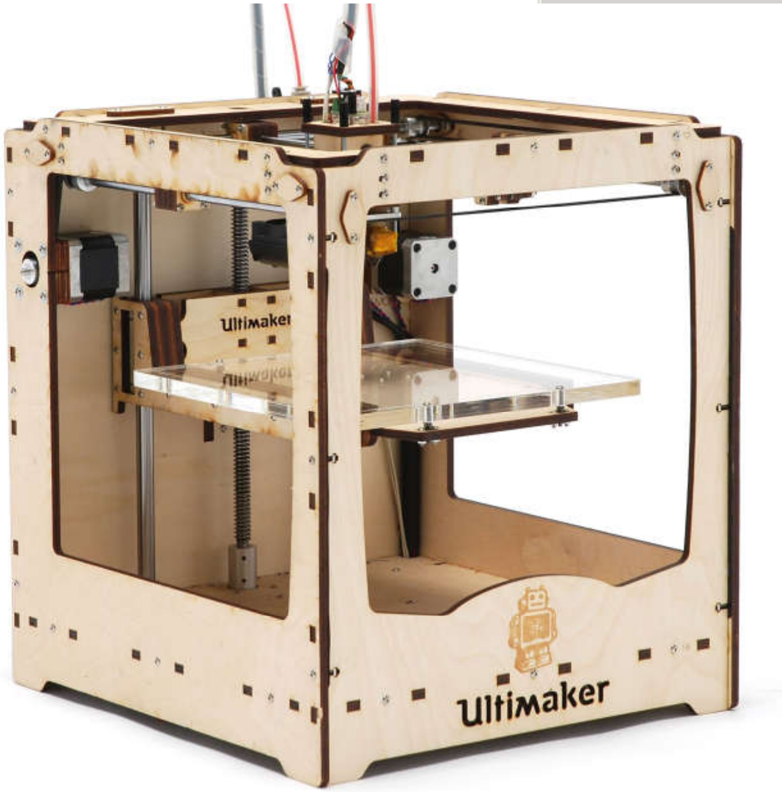
Nowadays, new tools: ubiquitous CAD/CAM and CNC. Main technological question? ***Integration.*** *Product development closely tied to the client: 1. concept 2. client consultation 3. prototype, repeat till satisfied client; make various, fast, low cost, prototypes upon* ***multiple consultations of the client****.*

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.

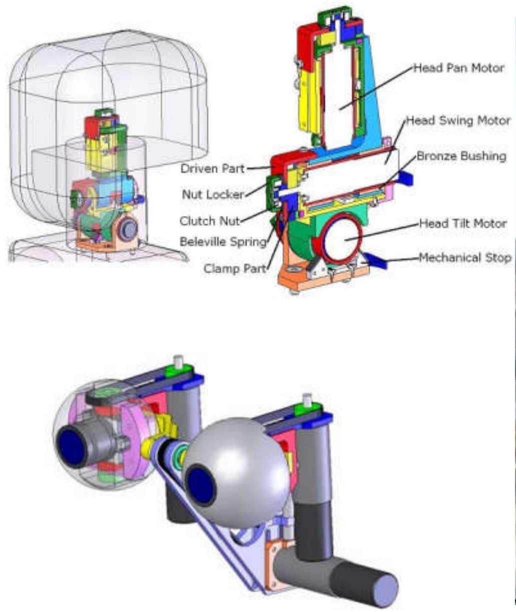
Resort to **CAD systems to design parts** and to manage the use of CNC machines.

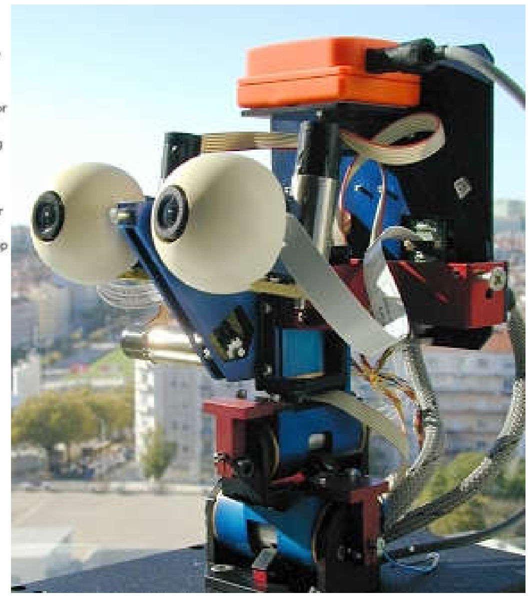
CAD/CAM and CNC

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***.

Computer Aided Design (CAD)

Allows the design in a computer environment.

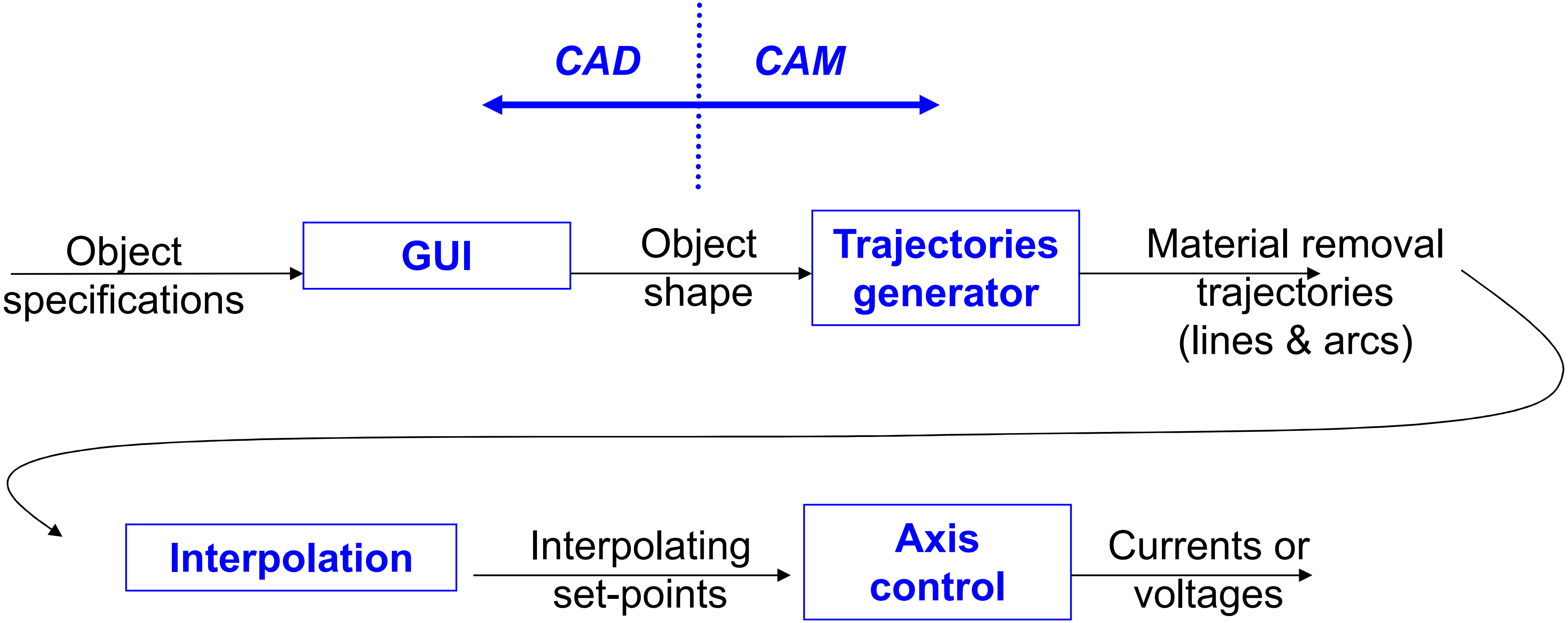
Ideas → Design

Computer Aided Manufacturing (CAM)

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.

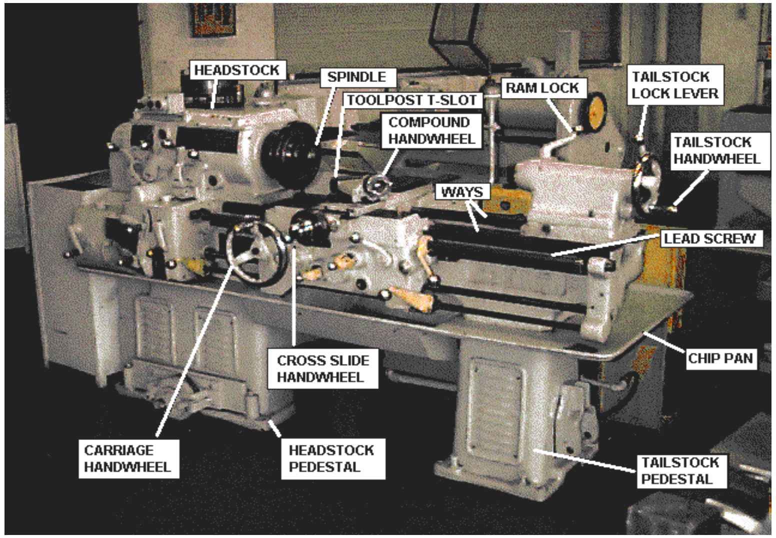
Advantages

- 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

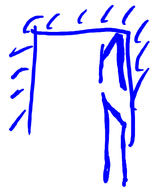
- High initial **investment** (30k€ to 1500k€)
- Specialized **maintenance** required
- Does not eliminate the human errors completely
- Requires more specialized **operators**
- Not so relevant the advantages on the production of small or very small series.

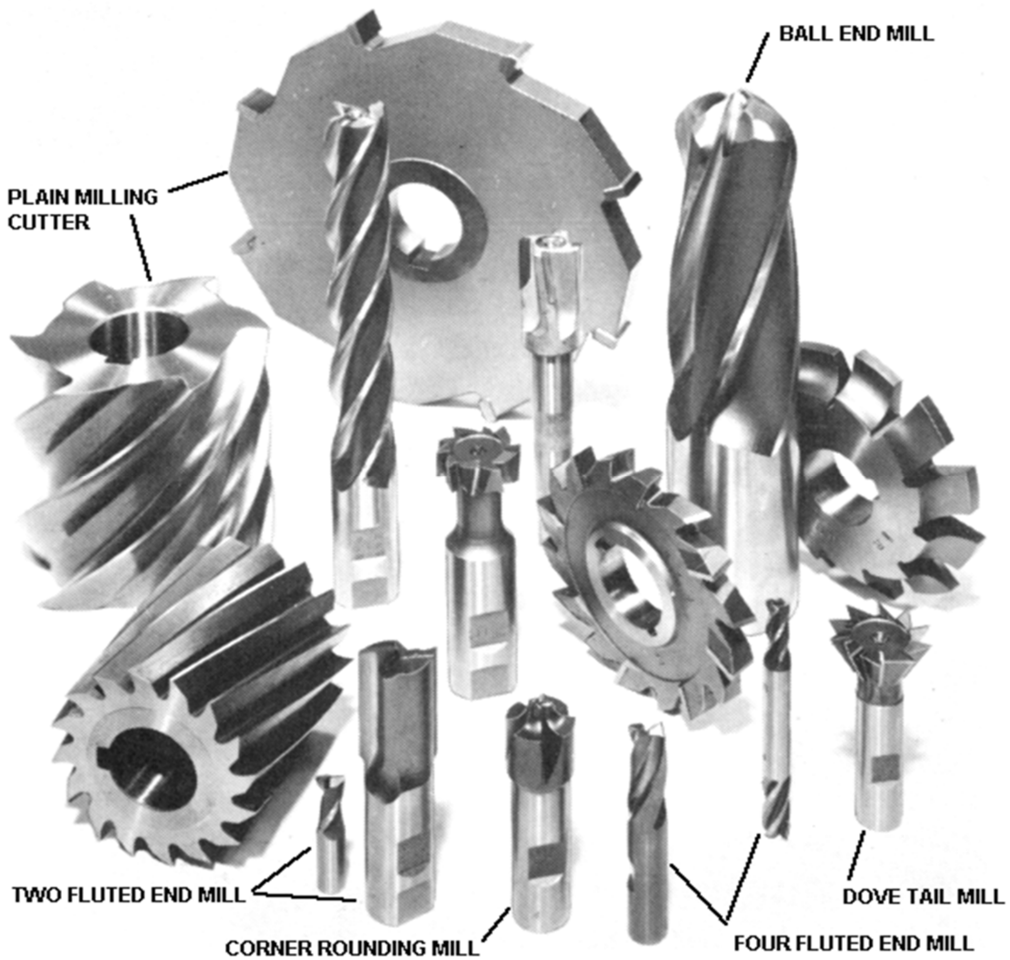
CAD/CAM and CNC **Tools**



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

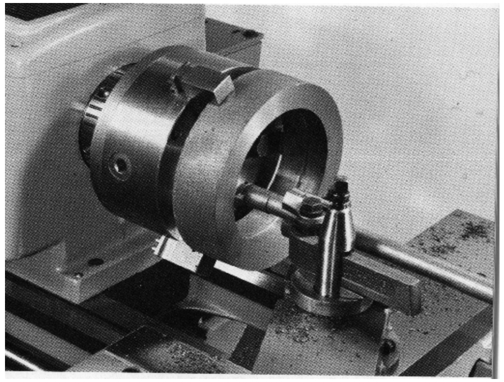
CAD/CAM and CNC **Tools :**

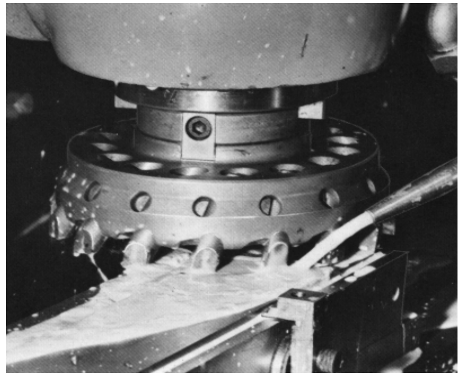


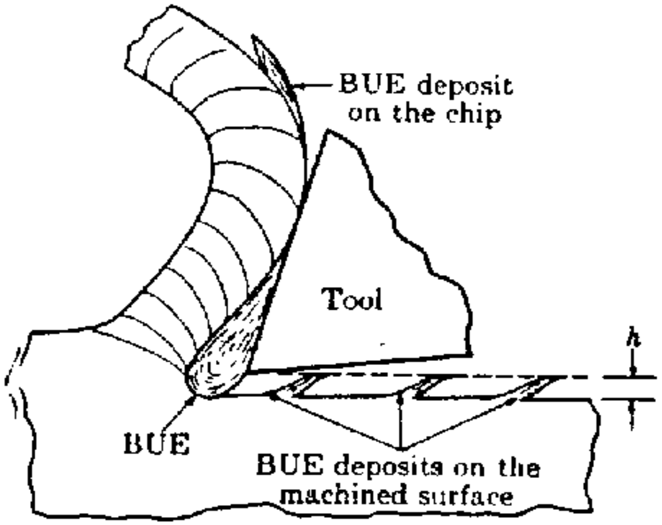


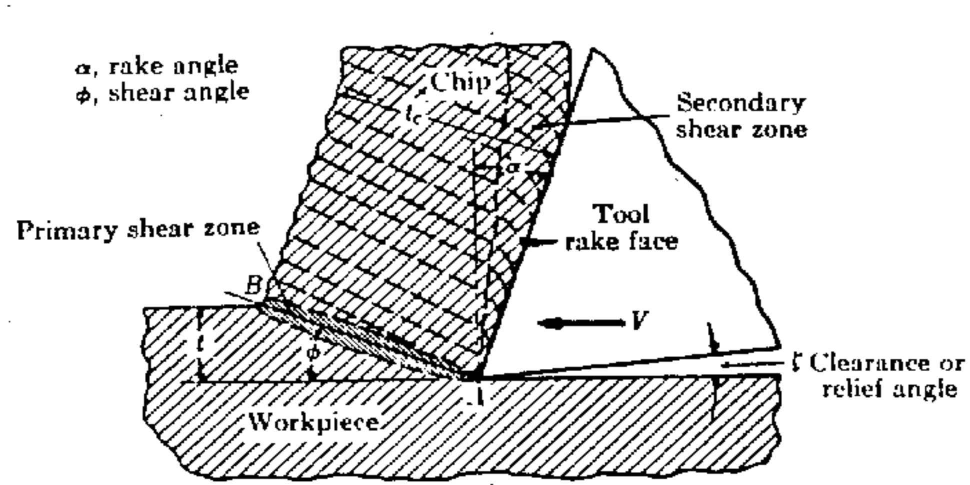
CAD/CAM and CNC **Tools :**

Attention to the constraints on the materials used ...





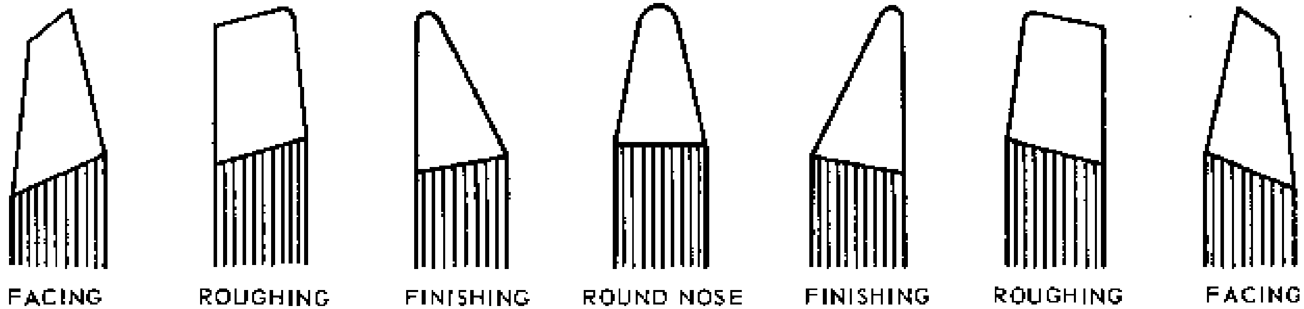




• Speed of advance • Speed of rotation • Type of tool

CAD/CAM and CNC

Tools :

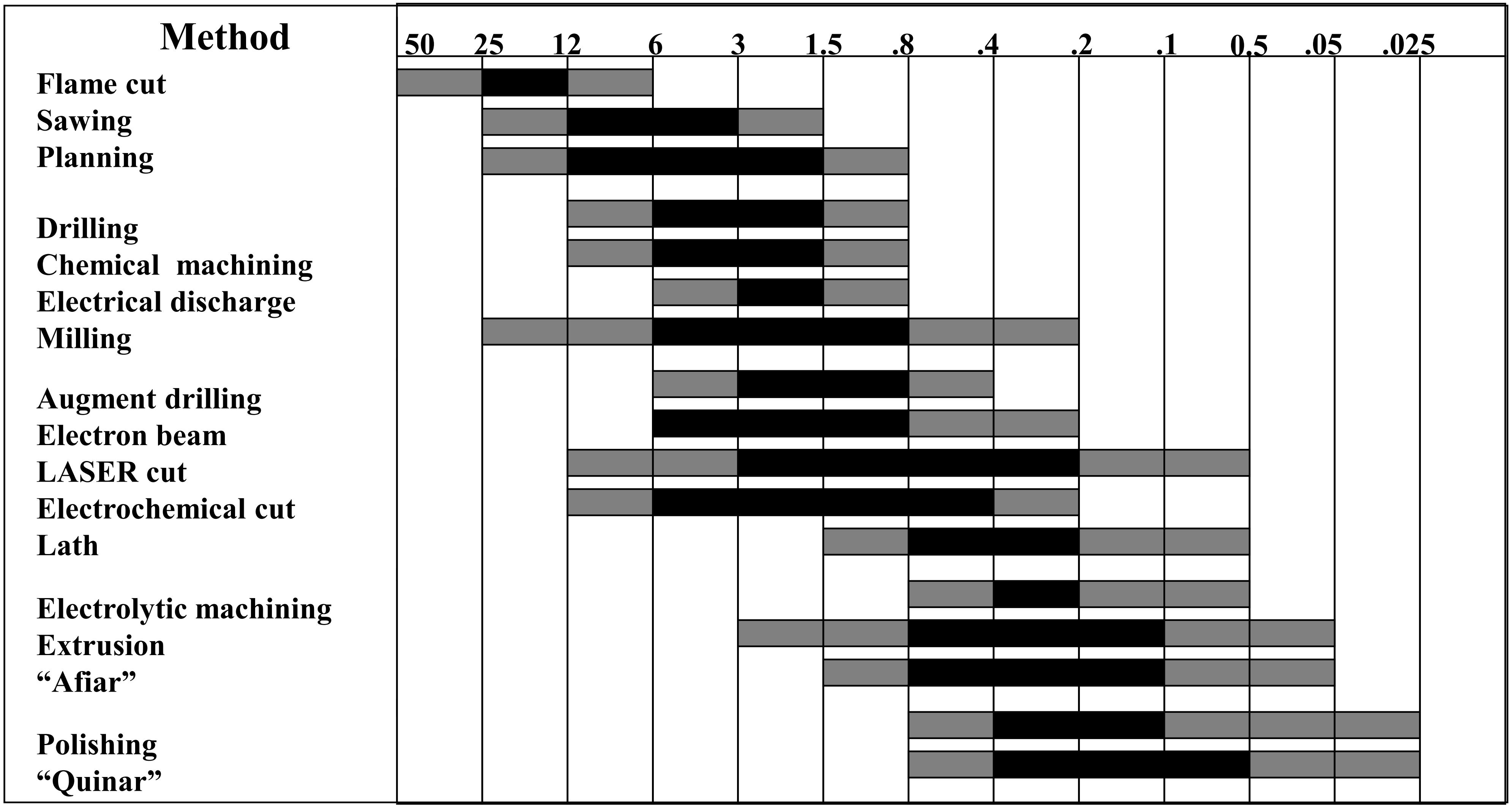


Specific tools to perform different operations.

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

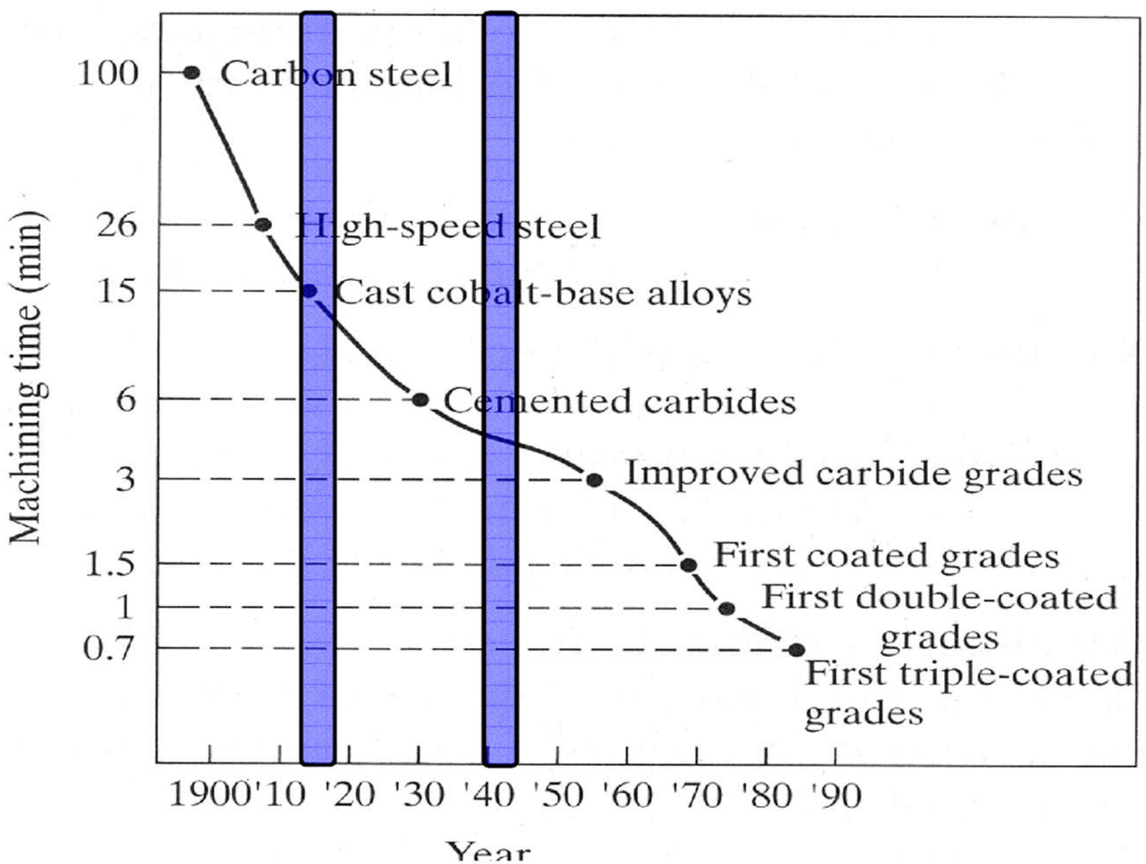
CAD/CAM and CNC

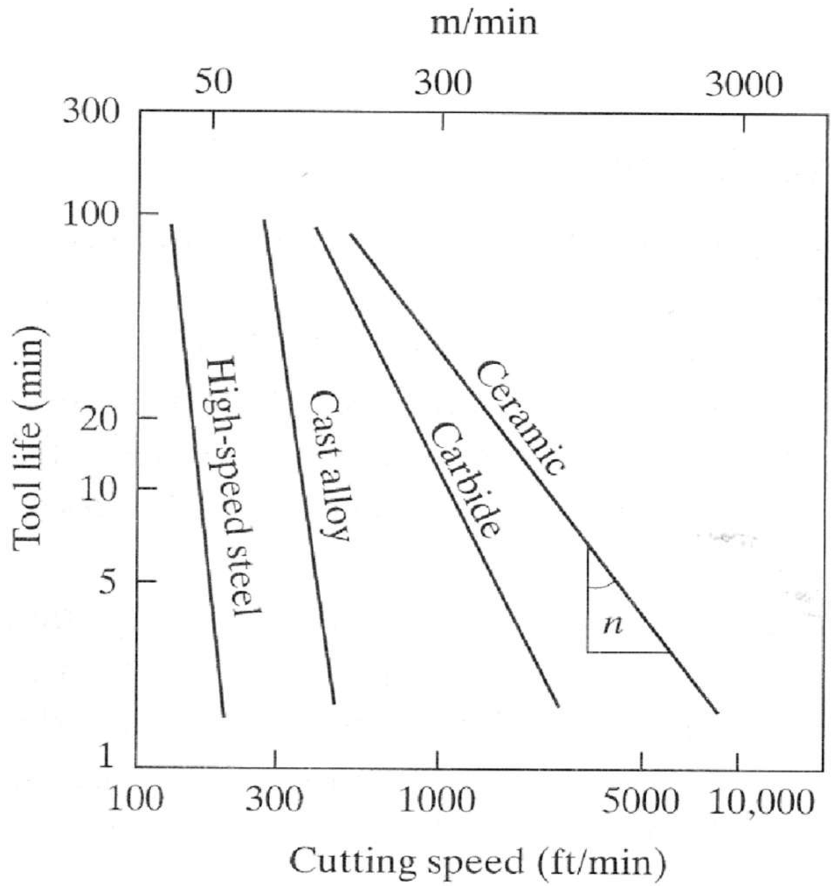
Tools: impact on the quality of finishing (μm)



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

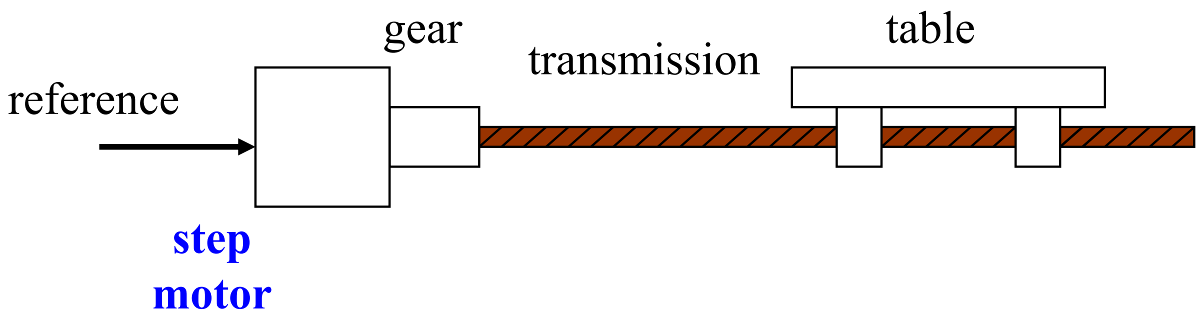
- Computer Numerical control (CNC)
  - A computer is on the core of each machine tool
  - Computation and interpolation algorithms run on the machine

- Distributive numerical control
  - Scheduling
  - Quality control
  - Remote monitoring

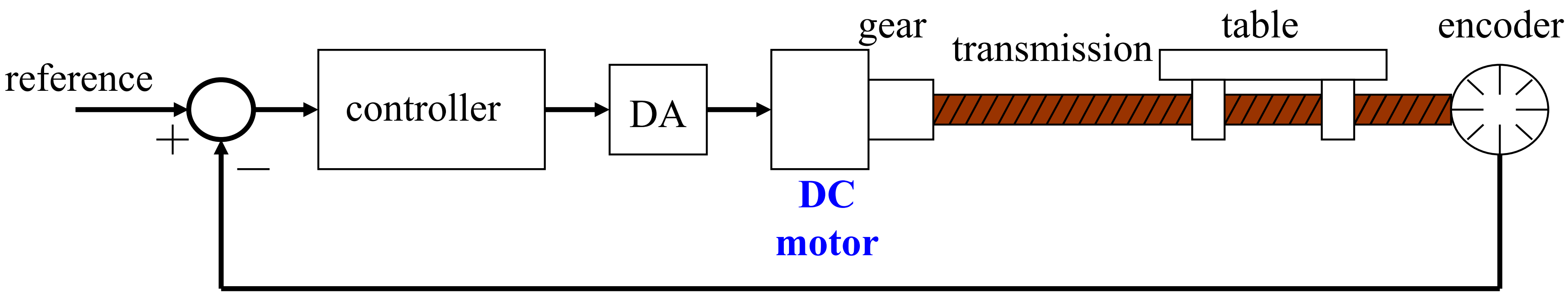
CAD/CAM and CNC **Numeric Control**

Architecture of a NC system: 1 axis

Open-loop

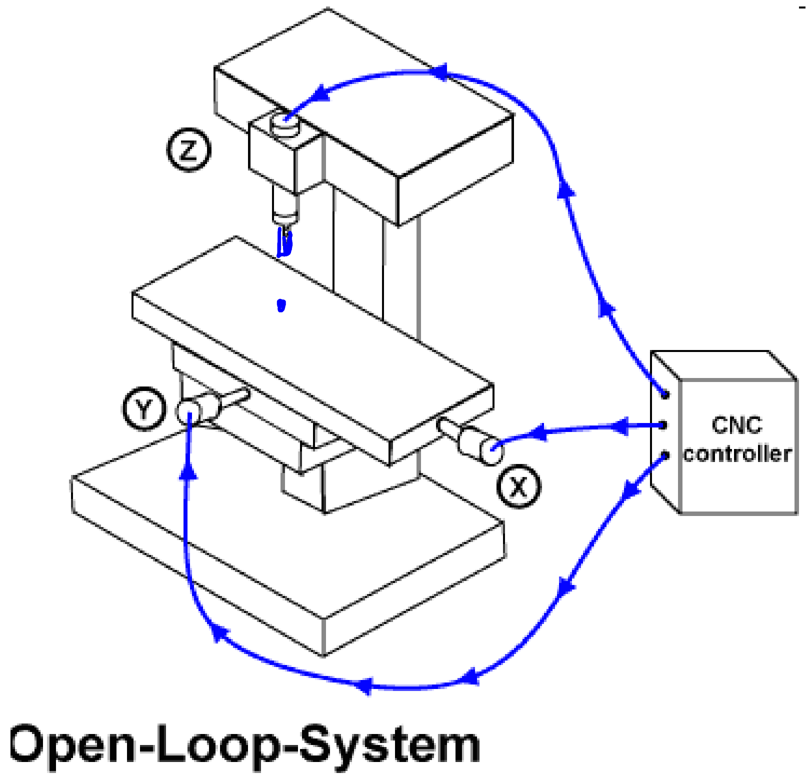


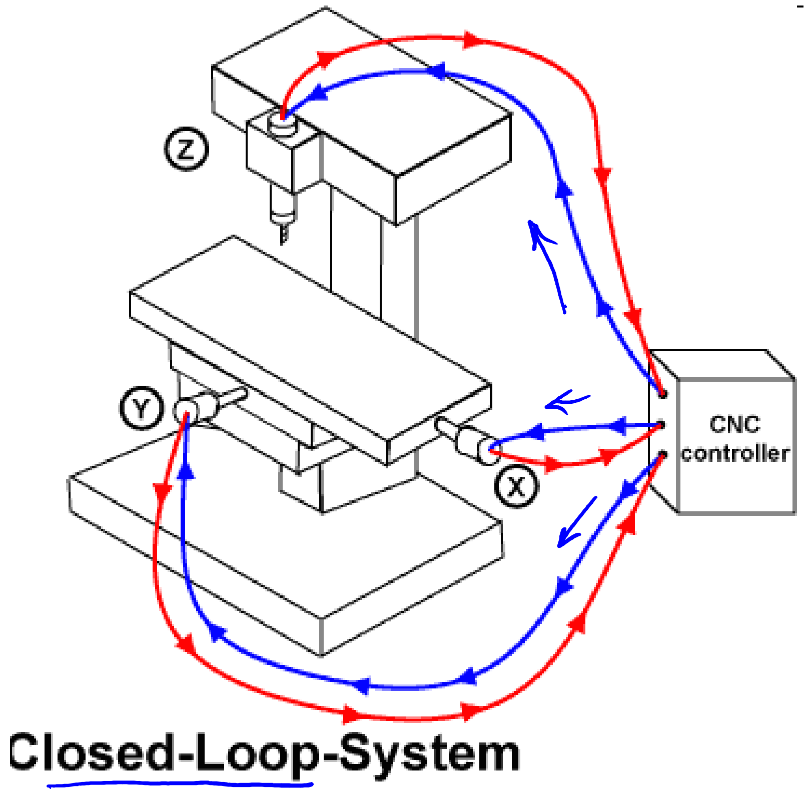
Closed-loop



CAD/CAM and CNC **Numeric Control**

Architecture of a NC system: 3 axis

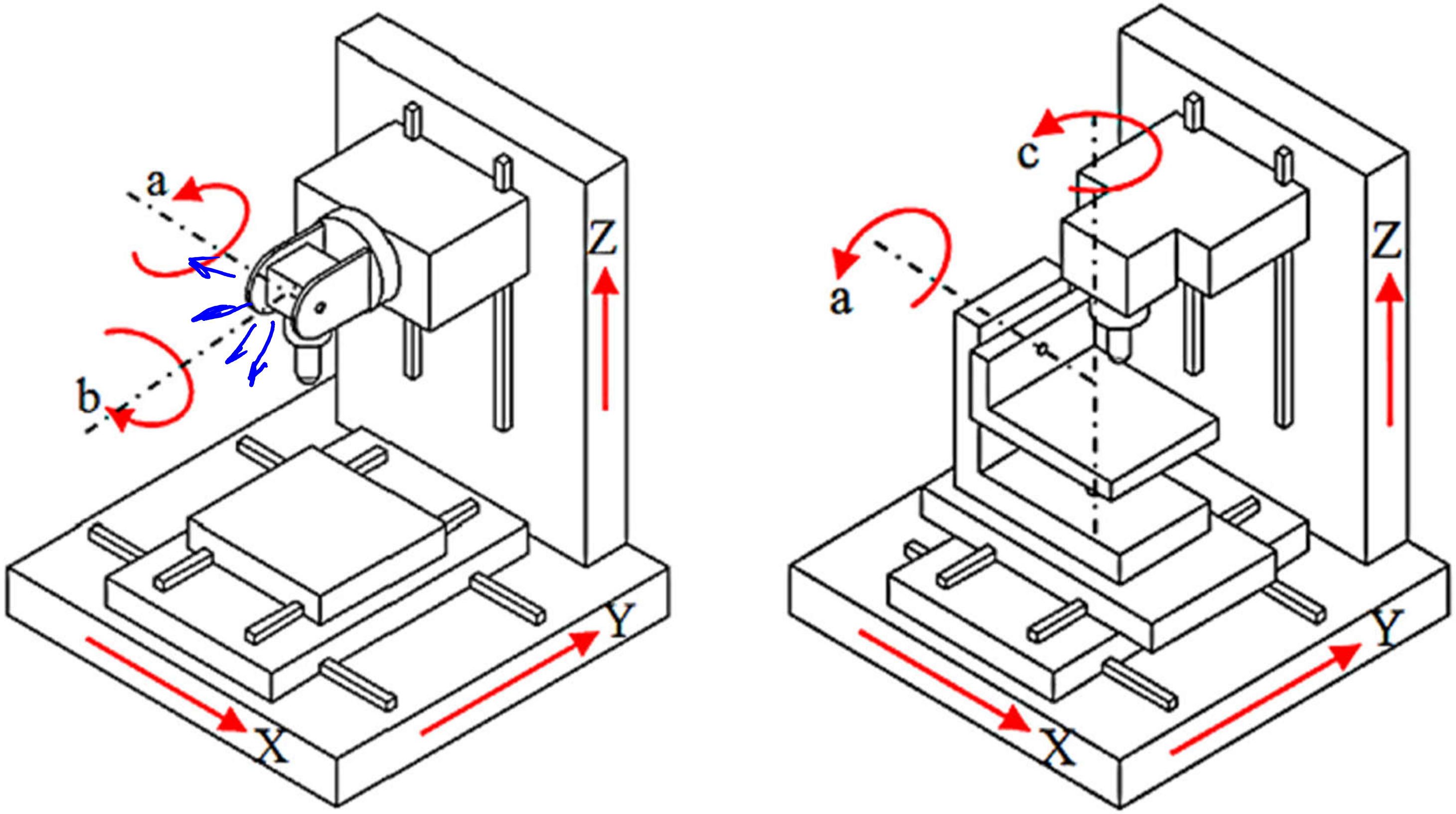




[http://www.kanabco.com/vms/cnc_control/cnc_control_03.html]

CAD/CAM and CNC **Numeric Control**

Architecture of a NC system: 5 axis

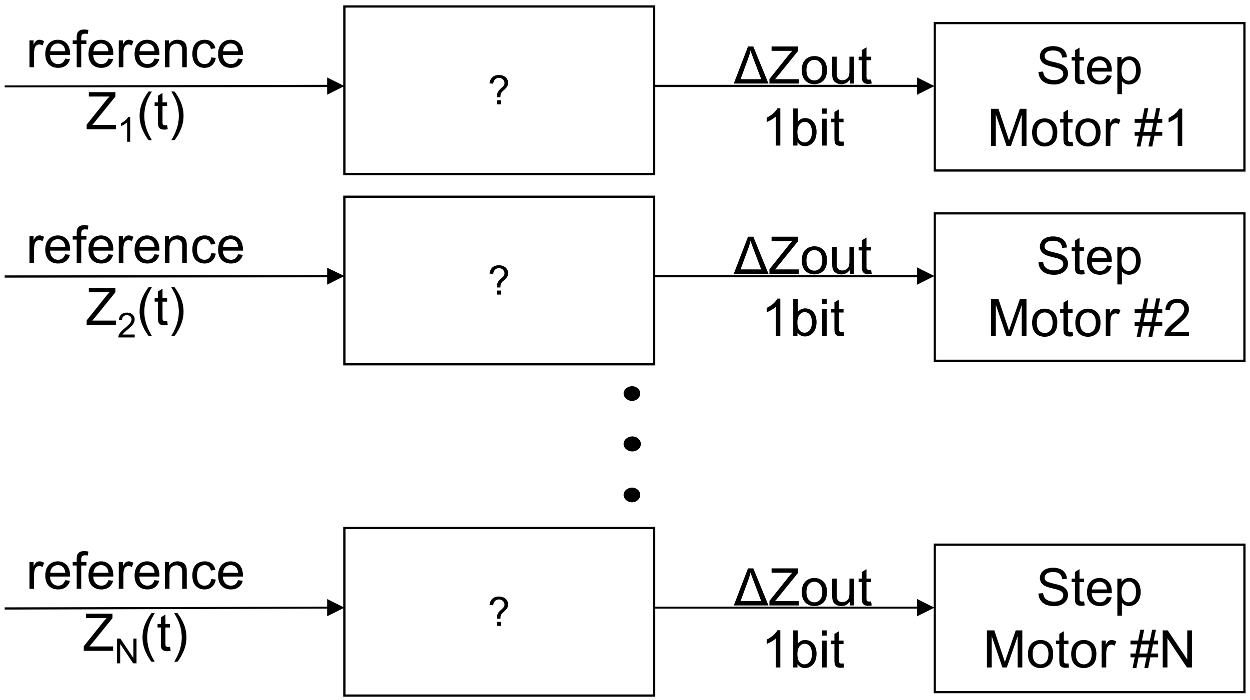


Standard configurations of the rotary axes on 5–axis CNC machines, an ***orientable-spindle*** machine (left) and ***orientable-table*** machine (right) [Faroukia'14].

[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

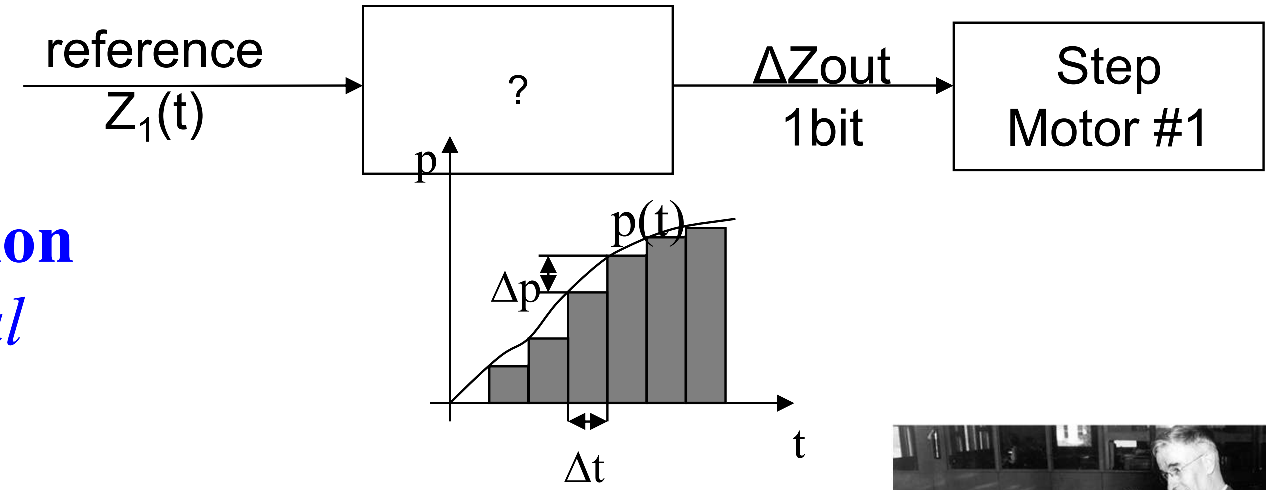
Interpolation Motivation



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

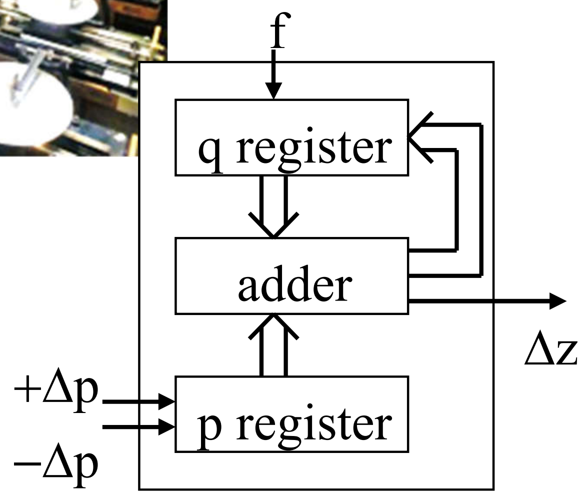
*Note2: Step motors count steps, i.e. are **numerical integrators***
*hence we have to convert Z(t) to an **incremental representation*** p_k

CAD/CAM and CNC



Interpolation: use incremental representation

Motivation from numerical integration



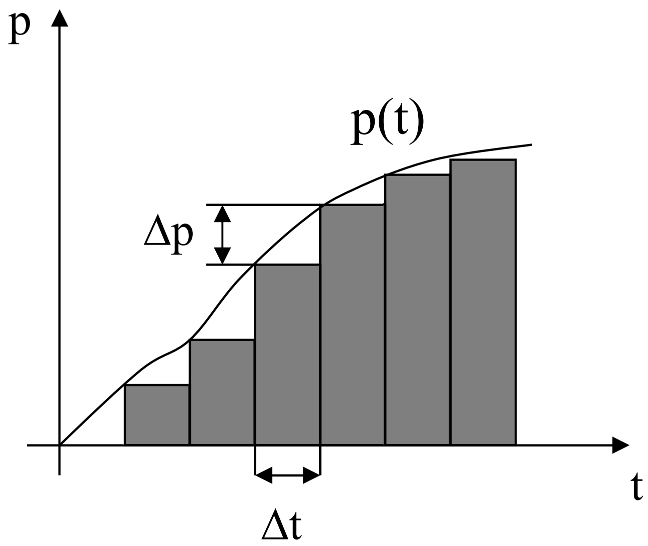
Differential Data Analyzer (DDA), timeline:

- 1876, First description of a device which could integrate differential equations of any order by James Thomson
- 1886, Mechanical integrators created to help with things such as analysis of ocean tides
- 1931, Bush torque amplifier and first differential analyzer built
- 1934, Differential analyzers began to be built in the US, Britain, Norway, Sweden, and elsewhere
- 1942, Rockefeller Differential Analyzer (RDA2) built
- 1943, ENIAC[1], an early digital device, used vacuum tube electronics to calculate ballistics tables
- 1949, Analog differential analyzers eventually replaced by digital differential analyzers
- 1959, Differential analyzers finally replaced by general purpose digital computers

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:

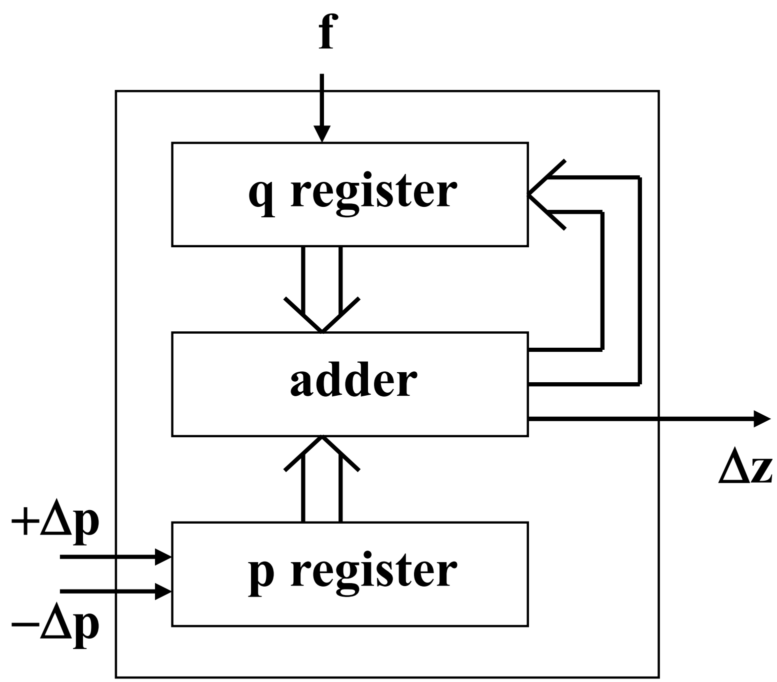
$$p_k = p_{k-1} \pm \Delta p_k$$

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

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

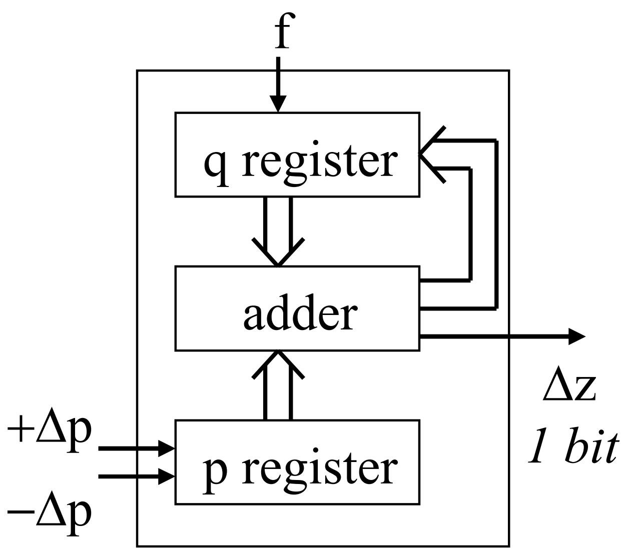
If the q register value exceeds (2^n-1) an overflow occurs and Δz=1:

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

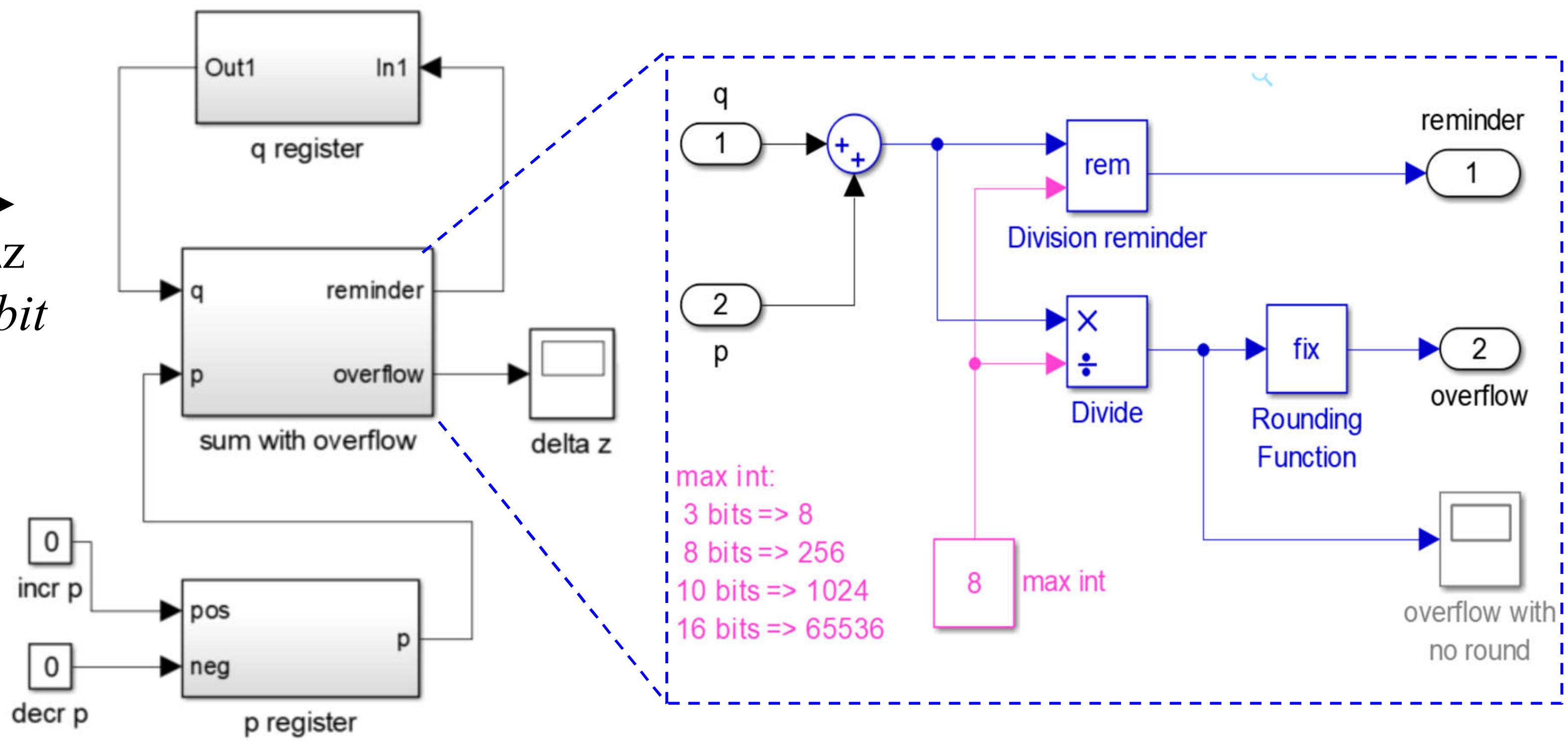
Defining C=f/2^n, and given that f=1/Δt, one has a scale factor from p_k to Δz_k:

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

Implementation of a Digital Differential Analyzer (DDA)



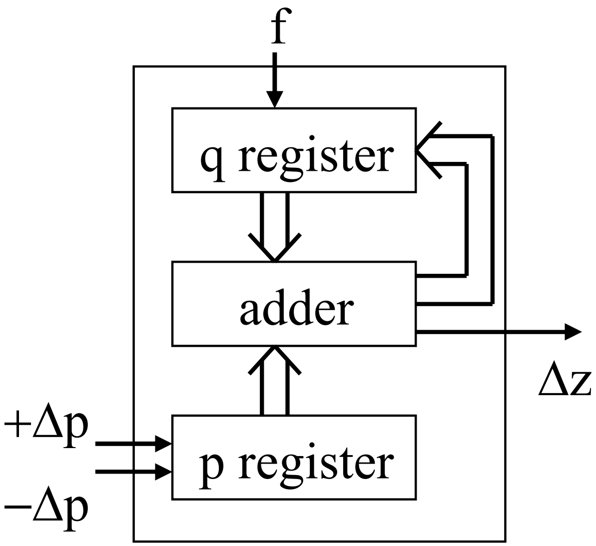
Matlab / Simulink



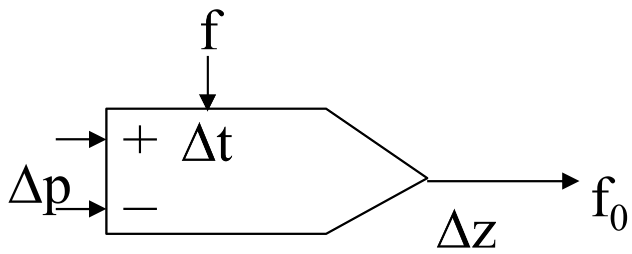
The q and p register are updated by a clock (frequency f).
The p register can be incremented and decremented.
The q register is a delay.

CAD/CAM and CNC

Digital Differential Analyzer (DDA) for Linear Interpolation (1 axis):



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

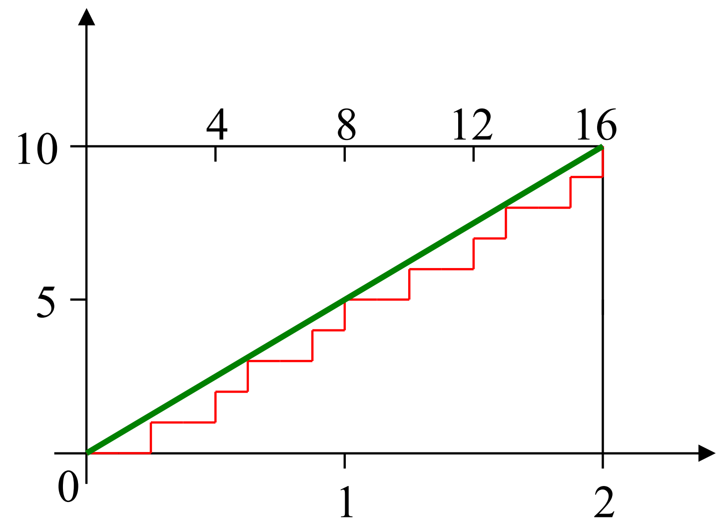


$$f_0 = \left(\frac{\Delta z}{\Delta t}\right)_k = C p_k, \quad \text{where} \quad C = \frac{f}{2^n}$$

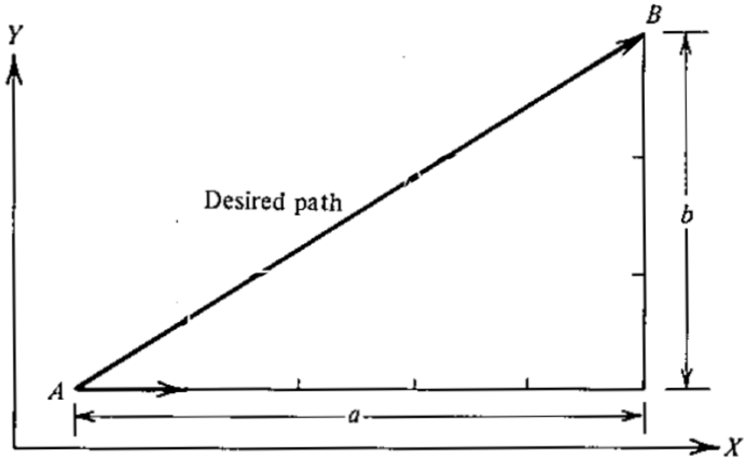
Step	q	Δz	Σ Δz
1	5		0
2	2	1	1
3	7		1
4	4	1	2
5	1	1	3
6	6		3
7	3	1	4
8	0	1	5
9	5		5
		...	

Detail step 2:

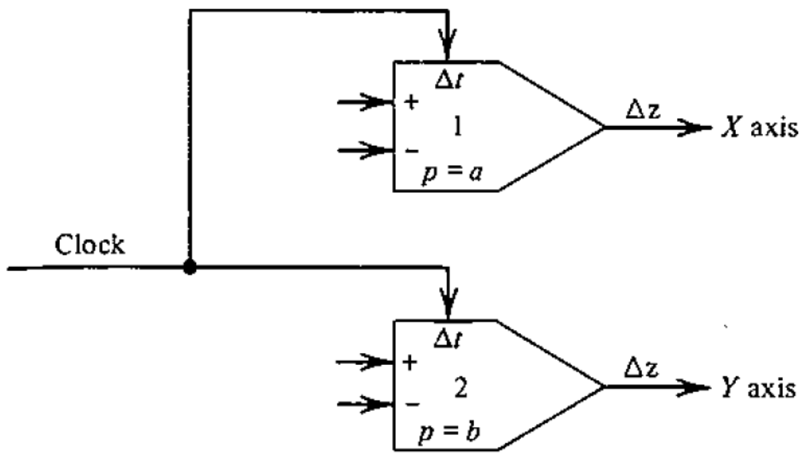
```
  1 0 1 = 5(10)
+ 1 0 1
-------
1 0 1 0
overflow  2(10)
```



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

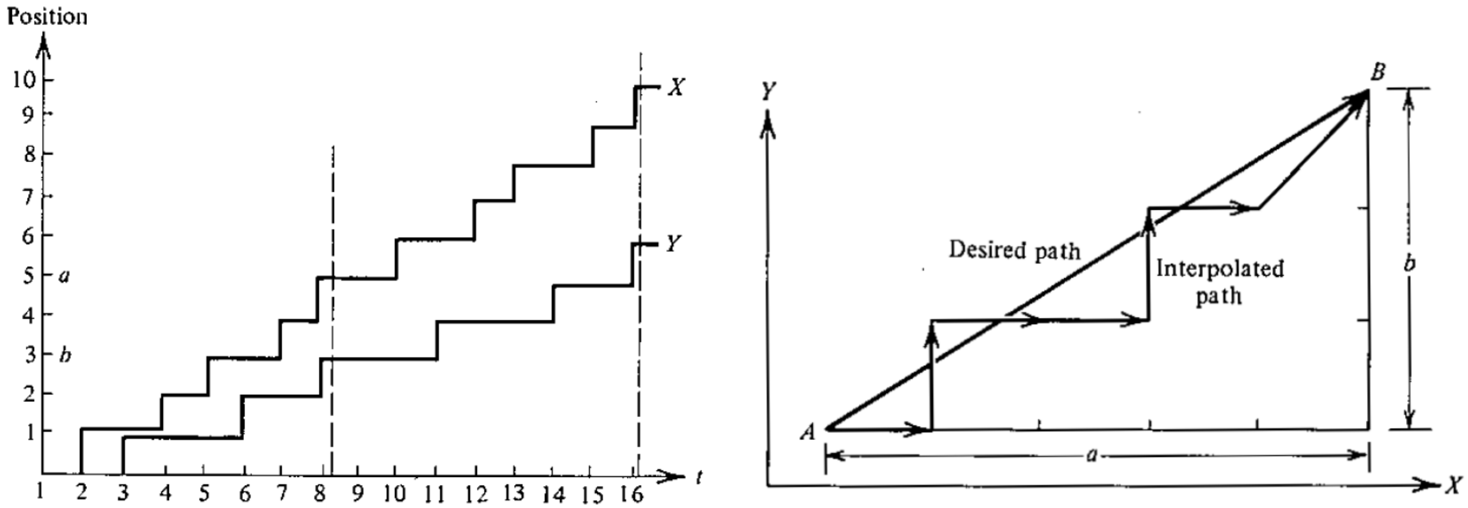


(a) Specifications



(b) DDA solution

(c) Results for $a=5$ $b=3$



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

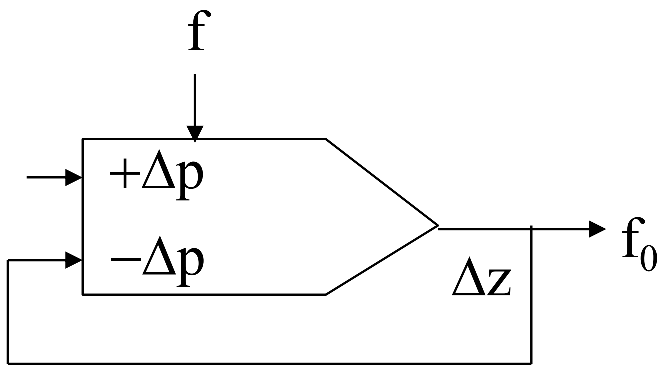
Let $p(t) = p_0 e^{-\alpha t} \Rightarrow dp = -\alpha p_0 e^{-\alpha t} dt$ and $\frac{\Delta z}{\Delta t} = Cp_k = Cp_0 e^{-\alpha t}$.

The differential of p(t) is approximately

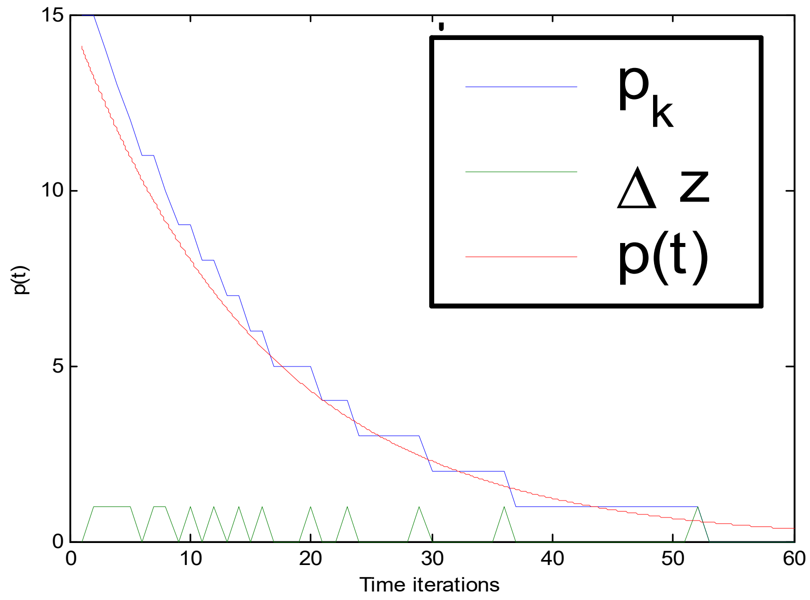
$$-\Delta p = \alpha p_k \Delta t$$

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

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



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



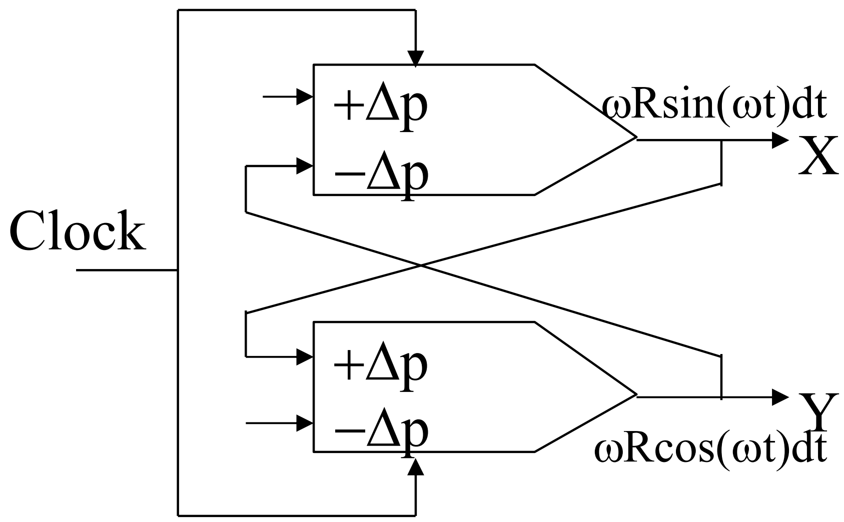
CAD/CAM and CNC **Circular Interpolation:**

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

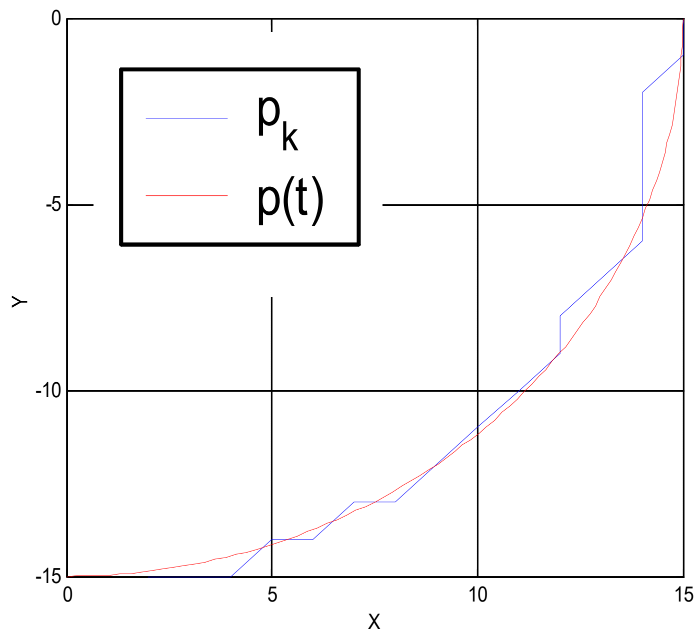
$$X = R(1-\cos(\omega t))$$
$$Y = R\sin(\omega t)$$

The differential is

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

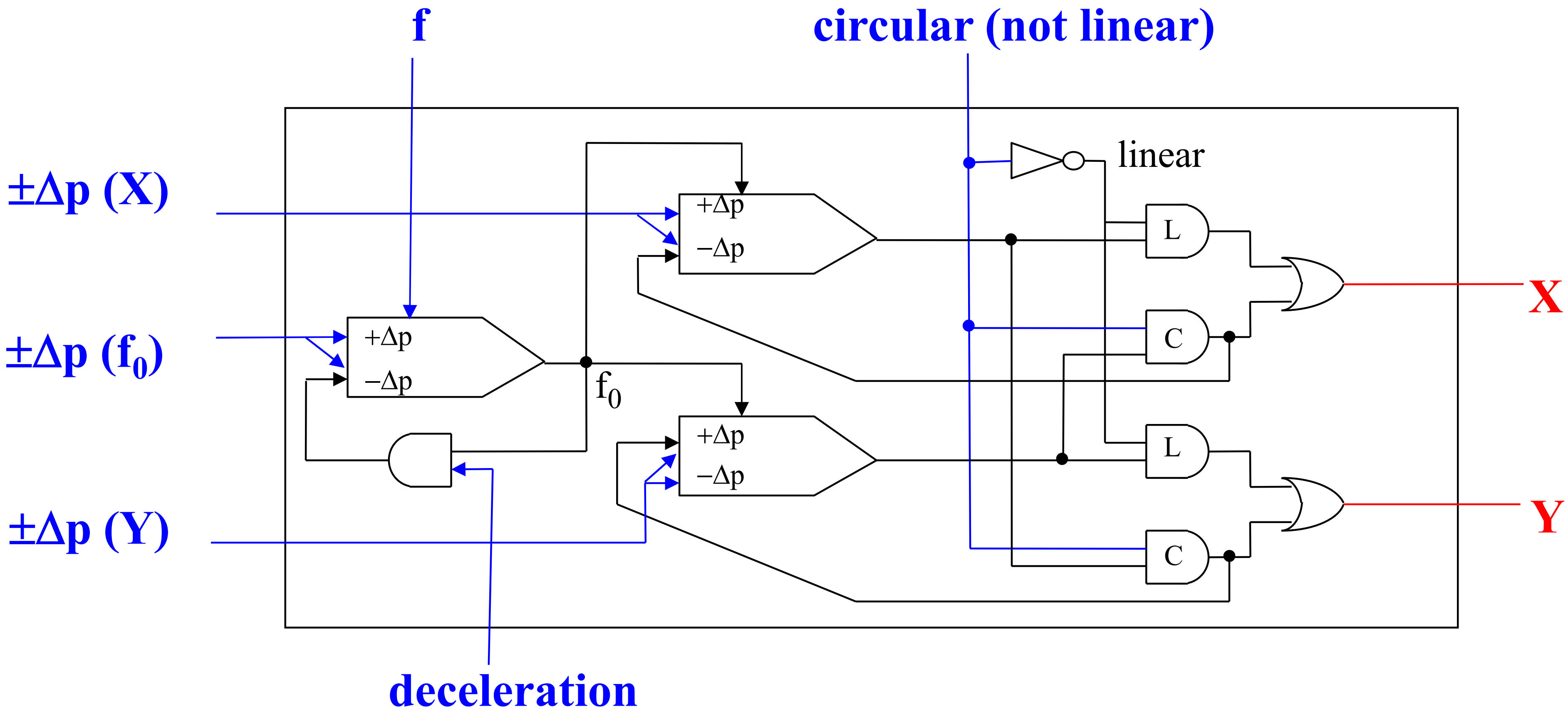


Example: Circumference of radius 15, centered at the origin.



CAD/CAM and CNC **Full DDA**

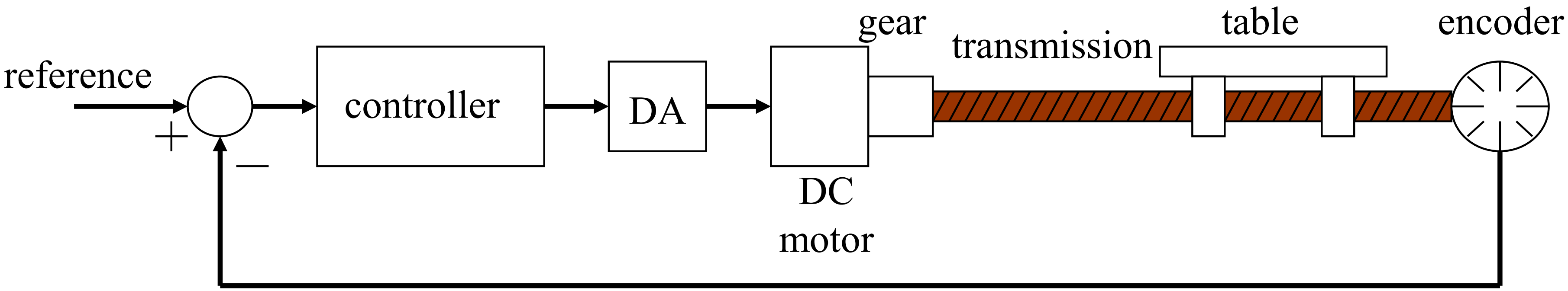
2D Line, 2D Arc, Acceleration / Deceleration



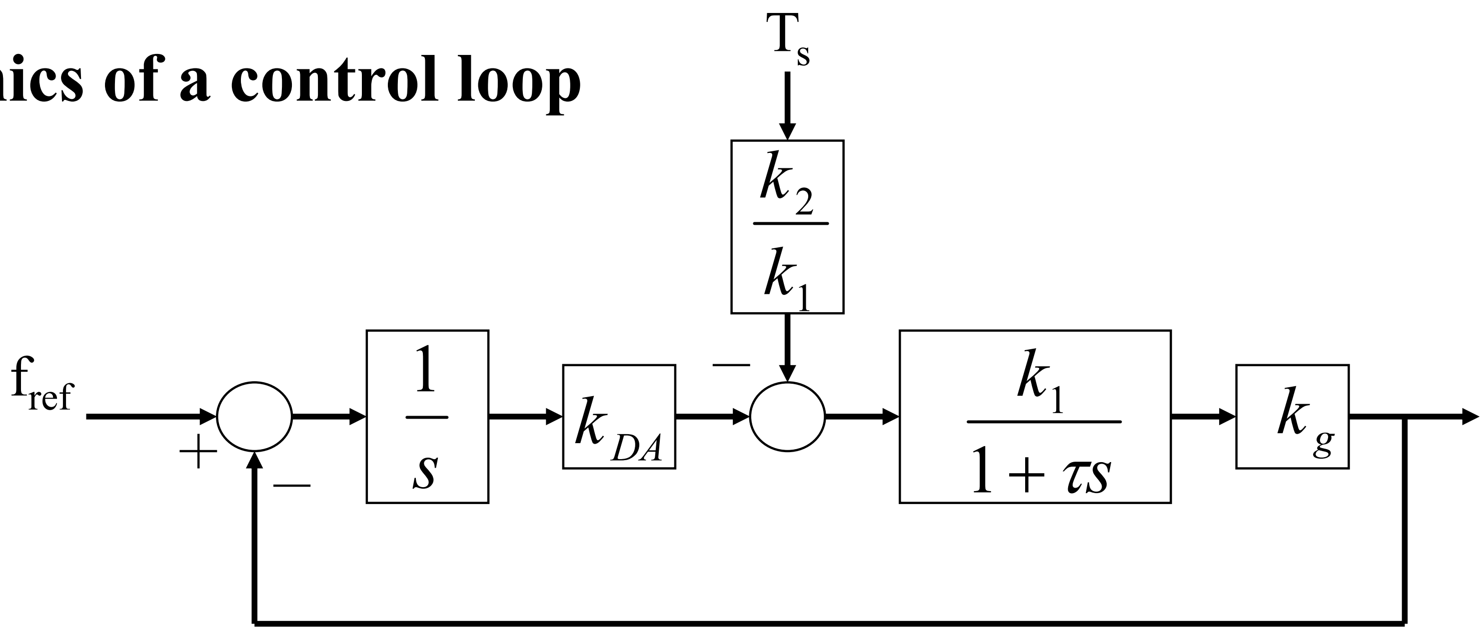
[Koran86] **Computer Control of Manufacturing Systems**, Yoram Koren, McGraw Hill, 1986

CAD/CAM and CNC

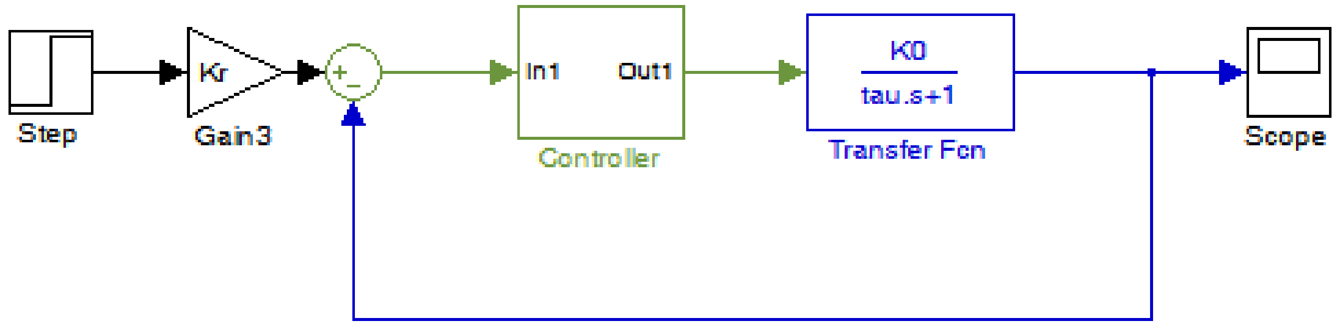
CNC Axes Control



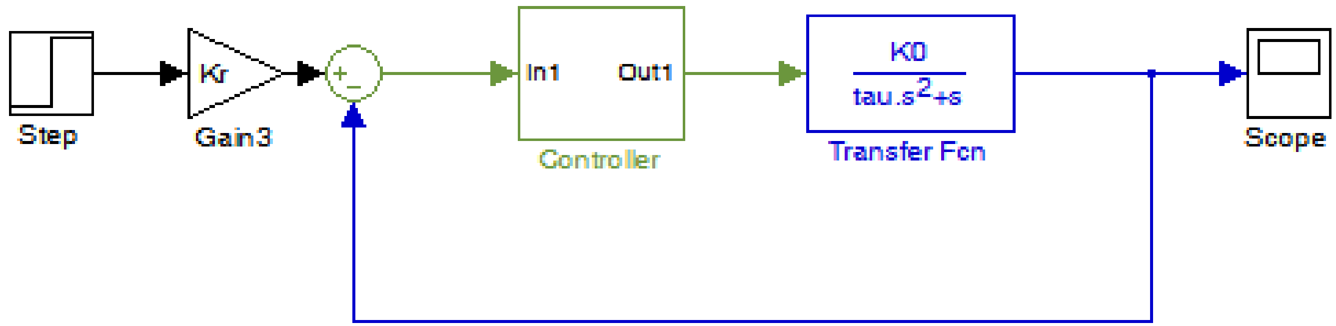
Dynamics of a control loop



DC motor - speed control



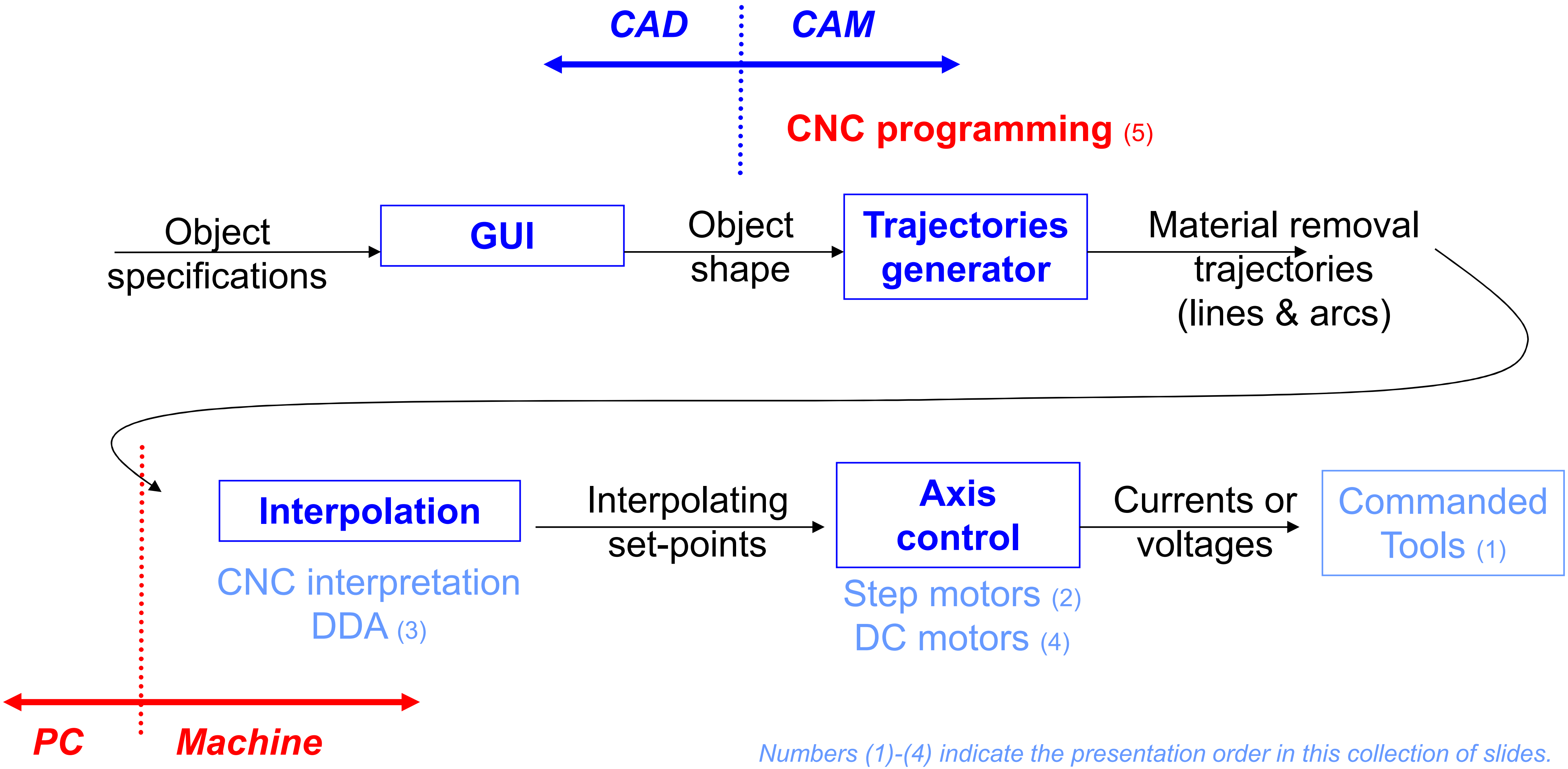
DC motor - position control



*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**

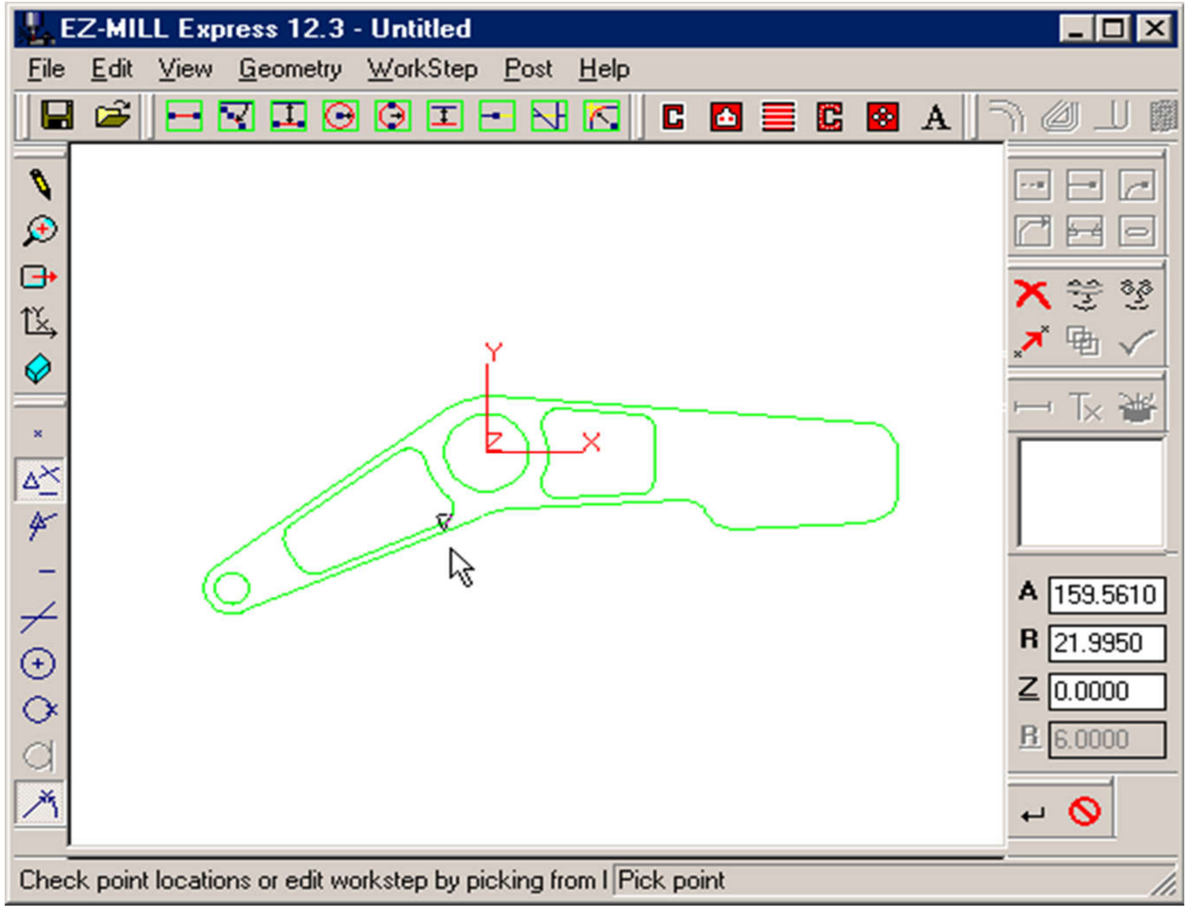


Numbers (1)-(4) indicate the presentation order in this collection of slides.
In the following we introduce (5).

CAD/CAM and CNC

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

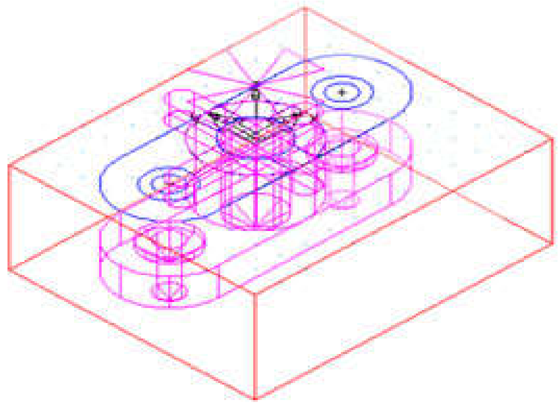
N70 X6.32

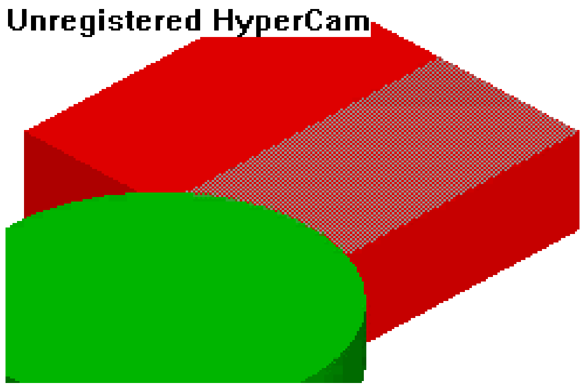
N75 Y2.82

N80 X-2.82

N85 G0 Z1.1

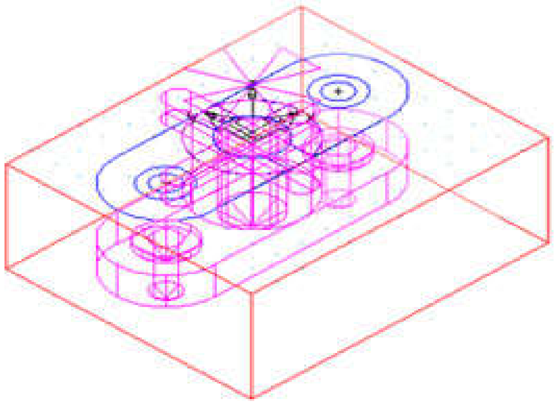
...





CAD/CAM and CNC

Example of CNC programming



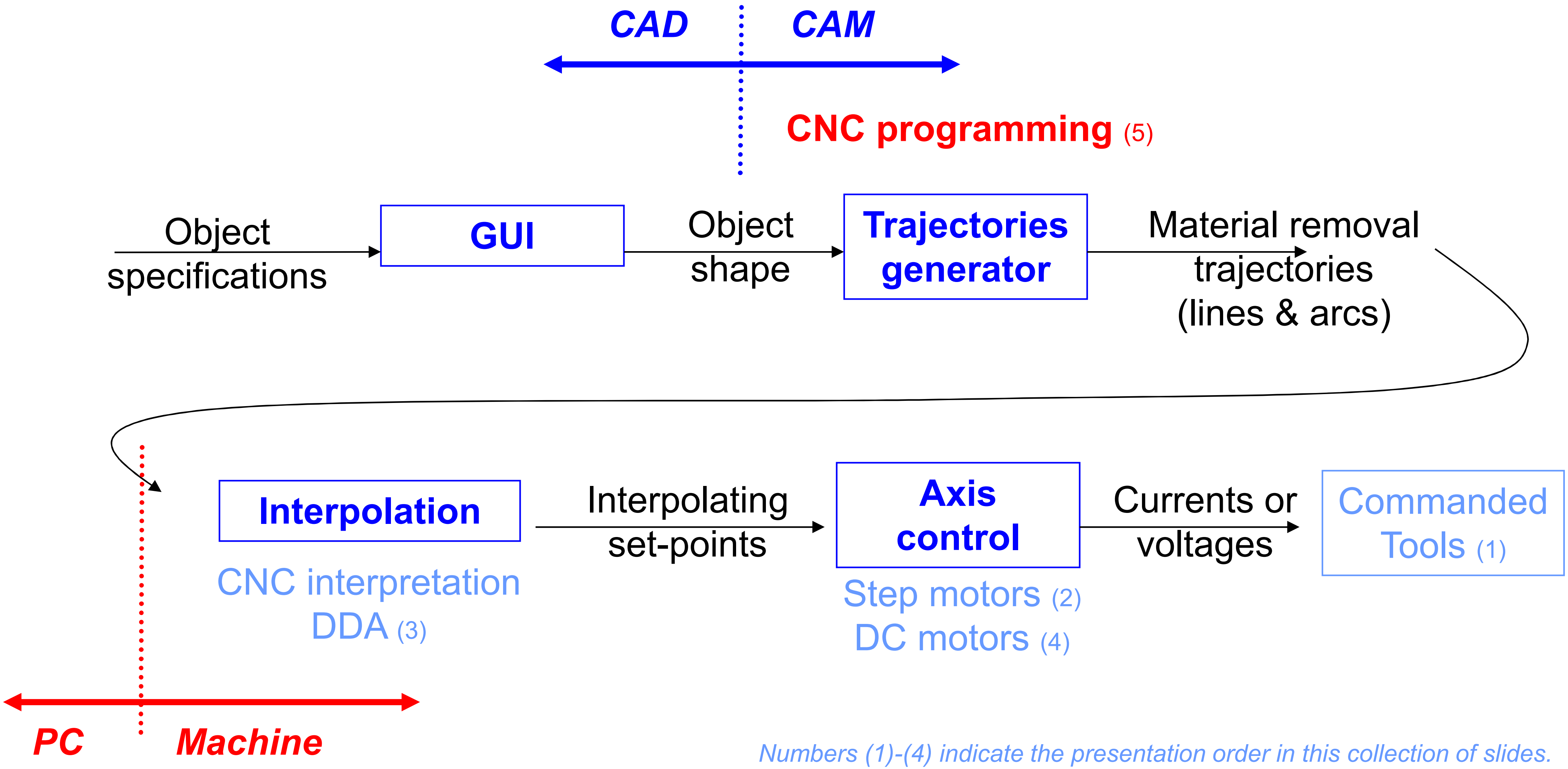
CAD/CAM and CNC

Example of CNC programming 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 **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 previous slides:

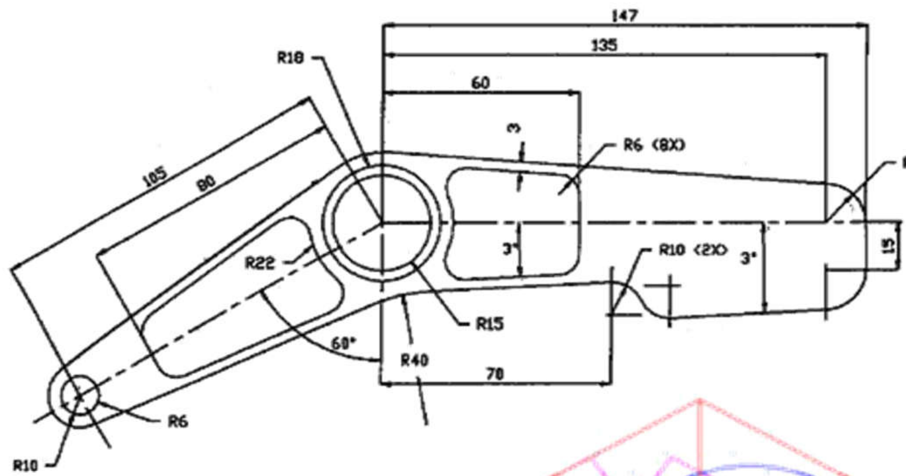
CNC machines know how to do **interpolation**, but not how to machine a complete part.

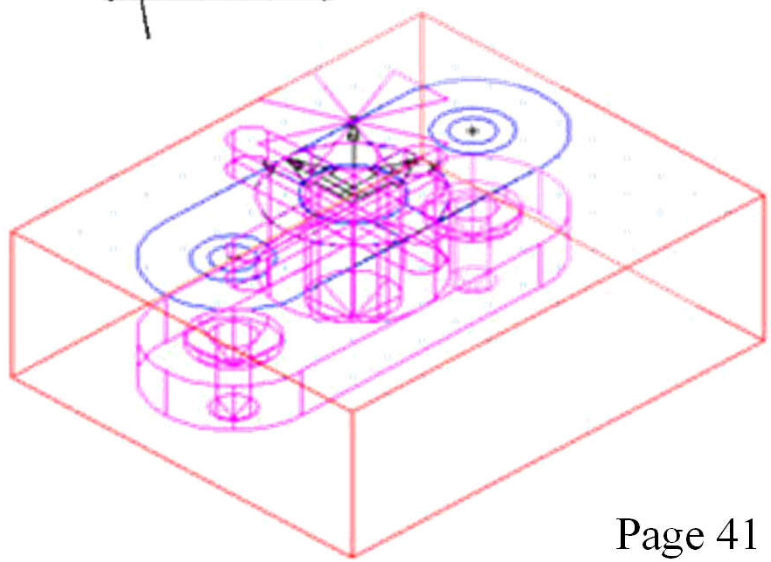
CAM helps to bridge the gap between **object shapes** and making **material removal trajectories** (to be interpolated).

In other words, CAM ends-up as **CNC programs**.

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

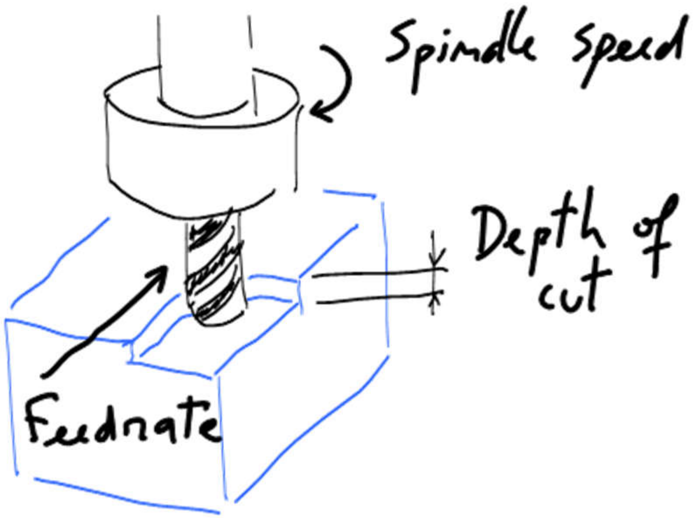
CAD/CAM and CNC - **CNC Programming**

4. Cutting data

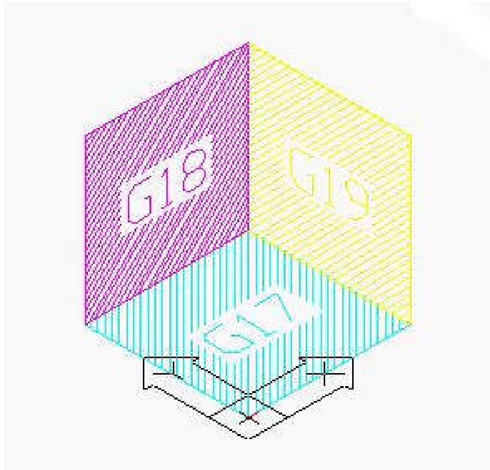
• Spindle Speed – speed of rotation of the cutting tool (rpm)

• 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 **N**umber
G	Preparatory Functions
X	**X** Axis Command
Y	**Y** Axis Command
Z	**Z** Axis Command
R	**R**adius from specified center
A	**A**ngle ccw from +X vector
I	X axis arc center offset
J	Y axis arc center offset
K	Z axis arc center offset
F	**F**eed rate
S	**S**pindle speed
T	**T**ool number
M	**M**iscellaneous 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

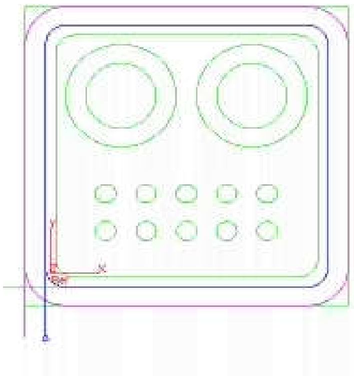
N85 G0 Z1.1

...

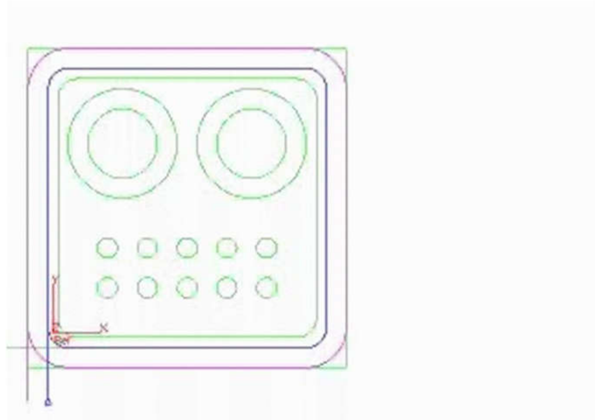
CAD/CAM and CNC - **CNC Programming**

Preparatory functions (inc.)

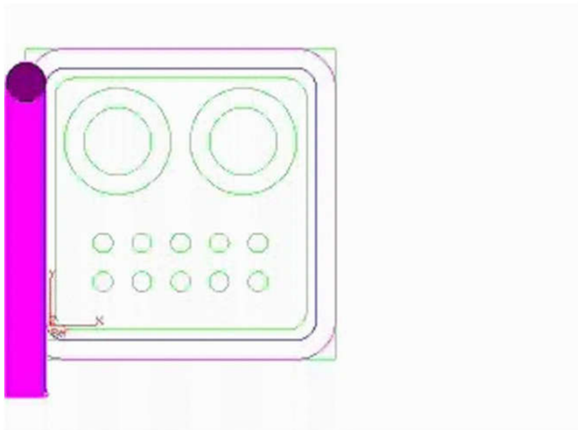
G00 – GO



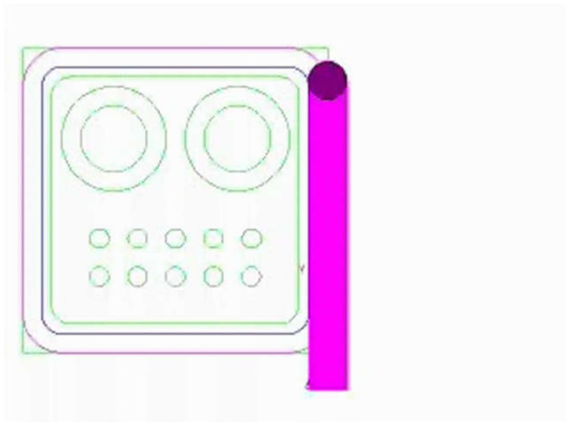
G01 – Linear Interpolation



G02 – Circular Interpolation (CW)



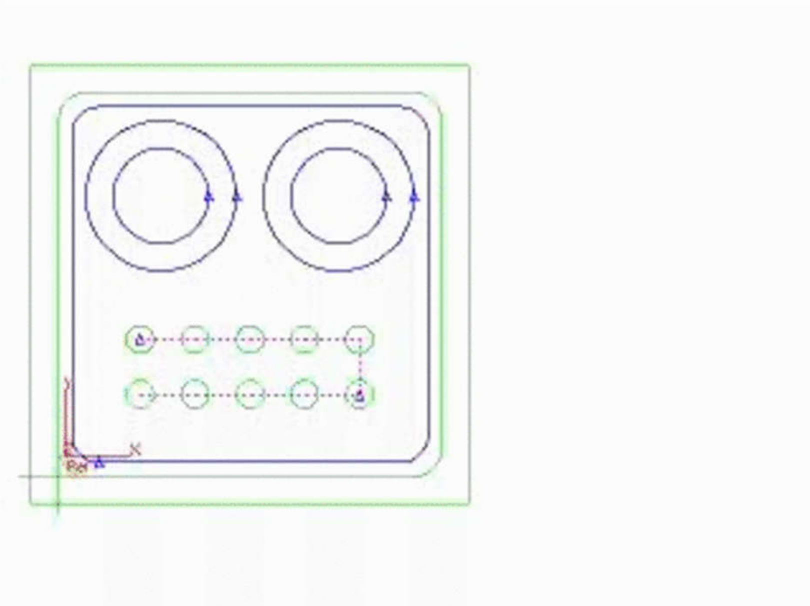
G03 – Circular Interpolation (CCW)



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

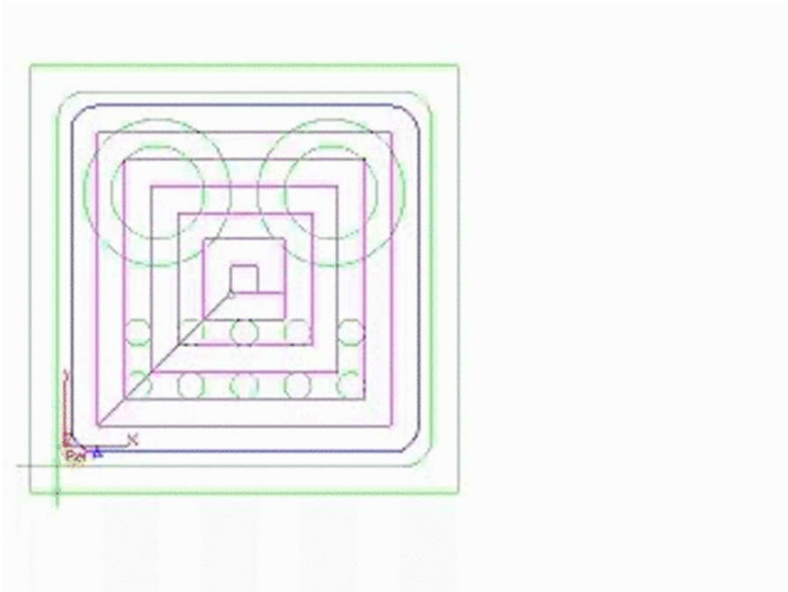
Canned Cycles

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)

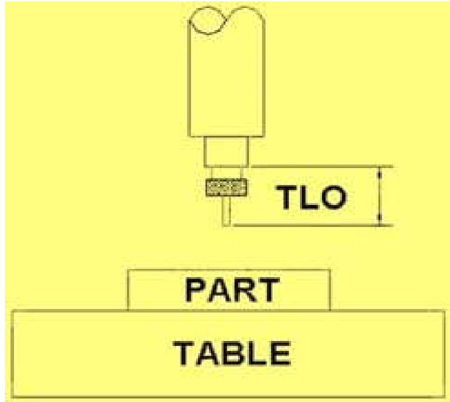
CAD/CAM and CNC **Machine operation**

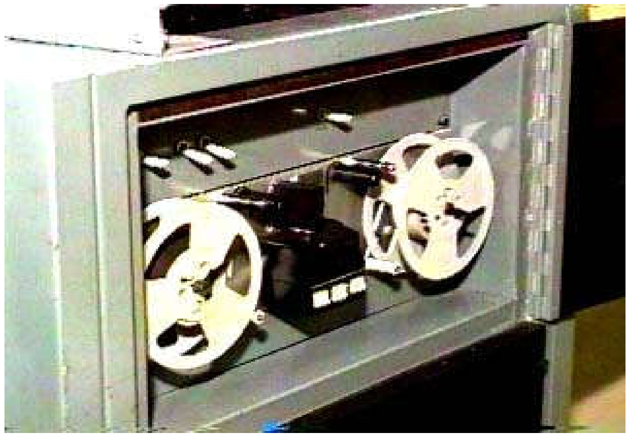
Rules of security

- 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

Advanced CNC programming languages

- Automatically Program Tool (APT), developed at MIT in 1954
- Derived from APT: ADAPT (IBM), IFAPT (France), MINIAPT (Germany)
- More references: Compact II, Autospot, SPLIT
- More recent, check the “landmarks/features” concept:

  https://www.autodesk.com/products/featurecam/features

Current trend in interpolation

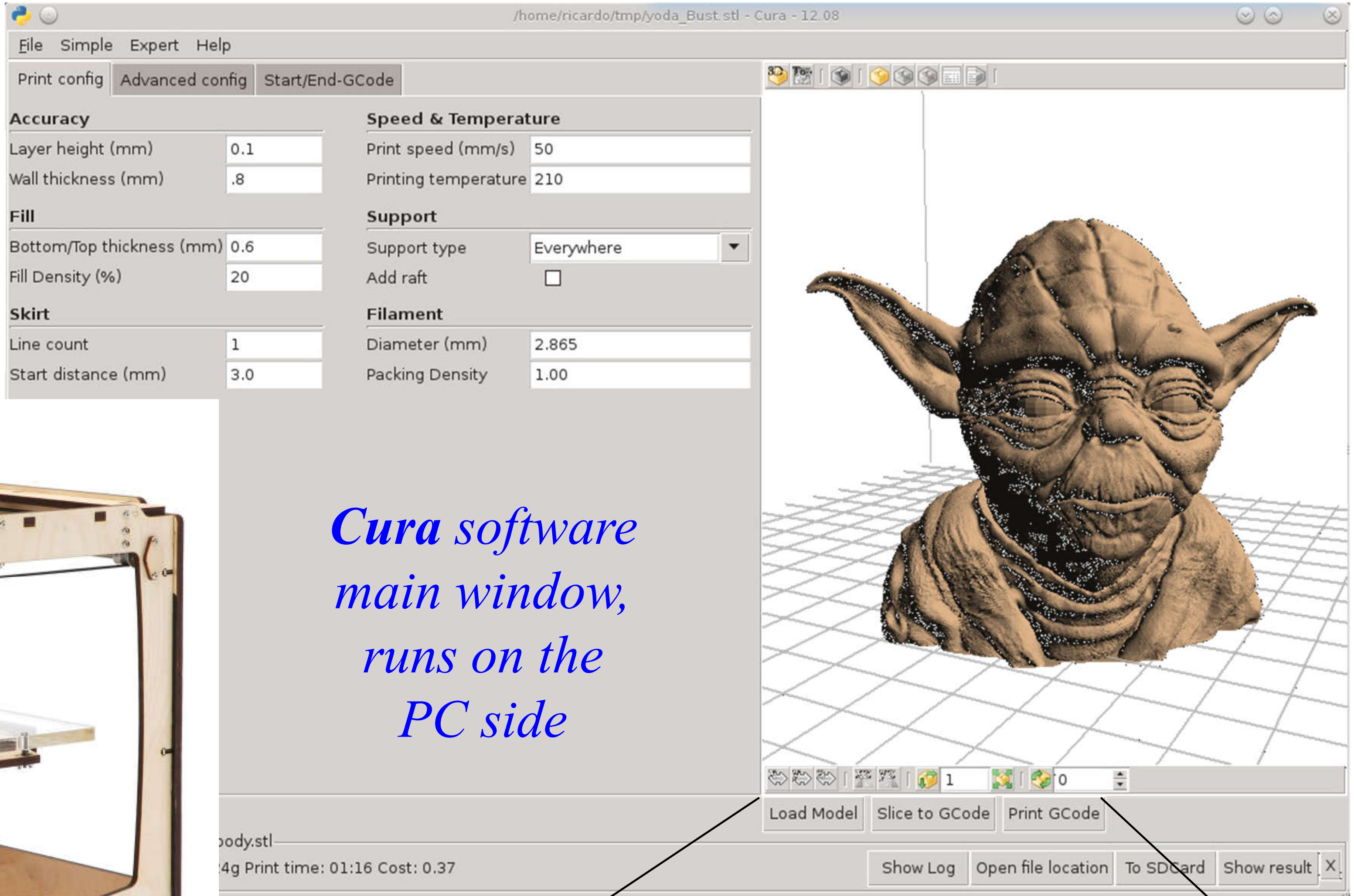
Modern CAD systems have progressively gained the capability to describe a wide variety of complex shaped parts (like dies and molds) through parametric curves or surfaces like the Bezier, B-Spline or ***Non-Uniform Rational B-Spline (NURBS)****. (...) NURBS is one curve interpolator that draws considerable 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

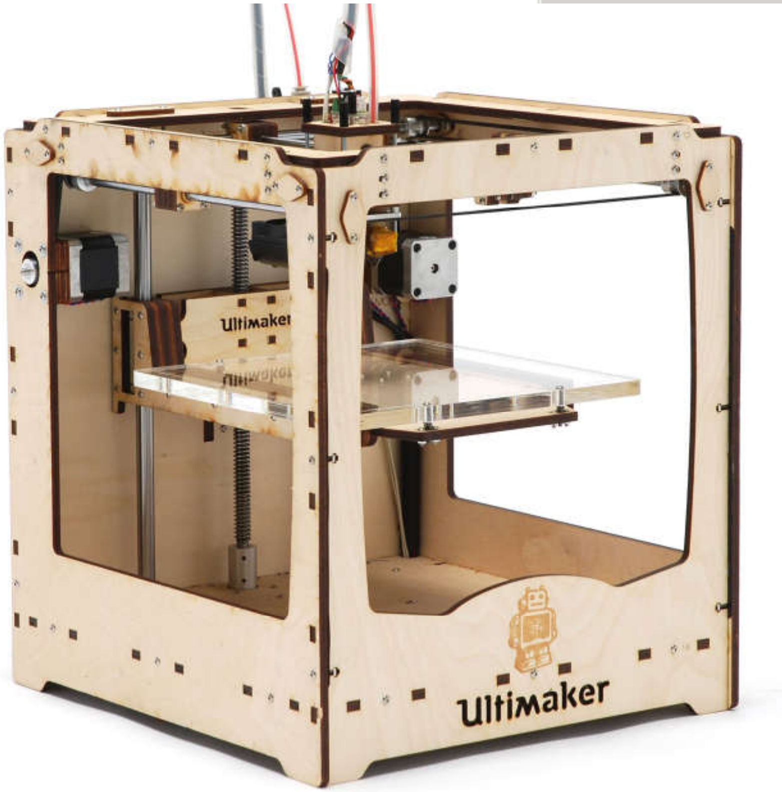
CAD/CAM and CNC at home!

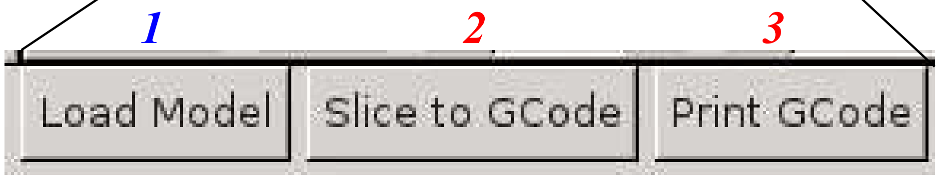
http://daid.github.com/Cura/

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

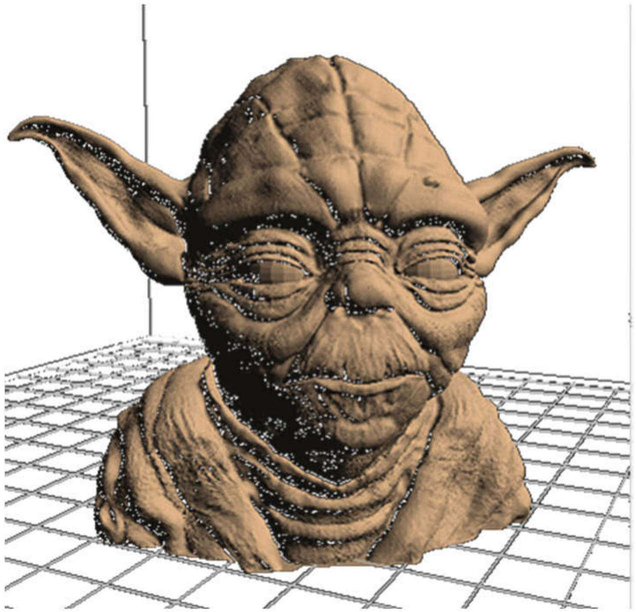


***Cura** software main window, runs on the PC side*





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

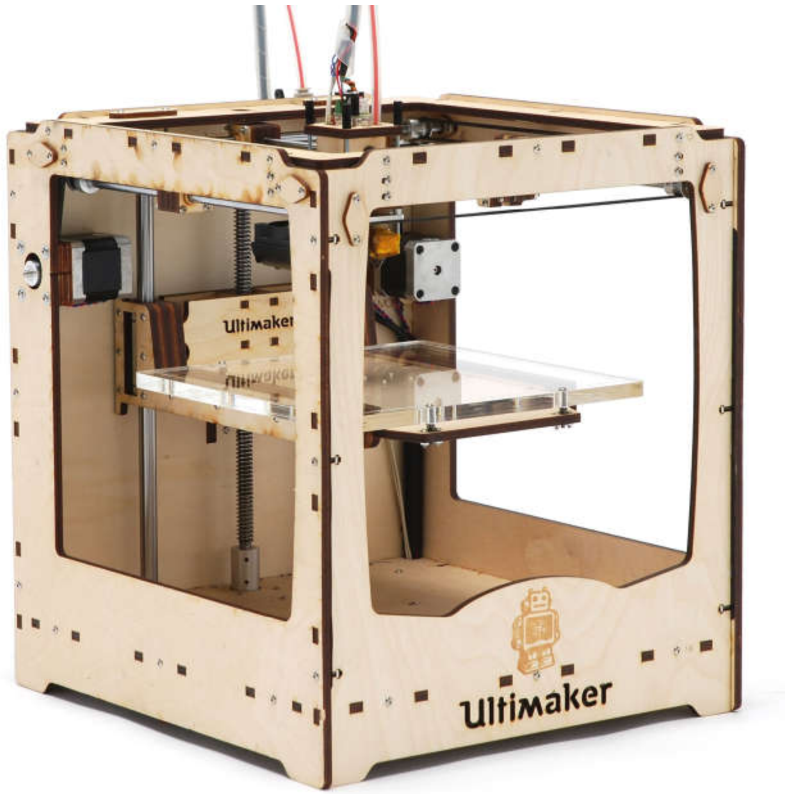


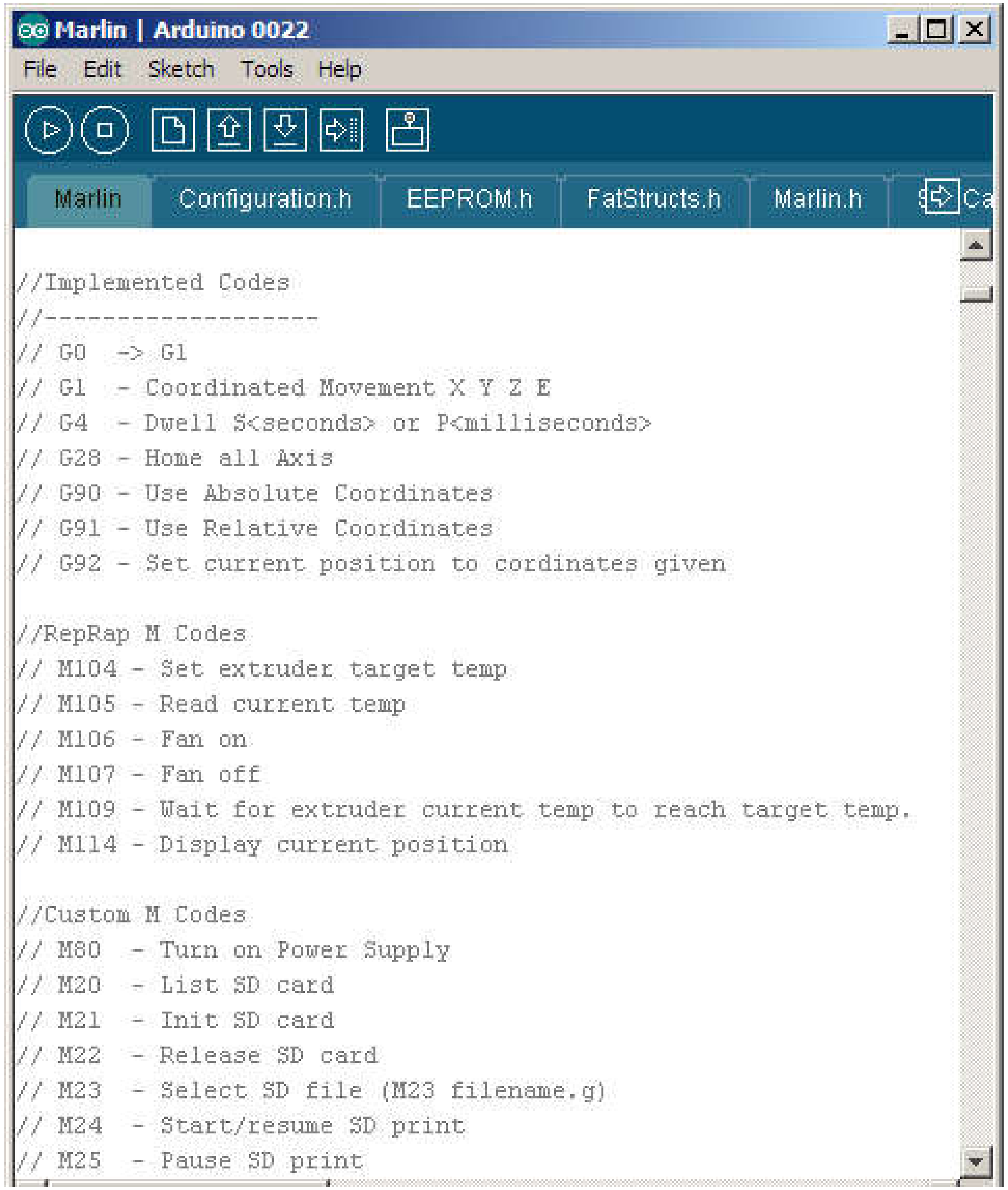
```
;TYPE:CUSTOM
M92 E865.888000
M109 S210.000000
;Sliced /home/ricardo/tmp/dump_body.stl at: Sun 28 Oct 2012 22:20:23
;Basic settings: Layer height: 0.1 Walls: 0.8 Fill: 20
;Print time:     1:16
;Filament used:     1.10m     9.24g
;Filament cost:     0.37
G21         ;metric values
G90         ;absolute 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
```

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

Cartesian printers use 4 axis: **X** , **Y** and **Z** for moving the printhead in space and **E** for "extruder".
E-axis refers to the amount of filament to be moved into (extruded) or out of (retracted) the printing head.

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
```

(... continues with many more lines of code ...)

```c
/* This struct is used when buffering the setup for each linear movement "nominal" values are as
specified in the source g-code and may never actually be reached if acceleration management is active.
*/
typedef struct {

  // Fields used by the Bresenham algorithm for tracing the line
  long steps_x, steps_y, steps_z, steps_e;  // Step count along each axis
  long step_event_count;                    // number of step events required to complete this block
  volatile long accelerate_until;    // The index of the step event on which to stop acceleration
  volatile long decelerate_after;    // The index of the step event on which to start decelerating
  volatile long acceleration_rate;   // The acceleration rate used for acceleration calculation
  unsigned char direction_bits;      // The direction bit set for this block
  long advance_rate;
  volatile long initial_advance;
  volatile long final_advance;
  float advance;

  // Fields used by the motion planner to manage acceleration
  float speed_x, speed_y, speed_z, speed_e;          // Nominal mm/minute for each axis
  float nominal_speed;                               // The nominal speed for this block in mm/min
  float millimeters;                                 // The total travel of this block in mm
  float entry_speed;
  float acceleration;                                // acceleration mm/sec^2

  // Settings for the trapezoid generator
  long nominal_rate;                  // The nominal step rate for this block in step_events/sec
  volatile long initial_rate;         // The jerk-adjusted step rate at start of block
  volatile long final_rate;           // The minimal rate at exit
  long acceleration_st;               // acceleration steps/sec^2
  volatile char busy;

} block_t;
```

from file "Marlin.h"

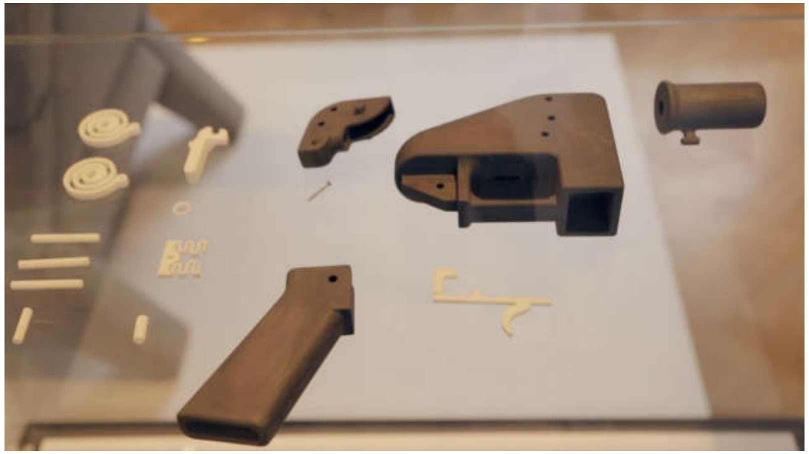
CAD/CAM and CNC at home!

Model and photograph of the 3D print.

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/

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

A Landmark Legal Shift Opens Pandora's Box for DIY Guns
By Andy Greenberg, Wired.com, 7th Nov 2018

Cody Wilson makes digital files that let anyone 3-D print untraceable guns. The government tried to stop him. **He sued—and won.**

Photo: Michelle Groskopf

https://www.wired.com/story/a-landmark-legal-shift-opens-pandoras-box-for-diy-guns/