Università degli Studi di Trento

Department of Industrial Engineering

Precision Engineering

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Course Notes

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Part I

Digital Manufacturing

Chapter 1

Industry 4.0

Digital manufacturing is the evolution of manufacturing where an **integrated approach** is centered around a computer system. The evolution can be seen from purely mechanical machinery, to **CNC** *computer numerical controlled* machines up to system of computer-controlled machines.

Digital manufacture goes in the framework of **Industry 4.0**, the fourth industrial revolution that politically *started* in 2013 after Angela Merkel's request in 2011 at the *Hannover Messe*. The final report of the *Industrie 4.0* committee defines

- design principles;
- challenges;
- impacts

that industry 4.0 present.

Objectives The main goals of this fourth industrial revolution can be summarized as

- the political idea of re-shoring of added value in western countries after the 2008 economical crises and in order to re-establish independence from chines production;
- sustain the salaries of both workers and the middle-class;
- sustain the e-commerce;
- mass customization; this has been possible after a change of mentality in production: previously products were massively fabricated, stocked and only finally sold for a *high* amount of time while now the time delay between production and final customer is reduced, improving the customization of the products;
- related to the previous point, a goal is to compress the life cycle of the product in order to make it available faster to the customers.

Design principles The main design principle driving the industry 4.0 are:

- the **interoperability** exemplified by the *Internet of Things* **IoT**, the *Industrial IoT* **IIoT** and the *Internet of People* **IoP**; this principle has the goal to increase the efficiency in communication between machines (*things*) or persons (*people*) with the goal to reduce the number of operators needed in a plant;
- the implementation of *Cyber-Physical Systems* **CPS**, mechatronic machines allowed to communicate and exchange information in order to improve the production chain;

Table 1.1: *order nd related human attribute substituted (with example) according to "the Yardstick of Automation" article.*

Order	Human Attribute	Example
0	none	manual tools
1	energy	powered machines and tools
2	dexterity	single-cycle automatics (*dexterity* means *self-feeding* in a sense of repeatable system)
3	diligence	repeats cycle, open-loop control; ability to perform all the action with the same accuracy
4	judgment	closed loop, numerical controls, self-measuring systems
5	evaluation	computer control, model of process required for automation
6	learning	limited self-programming and some artificial intelligence
7	reasoning	inductive reasoning (cause → effects)
8	creativity	performing original designs unaided
9	dominance	machine is a master

- the information transparency using **public** and **open protocols** that allows CPS to communicate with each-other using an unified *language*. The realization of **digital twins** as a model that simulate the behaviour of a real cyber-physical system is also important in order to estimate how the whole components will interact together;
- the implementation of **self-support** and **in-line help** to guide the operators in troubleshooting errors that might occur during normal functioning;
- the **decision de-centralization** giving autonomy to CPS in order to make machines perform trivial choices according to a specific stratification and prioritization of the tasks, allowing humans to better focus on problems that need an high supervision.

This design principle can somehow related to *the Yardstick of Automation*, an article published in 1962 by *Amber&Amber* that relates the order of automation by evaluating the human attributes that machines can substitute; such order are reported in table 1.1. At this stage, with the industry 4.0, we consider industries between order 4 to 6 of that table.

Challenges At this stage the main challenges of industry 4.0 are:

- cybersecurity: cyber-physical systems are *high-tech* equipment that has the weakness of being hacked with so the possibility of high damages to production and operators;
- reliability and resiliency of the communication *machine-to-machine* **M2M** mainly determined by the bandwidth of communication but most importantly it's latency;
- system should be design with a drop-in, plug-in approach on existing processes; plants cannot be re-invented from scratch in order to introduce a new machine, but all the pieces should be able to work together following the same unified protocols and standards;
- the protection of the intellectual property (that's put in danger with the high frequency of exchanging digital files);
- the reluctancy of plant owner to change the way industry processes are made and the need of re-train operators;
- the initial loss of labor that will be in the years reconverted into a *higher order* operators.

Impacts The main impacts provided by industry 4.0 can be summarized in:

- *servitization* as the passage from selling goods to selling services to people;
- the productivity and its resilience;
- safety for human operators;
- integrated design of product and process (the two things now will go together and shouldn't be consider as separate);
- the cos structure in terms of money allocation in the production process;
- the socio-economical factors;
- the ability to have a high number of data to analyse and process.

Digital manufacturing and industry 4.0

Regarding industry 4.0 and digital manufacturing some core enable technology are common such the M2M connectivity between cyber-physical system, the connectivity layer provided by the industry internet of things, the additive manufacturing as the dematerialization of the design and the machine learning/artificial intelligence to make autonomous decision possible.

CPSs Cyber-physical systems are mechatronic system, so mechanisms whose actuators are controlled by a computer system based on output from sensors and logics provided by algorithms. Digital manufacturing enables CPSs must be IoT-connected in order to provide the plant controller with information its own status and accept incoming tasks.
The industrial internet of things has to support communication (M2M) between a number of CPSs that can be theoretically huge. In this sense **IP protocols** standard have been created allowing $4.3 \cdot 10^9$ addresses for `IPv4` version and more recently `IPv6` allowing $3.4 \cdot 10^{38}$ unique addresses.

Networking model

According to the internet model, data can be exchanged between machines by creating a networking stack where the package is composed by 4 different layers stacked (as shown in figure 1.1). Such layers are:

L1) link layer made by the physical carrier standard (such Ethernet cable or WiFi) and it's protocol (`MAC`, `813.11`, `ARP`...) that explains *how* data are transmitted;

L2) internet (network) layer made by the addressing protocols (such `IPv4`, `IPv6` or `ICMP`) in order to properly address packages of information;

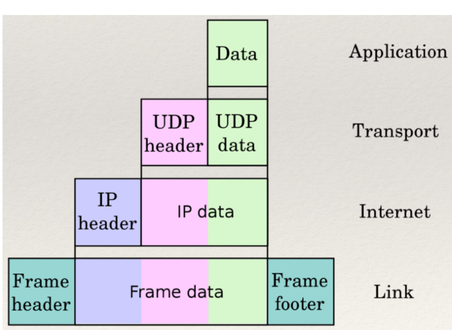

Figure 1.1: *4 layers and related package constitution used for communication using internet protocols.*

L3) transport layer (TCP, UDP protocols) that manages the connection between nodes in the network;

L4) application layer (such HTTP, FTP, IMAP, LDAP standards) that describes and contains encoded data.

The industrial internet of things must support communications between cyber-physical systems with a M2M communication; for the first layer L1, the link should be *as fast as possible* in order to have a low latency and for this reason the new 5G protocol seems promising. Regarding instead the application layer L4 protocols we can use the more verbose and complex standard such REST or more lightweight ones (such MQTT, ZeroMQ, AMQP and OPC-UA).

REST and HTTP overhead The REST (*REpresentational State Transfer*) is a protocol extended from HTTP and is characterized by a verbose (large) overhead, a complex syntax and by a connection n machine to 1 server. The communication starts by sending 3 first packages for a hand-shake communication synchronization (no information are exchanged at this point) and only after this operation data are exchanged between one machine and the server. The headers of this communication is large: considering in fact that the simplest request phrase requires 14 bytes, the associated full request stack is made by 437 bytes (need of bigger bandwidth) and the number of packages sent back-and-forth between machine and server is *high*, resulting in higher latency.

The combination of handshaking protocols and verbose frame headers/footers allows to have a reliable and robust connection with a needed increase of bandwidth and with an increased latency; for this reason more *machined based* protocols have been implemented in order to reduce latency while exchanging information between server and machines with the draw-back of reducing the number of packages sent resulting in less synchronization and confirmation (for example of package delivered).

In IoP messages are frequently *heavy* and seldom and the robustness of the HTTP protocol allows to better adapt the information exchanged between machines using different web servers or browsers. On the other hand IoT requires smaller messages sent with high frequency and so standard are enforced to minimize possible sources of unexpected conditions while still maintaining low latency.

In IIoT messages also should follow routes more complex than n-to-1 (n clients to 1 server) and so we need to minimize the overhead and support flexible topologies of the network infrastructure. A way to perform this operation is by using **message queuing protocols** (such MQTT, ZeroMQ) where clients can be both **publishers** and/or **subscribers** of the information; all this communication system is handled by the so called **broker**.
The idea behind such type of communication is that clients that join a broker as publisher can send information to this intermediate server that immediately notifies all the subscribed machined with the information provided.

Chapter 2

Manufacturing Systems

To give a shape shape to a block of raw material, namely ***workpiece***, various methods can be used involving a different required number of **motion axis**:

- the **forming** processes that are based on the plastic deformation of the workpiece requires and usually requires the simultaneous motion of 1 motion axis; for shaping the workpiece it's not important the motion of the machine but usually only the force. In this course such manufacturing process is skipped because the motion planning and control is (usually) trivial;
- **subtractive** processes are based on the removal of material from the workpiece and usually requires the simultaneous motion of at least 2 axis and a rotation;
- we can add more material to the existing block using **additive manufacturing** techniques that, as for subtractive processes, requires at least 2.5 motion axis (2 synchronized plus one position axis that can be moved to ensure a particular position).

In subtractive/additive manufacturing there is a **tool** performing the process (such mills, polarized wires, extruding nozzles...) whose motion is performed by a synchronized action of two or more axes (typically in cartesian arrangement); the union of **trajectory** and **speed** of the tool represent it's **motion** that must be planned according to **geometry** (trajectory) and **process specifics** (for speed).

2.1 Machining

The majority of products involves the **machining** process either directly or indirectly; machining involves a combination of linear and rotary motion and can be split in 3 main operational categories:

- **turning** where the workpiece is rotating and the tool is displacing; a good example of turning machining is the lathe (*tornio*);
- in **drilling** (performs holes) and **milling** (gives shape to a workpiece) the tool is rotating and there is a combined relative displacement between tool and workpiece.

The mechanism of **chip formation** (*formazione di trucioli*) generated by this processes depends on multiple **tool parameters** such:

- the relative speed of the tool and the workpiece, namely the **cutting speed** v (as the absolute value of the velocity vector);
- the cross section of the removed material.

This tool parameters strictly depends on the **machining parameters** as trajectory, rotation and translation speeds. Other relevant parameters to chose machining ones are the properties of the material used.

Usually tool parameters are provided by the producer of the component and they so allows to compute the machining parameters as it will be shown in detail in the next sections.

Turning

While dealing with **turning**, considering the scheme in figure 2.1, the main machining parameters that need to be calculated are the spindle speed, the feed rate and the spindle power.

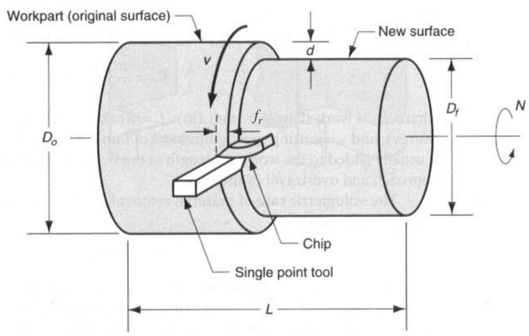

Figure 2.1: *main dimensions and parameters used for the calculation on turning's machining parameters.*

Table 2.1 contains a list of useful equations that can be used in order to compute the machining parameters; N is the spindle rotation in revolution per minute and depends on the tangential velocity v provided by the tool parameters; D_0 the external diameter of the shaft that has to be reduces to the value D_f; f is the **feed rate**, measured in mm/min, is the velocity in the displacement along the axis of the tool tip. The material removal rate MRR determines the volume of the removed material in cm^3/min; this parameters is needed to estimate the power that the machine requires to perform the process.

Table 2.1: *formulas for machining parameters*

Parameter	Turning	Drilling	Milling side	Milling face
$v(m/min)$	$\pi D_0 N$	πDN	πDN	
$N(1/min)$	$\frac{v}{\pi D_0}$	πDN	πDN	

Additional parameters are the specific power $p_s[W/cm^3]$ (depending on the material processed usually)

Drilling and milling

Considering the schematic representation of the drilling process in figure 2.2, the new parameters used to describe the process are the approach length A as the dimension of the surface edge that's worked.

Regarding milling (figure 2.3), such machining process can happen on the **side** or **face**: in the first case the rotary axis is parallel to the surface we are machining while for face milling the rotation axis is orthogonal.

Typically in spindle machines the rotational speed goes from $5\,000rpm$ up to $12\,000rpm$ (in extreme case up to $40\,000rpm$).

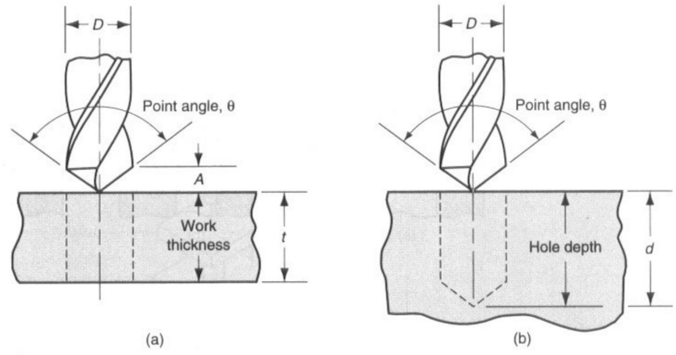

Figure 2.2: *main dimensions and parameters used for the calculation on turning's machining parameters for drilling.*

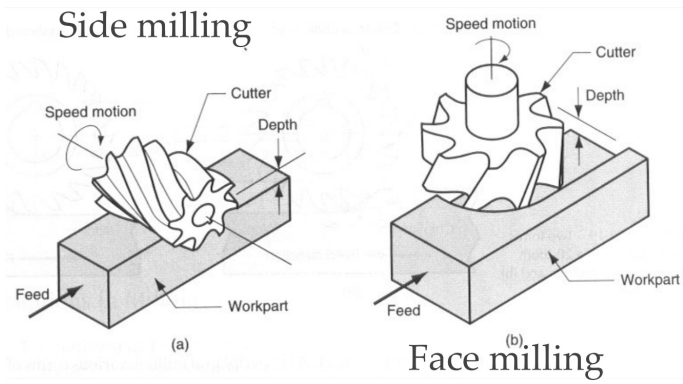

Figure 2.3: *main dimensions and parameters used for the calculation on turning's machining parameters for drilling.*

2.2 Cutting economics

The **cost** of machining depends on a set of factor such:

- the labour as the hourly cost of trained personnel;
- the machinery purchase cost and it's lifetime span;
- the starting cost of raw material;
- the consumables such tools, fluids and other disposable fixtures.

Costs can either depend or not depend on process parameters; an example are tool that removes material: the wear of the flanks of the tool depends on the tangential velocity v and the tool life T following the **Taylor's tool wear law**

$$vT^n = C \tag{2.1}$$

where n, C are function of the material and failure criteria. This means that

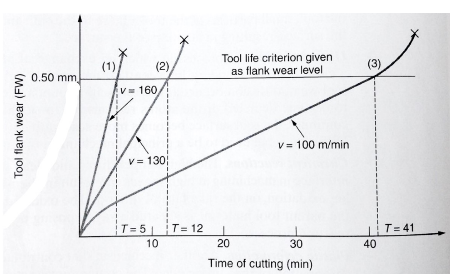

Figure 2.4: *example of diagram associated to the Taylor's tool wear law.*

Economical model

Considering a cylindrical turning process for simplicity, we can regard the cost per piece C_p as

$$C_p = C_m + C_s + C_l + C_t$$

where C_m is the machining, C_s is the setup, C_l the loading and C_t the tooling costs. In particular the machining cost depends on the time for machining T_m and the hourly costs related to labour L_m and for the overhead O_m (costs that you spend by still doing anything such rentals):

$$C_m = T_m(L_m + O_m)$$

Similarly the loading and setup costs depends on the loading and setup time T_l, T_s:

$$C_l = T_l(L_m + O_m) \qquad C_s = T_s(L_m + O_m)$$

RIVEDERE UN ATTIMO QUESTA PARTE: re-grinding tool

D_c is the depreciation as the price of the tool divided by the number of the allowable re-grinds; N_p represent the number of pieces that can be manufactured by a tool.

2.3 Machine tools

2.3.1 Lathes

Lathes are machines used for performing turning process; **parallel** or **engine** lathes (figure 2.5) are manual, while **CNC** ones are computer controlled and they can have a horizontal (single or multiple) spindle as well as vertical or with a sliding headstock (used for small components).

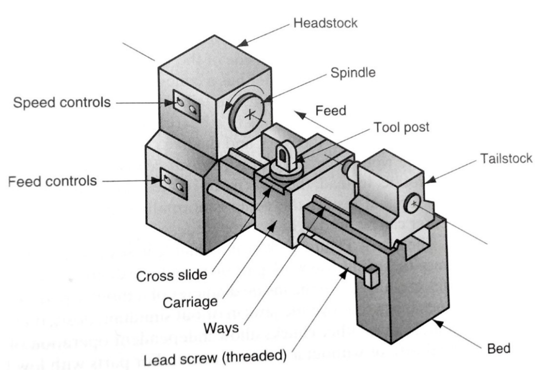

Figure 2.5: *schematic representation of a parallel (engine) lathe.*

CNC lathes are similar to engine lathes but are enhanced by a computer-numerical-controller. The mechanical layout is arranged in order to allow automatic chip evacuation. Usually controllers handles 3 axis and a spindle (or more motion axis); they can also have a rotary tool determining so an **hybrid turning-milling** machine.

They can dispose a **roller-turner** that automatically allows the machine to change the machining tool.

Such machines can presents multiple tools and spindles and so with an increased complexity.

Sliding headstock lathes presents a spindle that allows to axially move the component while the piecework is still rotating.

While dealing with lathes, the most important **parameters** to determine are the turning diameter and length (maximum dimensions that can be machined), the slewing (dimensions of the raw material that can rotate on the spindle (but cannot be worked), the travels along the z, x axis (but also other motion axis), the spindle speeds, the rapid speeds (maximum displacement speed along the axis, typically $10 - 40m/min$) and spindle torque/power. Note that working with lower diameters, the required rotational speed is higher (while bigger components requires more torque) in order to maintain the tangential velocity constant.

Usually graphs provided by manufacturer depends on the operating time `ED` as the values obtained considering, as example 100% time work-load or 40%.

2.3.2 Milling machines

Milling machines presents a huge variety of architectures whose common denominator is the rotary tool. Spindles can be both horizontals or verticals and when more then 3 axis are moving we refer them to **milling centers** that are sub-categorized as universal, pallet changes (the machine has two pallets: one that's objected of work and the other that can be accessed by the operator), travelling column.

Milling machines can be also realised using parallel kinematics (that's more complex to serial one) that realise faster movements for the same overall weight of the machine; a draw-back of this implementation is that the accuracy is not uniform in the whole working volume.

Vertical and horizontal spindles Vertical spindle machines are easier to implement, present an easy fixturing but has the problem of difficulties in the chip removal. Horizontal spindles presents a better chip disposal and allows for large travels with the draw-back of a more difficult fixture.

Parameters Parameters for milling machines are similar to the lathes, but comprehend also axes configurations and related travels.

2.4 Automation

Tasks of a CNC machine tool is to convert a machining description into machining movement and then run machining commands with *judgment* (level 4 on the yardstick table, page 3).

Given the **part-program** containing the information about the process that has to be performed, such file is passed to the CNC (the computer numerical control) that gives instruction to both **drivers**, the electronic systems controlling position and motion of machining axis with sync, and **PLC** (*programmable logic controller*, a separate hardware or a software in the same CNC machine), special controls that actuates supplementary axis (as safety doors or swingling arm for pallet change) that does take care on *discrete* states (a door is open or closed, it doesn't matter it's trajectory nor motion).

Linear axis control