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Ph.D. Thesis

Intelligent Machining Systems

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The best time to plant a tree was 20 years ago. The second best time is now

---

Chinese Proverb

Abstract

Machining is one of the most widespread manufacturing processes and plays a critical role in industries. As a matter of fact, machine tools are often called mother machines as they are used to produce other machines and production plants. The continuous development of innovative materials and the increasing competitiveness are two of the challenges that nowadays manufacturing industries have to cope with. The increasing attention to environmental issues and the rising costs of raw materials drive the development of machining systems able to continuously monitor the ongoing process, identify eventual arising problems and adopt appropriate countermeasures to resolve or prevent these issues, leading to an overall optimization of the process. This work presents the development of intelligent machining systems based on in-process monitoring which can be implemented on production machines in order to enhance their performances. Therefore, some cases of monitoring systems developed in different fields, and for different applications, are presented in order to demonstrate the functions which can be enabled by the adoption of these systems. Design and realization of an advanced experimental machining testbed is presented in order to give an example of a machine tool retrofit aimed to enable advanced monitoring and control solutions. Finally, the implementation of a data-driven simulation of the machining process is presented. The modelling and simulation phases are presented and discussed. So, the model is applied to data collected during an experimental campaign in order to tune it. The opportunities enabled by integrating monitoring systems with simulation are presented with preliminary studies on the development of two virtual sensors for the material conformance and cutting parameter estimation during machining processes.

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List of Abbreviations

ADC Analogic to Digital Converter.

ADS Automation Device Specification.

AIA Aircraft Industries Association.

ALE Arbitrary Lagrangain-Eulerian Tecnique.

AMC American Materiel Command.

API Application Programming Interface.

APT Automatically Programmed Tool.

ATC Automatic Tool Change.

BLE Bluetooth Low Energy.

CNC Computerized Numerical Control.

CPS Cyber-Physical System.

CPU Central Processing Unit.

CRC Cyclic Redundancy Check.

CSV Comma Separated Values.

DB DataBase.

DHCP Dynamic Host Configuration Protocol.

DNC Direct Numerical Control.

DOE, DoE Design Of Experiments.

DPDT Double-Pole, Double-Throw.

EMF Electromotive Force.

ERP Enterprise Resource Planning.

FB Function Block.

FFT Fast Fourier Transform.

FIFO First-In First-Out.

FRF Frequency Response Function.

GM General Motors.

GPIO General Purpose Input Output.

GUI Graphic User Interface.

GVL Global Variable list.

HMI Human-Machine Interface.

I/O, IO Inputs Outputs.

IEPE Integrated Electronics Piezo Electric.

IIOT Industrial Internet of Things.

IMU Inertial Measurement Unit.

IOT, IoT Internet Of Things.

IPC Inustrial PC.

IT Information Technology.

JSON JavaScript Object Notation.

M2M Machine to Machine (Communication).

MCU MicroController Unit.

MDF Medium-Density Fibreboard.

MDI Manual Data Input.

MEMS Micro-ElectroMechanical System.

MES Manufacturing Execution System.

MIT Massachusetts Institute of Technology.

MQTT Message Queue Telemetry Transport.

MRR Material Removal Rate.

NASA National Aeronautics and Space Administration.
NCK Numerical Control Kernel.

OECD Organisation for Economic Co-operation and Development.

PLC Programmable Logic Controller.
POC, PoC Proof of Concept.
PVDF polyvinylidene fluoride.

RAM Random Access Memory.
RF Radio-Frequency.
RMSE Root Mean Square Error.

SME Small and Medium Enterprise.
SOC, SoC System On a Chip.
SPI Serial Peripheral Interface.
SQL Structured Query Language.
SRAM Static Random Access Memory.
STO Safety Torque Off.

TSDB Time Series DataBase.
TwinCAT The Windows Control and Automation Technology.

WEF World Economic Forum.

Introduction

The introduction of new technologies, such as artificial intelligence and digital twins, in industry led to the development of new production paradigms. Despite the development of innovative production processes, such as additive manufacturing, machining processes are still widespread in manufacturing realm and covers a crucial role in production. The recent developments of information technologies, together with the diffusion of relatively low cost sensors and the advancements in automation technologies allow the integration of advanced monitoring systems in production machines. The process monitoring applied to machine tools has been studied since many years, however the implementation of these systems on actual production machine is still not so diffused despite the advantages related to the introduction of these systems. The adoption of intelligent machining systems could enable advanced functions for the machines and could improve the performances of the machines in therm of accuracy and effectiveness. The increasing attention to sustainability, and the increasing costs of raw materials makes important to minimize the waste in production so it's important to promptly identify, or evenly to predict, production issues and to adopt the countermeasures to correct the process in order minimize the defects.

The research works focuses on the development of advanced monitoring systems with different objectives and scope of applications but with the common aim to enables the development of intelligent machining system. Different solutions, based on consumer-grade and industrial-grade are presented depending on the scope of the systems. The main field of application of the proposed systems are machining processes, especially in milling operations. However some examples of intelligent systems for woodworking industries and power tools monitoring are presented in order to demonstrate the applicability of these technologies in different fields.

This thesis is structured as follows:

- **Chapter 1:** The first chapter provides a general introduction to CNC machines. A brief history of the development of NC machine is discussed in order to understand the reasons which led to the development of these machine and their development path. Then the structure of a numerically controlled machine tool is reported an described both from the mechanical and automation point of views. An introduction of the concepts of adaptive numerical controls is also given together with a brief overview on the industry 4.0, from its definition to the related technologies.

- **Chapter 2:** This second chapter is devoted to the discussion of some case studies about the development of advanced monitoring systems for industrial applications.

- **Chapter 3:** The third chapter is dedicated to the presentation of an example of machine retrofit in order to enable the implementation of intelligent machining systems on an existing machine. The second part of this chapter is dedicated to the identification and modelling of the machine structure and some parts of it in order to obtain mathematical models which can be used in the development of advanced monitoring algorithms.
- **Chapter 4:** The fourth chapter is dedicated to the presentation of three examples of milling machine monitoring systems. In this chapter three different developed monitoring systems are presented and their functionalities are described and discussed.
- **Chapter 5:** The fifth chapter present the process of implementation of a digital twin of machining process developed in order to be implementable in real-time into the outer control loop of a machine tool. The models for the cutting tool and for the milling tool are presented and discussed. Then a design of experiments is developed in order to tune and validate the model. Finally the functions enabled by the integration between simulations and process monitoring are presented and discussed.

Chapter 1

NC Machine Tools

1.1 History of Numerically Controlled machine tools

Figure 1.1: Aluminium ashtray produced in 1959 as part of a demonstration of a milling machine controlled by a computer punch tape. [69].

Numerical Control, known also as Computer Numerical Control, refers to the automated and direct control of machining tools by means of a set of instructions given by a computer or other devices such as, for example, punched tape reader. NC machine tools allow to produce complex-shaped pieces much easily if compared with traditional machine tools. If compared to mechanically controlled machine tools, which were widespread employed in large-scale production, numerically controlled machines allow economic automatic production also for small series and single pieces. [29]

A significant role in the advancement of manufacturing technologies was played by the Second World War. The growing demand for military aircraft was too high if compared tothe production capabilities of the aircraft manufacturer in US. Thus forced the conversion of the production of the auto industries that, for the time being, were very well developed and organized [95]. Production changeover allowed the cross-contamination of the know how and manufacturing technology between auto and air plane industries, this can be considered another factor for machine tools and materials engineering both for tools and construction materials [15].

As a consequence of aircraft industry expansion, also machine tools industry experienced a growth in demand of new machines. Between 1941 to 1945 800.000 machine tools has been produced by the American machine tools industry. [15]

MACHINE TOOLS	Total Units Now in Place	Units Over 10 Years Old	% Over 10 Years Old
Boring Machines	50 337	17 180	34
Broaching Machines	9 701	3 416	35
Centering Machines	3 458	800	18
Cutting-off Machines	75 756	25 922	34
Drilling Machines	307 664	119 989	39
Gear-cutting Machines	55 034	16 428	29
Grinding Machines	366 464	109 147	30
Honing and Lapping Machines	16 134	2 119	13
Keyseaters	4 466	3 202	72
Lathes	418 501	169 581	40
Milling Machines	171 763	63 986	37
Pipe Cutting and Threading Machines	10 241	5 014	49
Planers	16 427	12 813	78
Polishing and Buffing Machines	57 384	23 574	41
Rifling and Rifle Reaming Machines	1 486	500	34
Shapers	36 703	23 579	64
Threading Machines (exc. for pipe)	34 978	13 963	40
Other Machine Tools	44 122	32 619	74
GRAND TOTAL	1 711 137	652 185	38

Table 1.1: American Machinist's 1945 inventory of machine tools operated by metal-working industries - Summary Table. [27]

The American Machinist inventory of metal-working equipment taken in 1945 states that only the 38% of machine tools in use in metalworking industries were more than 10 years old while in 1940 these were the 72%. It's also worth noting that, if only aviation industry equipment is considered, this rate drops to 2%, while, in the sector "Business Machines" (which groups the producers of adding and calculating machines, cash registers and typewriters) the machines with more than 10 years are the 62% of 17 303 units installed. The table 1.1 lists a summary of the results of the American Machinist's Inventory of Metal-Working equipment taken in 1945. This survey was taken ever 5 years since 1925. The data where obtained by 22 000 metal-working companies all-over the United states and in all segments of the metal-working industry. The comparison of the data obtained from different editions of the inventory allows to understand the trend of development and renovation in metal-working industry. Specifically, by comparison between the data of the 1940 and the 1945 inventory an absolute raise of the number of installed machine-tools can bee seen, from 1940 to 1945 the total tools in place in US raised from 1 000 112 to 1 711 137 with an increase in installed equipment of more than 700 000 pieces. Another important data to account is the percentage of over 10 years old machines, this indicator highlights the state of ageing of the industrial plants, as can be seen in graph 1.2 this rate has been almost halved in the 5 years period between 1940 and 1945.

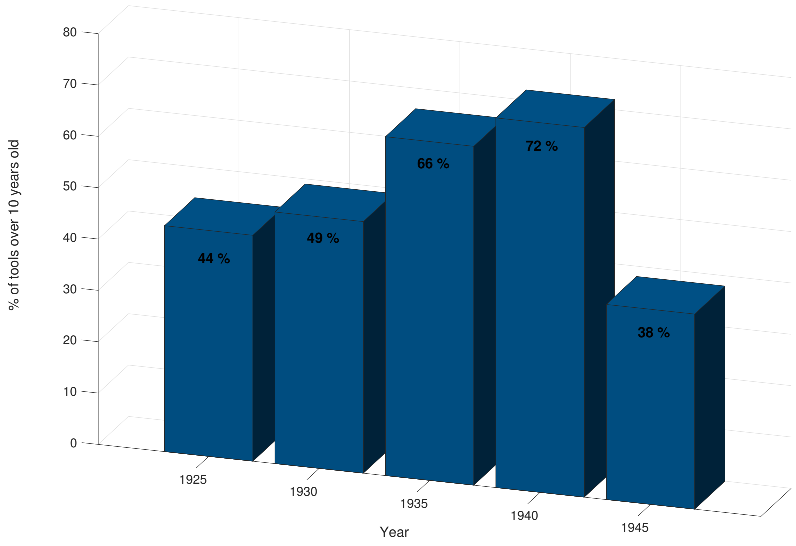


Figure 1.2: Percent of tools over 10 years old, 1925 - 1940 [27].

After the war ended and manufacturing industries were re-converted to civilian production, the advanced production methods and tools developed during the war were applied to civilian production. In America, the industries were heavily equipped with new machinery for high-volume production with an extensive use of mechanization. Also tools materials had a great advance during the WWII, in fact cemented carbide tools experienced a rapid and large diffusion among manufacturing plants in US.

While the main trust in manufacturing technology development had been in the improvement and extension of mass production methods, in early 1950s a new trend began;

with the increasing importance of aircraft industry, the need of producing small batches of complex shape parts with high precision requirements led to the development of a new class of machine tools. With respect to transfer machines and other highly automated machine tools employed in industry at that time, the new machines had to maintain the elevated automation with an higher level of flexibility in order to minimize the time needed to change between different production batches.

In those years, John T.Parsons, head of "Parsons Corporation", and his chief engineer Frank L. Stulen were developing computer methods to solve machining problems. In the first 1940s Parsons got a contract with Sikorsky Aircraft to build wooden parts for helicopter's rotor blades. The development of production technologies led Parsons to consider the practicability of using metal stamped stringers instead of wooden ones. The use of metal instead of wood would simplify the assembly procedures as well as make the structures stronger. However, there was a major issue: the complex shape of the stringers need to be replicated in a cutting tool made in tool steel. The production of the jig would not be too easy due to the complexity of the shape to be replicated and to the difficulties in machining tool steel. To try to solve this issue Parsons hired Frank L. Stulen which developed a method to perform automated calculations in order to obtain the coordinates of the points of the outline of he stringer profile. The points generated had to be offset by the radius of a mill cutting tool so that cutting each of these points would produce a relatively accurate cutout of the stringer. Stulen developed the program and run the calculation so he obtained large tables of coordinates which were taken onto the machine floor. In the workshop a machine operator read the table while two other operators, controlling respectively the X and the Y axis of the mill, would move the cutting head to the indicated coordinates and then lower the tool to make the cut[72]. This was called "plunge-cutting positioning" [69] and can be considered a first prototype of today's 2.5 axis machining. It's worth noting that there were no automation so the production was labour-intensive also because the work-piece needed to be filed to have a smooth shape.

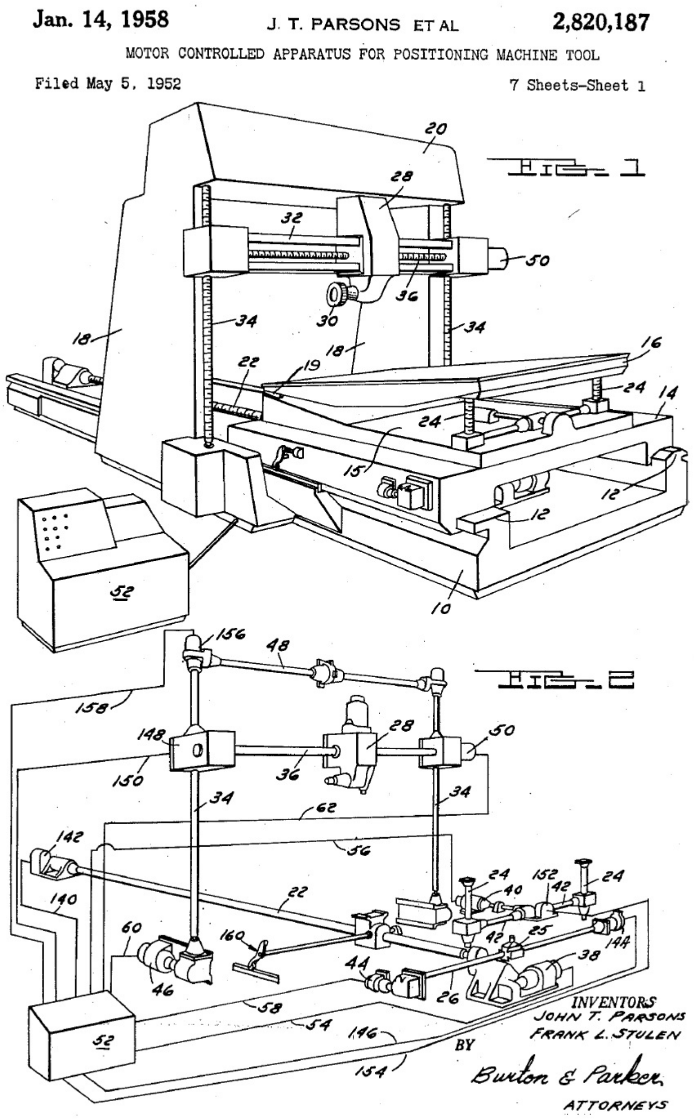
This first attempt was the base for the development of a fully automated machine tool, with enough points on the outline the machine could be directly moved by servomotors and no manual intervention would be needed to finish the outline.

In 1949 Parsons had some contact with Lockheed which was developing a new jet-powered aircraft for US Air-Force. Along with Snyder Machine & Tool Corp, Parsons started developing his own automated machine with the funds arranged by Lockheed however they had serious issues with the accuracy because of the non linearity of the control.

Parsons decided then to contact MIT's Servomechanism Laboratory to try to advance the project. Then, in 1952, Parsons filled for a patent on "Motor Controlled Apparatus for Positioning Machine Tool", so he received US Patent 2,820,187 on 14 January 1958 [74].

The first public demonstration of the milling system developed by MIT, was held in September 1952 [64]. Despite the outstanding success, MIT's machining system was terribly complex and not so much reliable for a production environment.

The machine presented by MIT was developed on a Cincinnati Milling Machine Company "Hydro-Tel" mill. The system was substantially composed by two parts, the actual



Jan. 14, 1958 J. T. PARSONS ET AL **2,820,187**

MOTOR CONTROLLED APPARATUS FOR POSITIONING MACHINE TOOL

Filed May 5, 1952 7 Sheets-Sheet 1

INVENTORS
JOHN T. PARSONS
FRANK L. STULEN
BY
Burton & Parker
ATTORNEYS

Figure 1.3: First page of the patent on “Motor Controlled Apparatus for Positioning Machine Tool” [74].

milling machine ant the so-called “director”. The machine had a work capacity of 64 x 30 x 14 inches. All three of its axis were equipped with servomotors an feed-back systems connected to the numerical control in order to allow any combination of the tree motions to take place synchronously.

The director was the governing unit of the system. The director consisted in five cabinets containing the functional parts of the system. It was built by three main elements:

- The data input system, whose purpose was to take the instructions from the punched tape and route them into the command interpreter;
- The data interpreting system. The main purpose of this system was to convert the numerical instructions provided by the tape reader in pulse instructions which were then transmitted to the decoding servomechanisms;
- A set of three decoding servo-mechanisms which converted the digital signals, coming from the data interpreter in the form of a pulse wave, into analogue signals. These devices were quite complex as they involved both electronic and electro-mechanical devices needed for the conversion [75].

The machine was controlled by a 7-track punched tape (figure 1.4). The three bottom tracks encoded the different axes movement while the four top tracks contained some control informations. The center track, with smaller holes, was used by the feeding mechanism to move the tape into the reader.

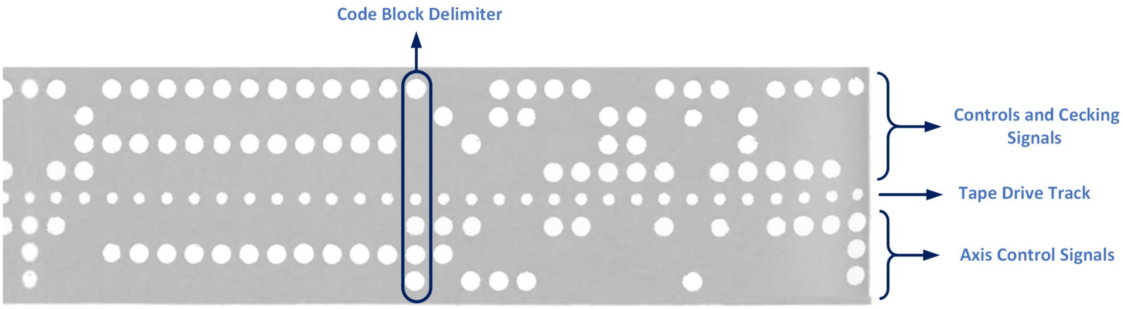


Figure 1.4: Example of punched tape used in NC Machine.

In 1953 the Air Force Numeric Control ans Milling Machine Projects was formally concluded. However the development of the machine still continued at Gidding and Lewis Machine Tool Co., which became the main sponsor for the project, and other locations. In this years, many firms started developing their own numeric controlled machine tools, among them are notable Monarch Machine Tools, and Kearney & Trecker which at the 1955 Chicacgo Machine Tool Show presented respectively a numerical controlled lathe and the Milwakee-Matic, a NC milling machine which could change its cutting tool automatically under numerical control.

Along with the development of the machine itself, MIT conducted an economic analysis among the main American aircraft firms to study the expected impact of these new technologies in productivity and efficiency of the factories. With these studies, MIT attempted to directly compare the costs of a piece produced on their machine with the costs of the same piece produced by conventional methods. The engineers briefly encountered as strong issue: it appeared impossible to obtain reasonable estimates of the costs of the pieces produced with both the production methods. A team from the MIT School of Industrial Management hence supported the engineers for the advance of the research. The work carried out by researcher didn't find a definitive answer to the question of relative cost however it provided rough costs comparisons. The most important outcome of this research was represented by the identification of the most profitable area for future development, which was the programming part [96].

Programming an NC machine involved a series activities which ranges from the decomposition of the curves in a series of segments, to the calculation of the points delimiting the segments, to the realization of the punched tape. As explained by Arnold Siegel, part of the Whirlwind project, the process of production of a control tape for a numerical control machine tool may require many hours of tedious hand work even for a relatively simple piece [71].

Aside from the economical point of view, the time and effort required in the preparation of the NC tapes also introduces possibilities of errors. These reasons drove Air Force to initiate many projects with MIT for the development of Automatically Programmed Tool (APT) and Computer-Aided Design.

In those years the MIT Servomechanism Laboratory in partnership with US Navy was working on the Whirlwind project for the development of the first digital electronic computer that operated in real-time, called Whirlwind I. John Runyond decided to use the computer to produce the tape for the NC machine tool. Hence he coded a subroutines library which allows the user to automatically produce a punched tape by entering into the pc a list of points and speeds. The automated programming process drastically reduced the time required to produce the punched tape.

Based on the success of the Runyond library and the promising results of the Air Force-sponsored project for the development of the first automatic programming language, the team decided to submit to the Air Force a proposal for further development of automatic programming at MIT laboratories. The Air Force Accepted the proposal and, from June 1956, the project for the development of Automatic Programming Tool started at the newly created Computer Applications Group [80].

As a consequence of this change of focus from the development from the engineering and the development of the servomechanism to the study of programming languages and computer applications led almost all the staff of the engineering project to left the Laboratory to form Concord Controls, Inc. which, in conjunction with Giddings and Lewis, worked on the improvement of the director system on a more commercial basis [21].

Due to the increasing interests in the field of production automation, in 1957, Air Materiel Command (AMC) and the Aircraft Industries Association (AIA) joined with MIT in the so called “Joint Effort”. This joint program was aimed to standardize the programming language and to produce a comprehensive computer-controlled NC system [96].

On 25 February 1959, a press conference was held at Massachusetts Institute of Technology. The conference was jointly sponsored by AIA, AMC and MIT and was attended by many members of technical and popular press from all over the world. The conference presented the results of the first APT project. To demonstrate the potential of CNC machines, a 3D machined aluminium ashtray was included in the press kit distributed to attendants. [69] These conference can be deemed as the inauguration of the Computer-Aided manufacturing era [80].

In the last ’50s MIT’s Lincoln Labs was advancing in the development of computers. The aims of their research was to build a transistorized version of the Whirlwind, which was called TX-2 (Transistorized eXperimental computer 2). The use of transistors in spite of vacuum tubes allowed a drastic reduction of computers dimensions and costs, encouraging the diffusion of these system in industries. Further, the advances in electronics led to a general reduction of costs of electronics components, included the devices related to motor control and feedback circuits. These factors all contribute to the diffusion of CNC machine tools but the real push to the widespread deployment of these machines came from the introduction of microprocessors in the 1970s.

The progressively reduction costs of CNC machines changed the manufacturing industry. Complex shapes and 3D curves were then easier to be produced and also consistency and quality of products were drastically improved without the need to increase operators' specialization and skills. The introduction in industry of CNC machine tools allowed the emergence of new professions such as CNC programmers and operators and automation experts.

Figure 1.5: Vertical Milling Centre *Haas Automation Inc.*

1.2 Structure of CNC Machine Tools

The components of a machine tools systems can be divided in three main categories:

- Mechanical structures

- Drives
- Controls

1.2.1 Mechanical structure

The mechanical structure of a machine tool is composed by moving and stationary bodies. In stationary bodies frames, columns, bridges, basements, beds, and gearbox houses are included. Their main task is to support and carry moving bodies such as carriages, tables, slides, spindles, and gears. To reach high precision and repeatability, the structural design of these components requires high rigidity, thermal stability, and damping. In General, the size of machine tools parts is overestimated in order minimize static and dynamic deformation during machining. However, nowadays, due to the advances in electronics and controls and to the raise of costs of raw materials, machine tools producers are developing machine with lighter structures, also using advanced materials like carbon fibre reinforced polymers.

The study of the dynamic behaviour of machine's structure is fundamental as it heavily affects machining precision. In order to maximize machining performances without affecting precision, is important to pay a particular attention to static and dynamic compliance of the structure of the machine and the relative compliance between the tool and the workpiece. These can be evaluated during the design phase with analytical methods but they can be experimentally measured on the actual machining system.

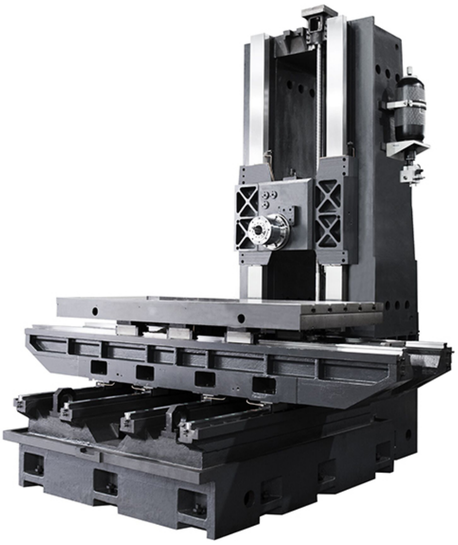
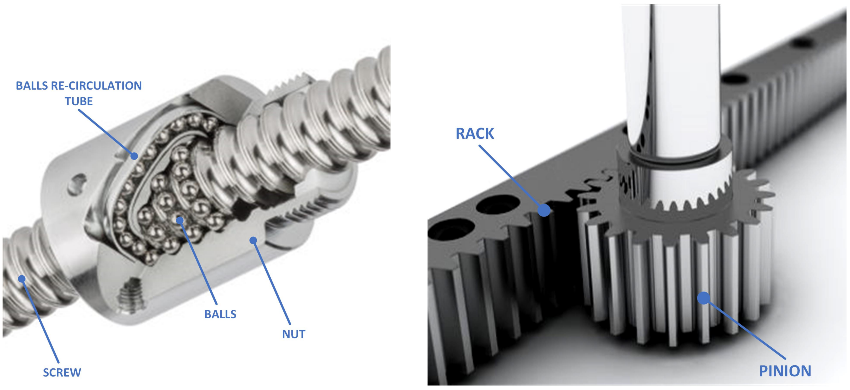


Figure 1.6: Horizontal Milling Centre Frame

1.2.2 Drives

In machine tools, two main groups of drives can be found, spindle drives and feed drives. The first group of drives is the one devoted to spindle management. Spindle drive has to provide sufficient angular speed, torque, and power to a rotating spindle shaft. The spindle shaft is held in his housing with roller, magnetic or hydraulic bearings. Low and medium speed spindle shaft are connected to the electric motor via V belts. Depending on the application, there may be a single-step gear reducer and a clutch between the spindle shaft and the electric motor. In case of high-speed spindles, the electric motor may be integrated into the spindle assembly, this to reduce the inertia and friction produced by the couplings between spindle and motor. Carriages and tables are actuated by feed drives. The most widespread actuation mechanism is the leadscrew. This mechanism involves a leadscrew mounted under the machine table. The drive motor is connected to the screw. The connection between motor and screw could be either direct or via a gear system, depending on the required feed speed, inertia, and torque. Except for some special construction, each leadscrew has a dedicated drive motor and drive. In some particular cases, such as high-speed machine tools, linear motors and drives can be used instead of feed screws and nuts or pinion and rack drive systems. The main advantages when using linear direct motors are the higher speed and the best acceleration performance, the improvement of positioning precision and the dramatic reduction in friction and inertia if compared to screw-actuated drive systems.



(a) Ballscrew (b) Rack and Pinion

Figure 1.7: Examples of actuation mechanisms

1.2.3 Controls

The main difference between conventional machine tools and CNC machines can be found in the control part. In a conventional machine tool the control is mainly electro-mechanical and includes relays, limit switches and operator-controlled potentiometer and switches. Its main task is to provide the power to the spindle and to the feed motors and auxiliaries. The operator has to control and to set motor speed and directions acting directly on the gearboxes. There are no automations in the machine. In a CNC machine tool the control part is much more complex as it includes motors, amplifiers, electronic boards that are controlled by a computer which activate the devices in a controlled sequence and time. The control cabinet of a CNC machine tool can contain many computers, depending on the amount of functions that are implemented in the machines such as automatic tool change, pallet changer, and bar feeder. Fieldbuses plays a crucial role in modern CNC machines controls as they provide a safe and time determined digital communication channel between the different parts of the machine tool. The use of a fieldbus instead of parallel wiring and digital IO allow many advantages, such has reliability and interference immunity.

1.3 NC Structure

The NC unit is the fundamental component of a CNC machining system. The numeric control unit is in charge of the control an management of all devices in the machining system, from servo mechanism to auxiliary devices, from power to safety devices. Both hardware and software components are included in the NC, which is indeed a complex system.

Looking at the NC from a functional point of view, three units which carry specific tasks can be identified. These elements are:

- HMI unit - *Human Machine Interface*, it provides the interface between the machine and the human operator. It collect the commands givent by the operator and send them to the execution units. HMi also displays information about machine status and diagnostic. It can moreover have complementary functions such has part-program editor or graphical simulations;

- NCK unit - *Numerical Control Kernel*, this is the core of the CNC system. NCK is in charge of interpretation of part-program instructions and execution of interpolation, position control and error compensation. Servo system is also directly controlled by the NCK.

- PLC unit - *Programmable Logic Control* it controls the base functions of the machine tools. PLC controls all the machine's system apart from servo system. PLC controls, for example, automatic tools and workpiece change as well as input and output signals to and from the machine. PLC can also control the spindle and its speed if this is not controlled by the servo system. PLC can also controls safety device such es emergency switches, light barriers, interlocks and so on and can be able to stop the execution of the part program in case of safety issues.

These three components can be distributed in three different hardware unit one for each function but nowadays, with virtualization and advanced task management, a single processing unit can host the three function in separate processes and task. In this case we have the so-called soft-PLC and soft-CNC which are increasingly used in modern machine tools.

1.3.1 HMI

HMI provides the functions needed by the user when operating the machine tools. The functions provided by the HMI can be grouped in five categories.

1. **Operation Functions**: This first category groups all the functions which are usually exploited for the normal operation of the machine and to check the actual machine status (i.e. axes position, spindle speed, active g-codes etc.). By using these functions the operator is also able to change the mode of operation of the machine changing for example from program, to MDI or jog or to program editor etc.

2. **Parameter management and settings**: a set of functions for displaying, searching, editing and storing the various parameters which can be used to tune the numerical control and to customize it to fulfil the application requirements.

3. **Program editor**: These functions enable the operator to modify the part program directly on the machine. Although their usefulness these functions are actually difficult to use and require, from the operator, a good knowledge of the G-Code and the execution of some mathematical and geometric calculations. The recent developments on the HMI presented by the various CNC firms are going in the direction of the simplifications of the on-machine programming and program editing by using wizards and guided procedures.

4. **Alarm and monitoring**: in this category are collected the functions related to the continuous monitoring of the machine status (for example the status of the different IOs connected to the PLC). Also some functions needed in case of system failure are included in this category (i.e emergency recovery function, or recovery of ATC in case of issues during tool change cycle).

5. **Auxiliary, Utility and Service functions**: here are grouped the functions that are not strictly required for the normal operation of the machine tool but are still important as the can assist the user during the operations. In this category there are function for the remote control of the machine (es DNC) or functions for the connection of the machine to the network.

1.3.2 NCK

The numerical control kernel is the core part of the CNC. It is the component that actually reads the part program a row at a time, store in memory the data obtained by program parsing, dispatch the commands to the servo-drive system and observe the feedback signals coming from the machine. NCK is also involved in all the mathematical calculations related to the movement of the machine. For example it is in charge of the synchronization between the axis of the machine when moving along a circular trajectory or in any other kind of trajectory which involves the simultaneous movement of more than one axis. NCK is moreover constantly connected with the PLC as, based on the instruction contained in the G-CODE, the NCK needs to dispatch to the PLC commands for the activation or deactivation of spindle and auxiliary components such as coolant or to trigger the tool-change routine. For a better understanding of the working principle of the NCK, it can be divided in four functional blocks, each of these is in charge of a specific task.

1. The **interpreter** is the first functional block of the numerical control kernel, its main function is to read the part program, to interpret the blocks and to store the interpreted data in the memory buffer. To prevent the stop of the machine due to the possibility to have complex data blocks whose interpreting take more time then the time employed by the machine to complete the active program, there is a temporary buffer where an appropriate quantity of commands are stored waiting to be executed.

2. The **intepolator** is the unit which sequentially reads the data from the buffer. Basing on the data read from the buffer, the interpolator, performs the calculations needed to obtain the position and the velocity per unit time for each axis. The results of the calculation are stored in a FIFO buffer.

3. An **acceleration/deceleration control** is performed in order to avoid vibrations and shocks of the machine's axis caused by excessive accelerations and decelerations. This control can be performed before or after interpolated data is sent to the position controller.

4. The last part is the **position control**. This part is the nearest to the machine drive system and is the component which actually exchange data with the servo drive system. It can be represented as a PID control loop with as input the target position and speed. The control loop take as feedback the position information coming from the encoder and then act in order to minimize the difference between the target position and the actual position of the axis. The control loop can have also other advanced features like feed forward loops and notch filters to improve the performance of the system in therms of response and stability.

1.3.3 PLC

The programmable logic controller performs the control of the low-level functions of the machine. It is the evolution of the electro-mechanic logical controller which were built using relays, contacts and coils in large cabinet. With respect to the hardware logic controller, PLC offers more flexibility and a better manageability of the system. PLC is substantially a micro-controller, with real-time capabilities, which cyclically executes a sequential program so if a change in the logic of the control is needed, the only thing to be modified is the program without the needs for hardware modifications. In CNC the PLC controls the input and output signals. PLC is hence able to control the status of auxiliary devices like hydraulic pumps, conveyors, lights and all the devices excluded the servo-drive system. The PLC is also in charge of the control of safety of the machine. This particular PLC is called safety PLC and is usually a dedicated unit well recognizable in control cabinet since its characteristic yellow-coloured casing. Safety PLC monitors all safety inputs such as emergency buttons, light barriers, laser scanners etc. and can toggle the safety outputs which usually are brakes, locks, lights and sirens. Safety PLC is eventually able to stop the machine in case of safety issues or to put the machine in a safe state (for example STO *Safety Torque Off*) in which the machine is still active but the maximum torque and speed of axes are lowered to a safe level.

1.4 CNC architecture

In general a CNC machine can be divided in three functional blocks,

- Numerical Control, which encompasses most of the logic of the machine;
- Drives, in which are grouped all the power electronics devices for axes, spindle and auxiliary devices;
- Machine tool, which contains the motors with their transducers and the mechanical structure of the machine whit the position transducer eventually installed on the axes.

During the operation of the machine there is continuous data exchange among these blocks, in particular analyzing the working principles of the CN machine and its components, it's possible to identify three feedback loops that are fundamental for the machine operation. These are the motor current feedback loop, the speed feedback loop and the position feedback loop. Depending on which of the three blocks is in charge of the management of the feedback loops, three basics CNC architectures can be identified.

1.4.1 NC centralized control

In NC centralized control all the three feedback loops are closed by the NC. It contains a position regulator, a speed regulator and finally a current regulator, the drives are substantially current amplifiers which receives an analog signal from the NC then amplifies it to a power signals to feed the motors. This architecture ensures a better communication between hardware and software communication among the logics part of the machine which are indeed all concentrated in the NC.

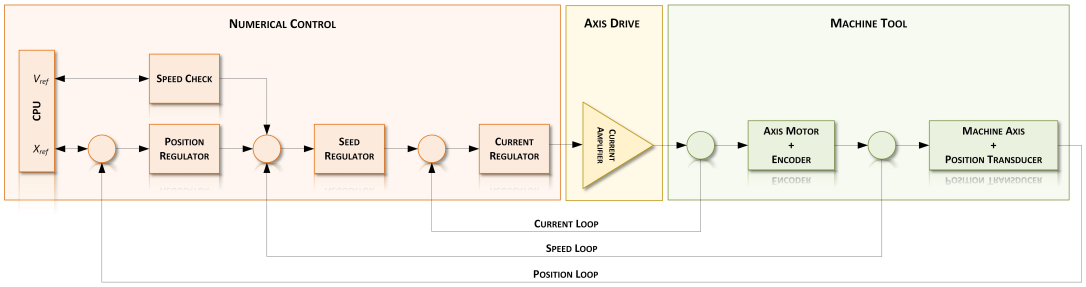


Figure 1.8: Scheme of NC centralized control

1.4.2 Drives centralized control

This architecture is characterized by all the three loops closed by the drives. In this case part of the logic of the is included in the drive which can be considered a smart drive. Each drive receives from the NC the target position and a target speed, then has to execute all the calculation needed to regulate properly acceleration and speed in order to reach the target point. This architecture implies a large amount of data sent from the NC to the drives so it's feasible only if high speed communication bus between NC and Drives is available. This architecture is typical of modern machines with servo drives.

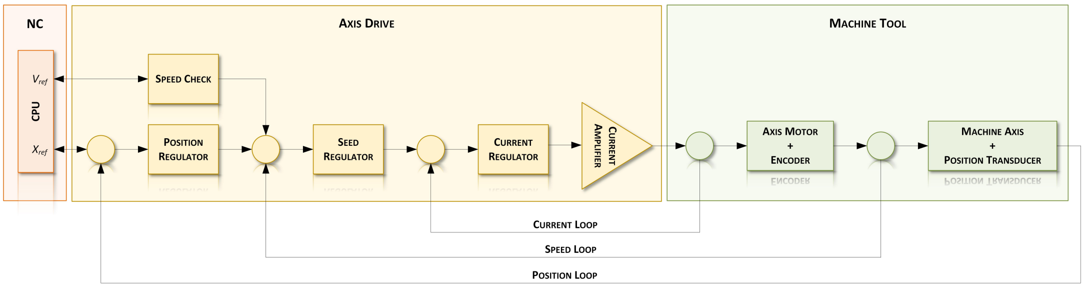


Figure 1.9: Scheme of Drives centralized control

1.4.3 Mixed Control

In this case the NC is in charge of position and speed control while the drive controls the motor current loop. In this case the NC send to each drive a speed signal and the drive has to regulate and amplify the current in order to reach the target speed. This architecture is typical of some machines actuated by stepper motors in which the NC send to the drives a train of pulses of frequency proportional to the speed to be reached by the motor and a direction signal, then the motor drive has to generate and regulate the appropriate current in order to move the motor at the requested speed.

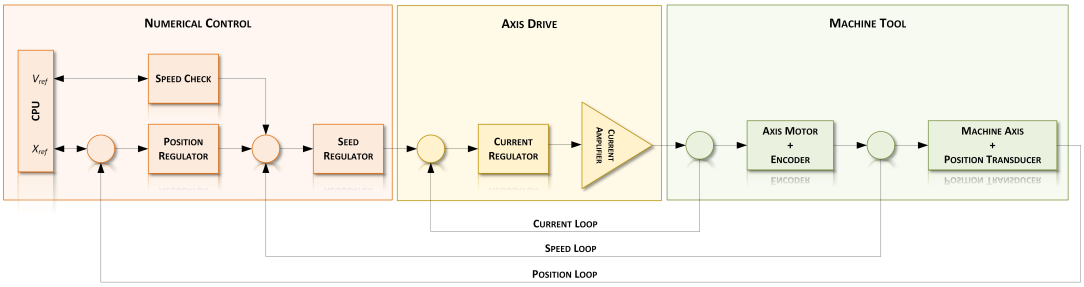


Figure 1.10: Scheme of Mixed control

1.5 Adaptive Numerical Control

The introduction of numerically controlled machine tools led to deep changes in manufacturing realm allowing the production of complex shaped parts with a relatively reduced effort, providing high quality and precision products. Despite the great improvements in CNC machine technologies, many tasks are still in charge to the machine operators and programmers. One of the most important tasks that CNC programmer has to carry out is the choice of the cutting parameters. These are usually chosen basing on the past experiences or from workshop manuals and handbooks. CN machine programmers has to consider many aspects and usually the parameters are chosen considering the so-called worst case scenario in order to reduce the risks of issues during the operations [76]. Parameters selected with these approaches lead to work under the potential of the machine o with non-optimal cutting parameters [19]. In the last years, many researchers studied and developed advanced numerical control systems which allows real-time cutting parameters variation in order to adapt them to the current working conditions. It's worth noting that the meaning of adaptive control in this context is slightly different from the definition of adaptive control usually given in the field of automatic controls [51]. In this context an adaptive control is a techniuqe of numerical control of machine tool which allows the adaptation of some or all the machining parameters in order to comply with one or more objectives wile respecting imposed constraints.

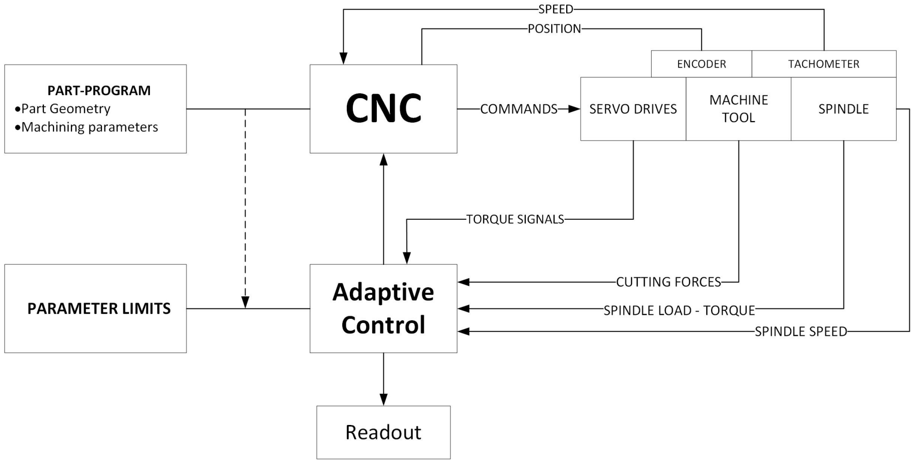


Figure 1.11: Schematic illustration of the application of adaptive control [48].

The objectives of an adaptive control could be:

- Production rate optimization;
- Increase and optimization of products quality;
- Production costs minimization;
- MRR (Material Removal Rate) Maximization;
- Chatter reduction and avoidance.

1.5.1 Classification of Adaptive Controls

Basing on the optimization objectives, Adaptive Control systems can be classified in three categories:

- **GAC** *Geometric Adaptive Control.* The aim of this kind of adaptive control is to optimize the dimensional quality of the product in terms of dimensional accuracy and roughness. In this case the adaptive control acts directly on tool trajectories in order to compensate tool's or machine's deflections due to cutting forces or thermal gradients. This kind of adaptive control is ideally utilized in finishing phases when MRR are low but the dimensional accuracy is crucial.
- **ACO** *Adaptive Control with Optimization.* The objective of this adaptive control is to optimize a performance index such as production time, machining costs, energy consumption or cutting tool duration. In this cases machining parameters are varied in order to optimize the performance index. The most used performance index is the material removal rate, which describes the specific amount of material removed per time. This type of optimization may act on different cutting parameters such as feed-rate or depth of cut, however some constraints has to be fixed. For example a limit can be set for cutting forces, cutting speed, machined surfaces roughness. This kind of adaptive controls could also be implemented to work on multi-objective optimization.
- **ACC** *Adaptive Control with Constraints.* This kind of adaptive control is usually exploited in roughing operations were there aren't strict limits on dimensional accuracy or surface roughness but the objective is to remove as much material as possible. In this case the objective of the adaptive control is to maximize the MRR maintaining the cutting forces as higher as possible. The constraints are represented by the available feed motor power and by the maximum admissible force on the cutting tool. ACC can be essentially considered as a closed loop control in which the feed speed is adapted to cutting force and varies along with the variations in machining conditions.

1.6 Industry 4.0

> *"Industry 4.0 is a comprehensive transformation of the whole sphere of industrial production through the merging of digital technology and the internet with conventional industry."*

This is the definition of Industry 4.0 given by the German Chancellor, Angela Merkel, during her speech to the OECD conference in February 2014. The origin of this therm can be traced back to 2011. In this year H. Kagermann, W. D. Lukas and W. Wahlster published *"Industrie 4.0: Mit dem Internet der Dinge auf dem Weg zur 4 Industriellen Revolution"* (Industry 4.0: with the Internet of Think towards the 4$^{\text{th}}$ industrial revolution) [47]. The article was presented in 2011 at the Annover Fair in occasion of the public presentation of the "Project for the future industry 4.0" which was already been presented to the government for the approval.

The main objective of the project was to promote the computerization and digitalization in manufacturing implementing machine to machine data exchange (M2M) and exploiting the internet of things (IOT). The mission of German strategy was indeed to enable local companies to produce strong customized products with highly flexible and automated plants. To reach such objectives new technologies needed to be embedded in production plants to support workers in their increasingly complex work.

The concept of industry 4.0 was then extended to a wider audience thanks to the article written by Klaus Schwab, the founder and executive chairman of the World Economic Forum - WEF, and published by Foreign Affairs in December 2015 [84]. Moreover in 2016, the theme of the WEF Annual Meeting was "Mastering the fourth Industrial Revolution". In the same year WEF announced the opening of its new Centre for the Fourth Industrial Revolution in San Francisco and Schwab published a book entitled “The Fourth Industrial revolution” [83].

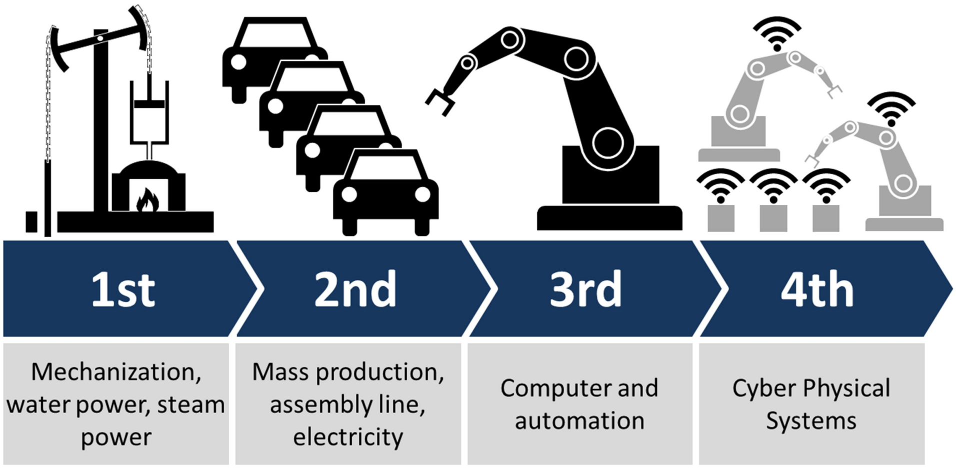


Figure 1.12: Industrial revolutions, from mechanization to CPS [78]

1.6.1 Industries through four revolutions, from steam power to digitalization

Since the ancient times, men used to produce the tools they needed. The production techniques evolved along times with the discover of new materials and the inventions of new tools and machines. In the realm of industry evolution, some milestones can be found. Industrial revolutions are conventionally identified in the introduction of a technology which had a tremendous impact in the industry transforming the production processes. Four industrial revolutions have been identified so far. In the next paragraphs, each industrial revolution will be described with particular focus to the characterizing technology and to the main changes in industries.

First Industrial revolution

The First Industrial Revolution (or Industrial Revolution) took place in the period ranging from 1760 to 1840 firstly in Great Britain, then in continental Europe, then in America. At these time Great Britain was the world leading nation for commerce and industry. The main industry, in terms invested capital, number of employees and output value, was the textiles. Conventionally the start of Industrial Revolution is dated 1780 with the invention of mechanized machines for textiles production. However the revolution impacted on many different industries, ranging from steel-making to transportation. The revolution had also many social effects, such as the growth of population and drastic changes in standard of living, hosing, nutrition and other social aspects.

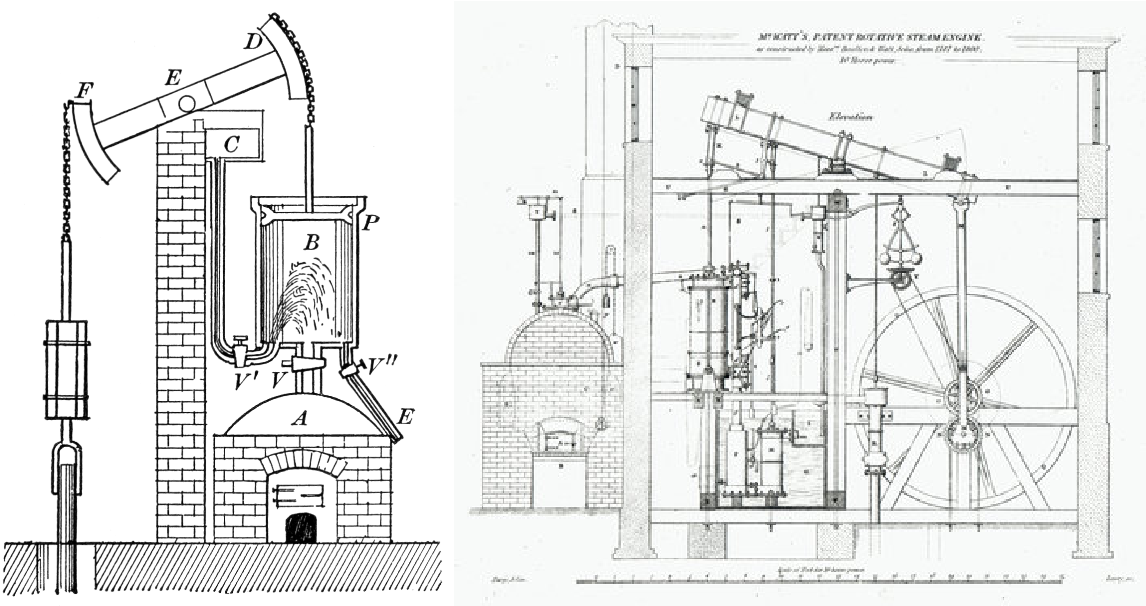
The key aspects of this revolutions are the mechanization of production, and the diffusion of steam or water powered plants and machines.

One of the most important element of the Industrial Revolution was the stationary steam engine. Before the diffusion of steam engines, the factories were powered mostly by water and wind mills. The first working piston steam engine was created by Thomas Newcomen in 1712. Newcomen's engine had a maximum power of *(*5 hp) and required huge investments. It's worth noting that this first engine was an *atmospheric engine*, this means that one end of the piston was open to atmospheric pressure, this was a limiting factor for the power and the efficiency of the engine. The engine produced a reciprocating movement, thus make it unusable for rotating machines however it was extensively exploited for drainage-pumps in mines. This allowed the expansion of mines, especially coal mines [77]. After, in the late 1770s James Watt and Matthew Boulton refined Newcomen's steam engine in order to improve its efficiency and applicability.Among the improvements developed by Watts, are worth noting the closing of the upper part of the cylinder and the introduction of a crank-rod mechanism to transform the reciprocating motion to rotating motion which can be easily used to directly drive the rotary machines of a mill or a factory [41]. Further subsequent improvements on the steam machine were done by Trecithis and Evans which increased the power density of the engine (i.e the ratio of power vs motor dimensions) enabling the building of steam engines for mobile application such as locomotives and steam boats. In the real of machine tools, steam engines were largely employed to power lathes, drills and mills through a complex mechanism of belts and shafts which distributed the power from the steam engine to the various machine tools in the plant. Moreover the development of machine tools allowed further improvements on steam construction.

Second Industrial Revolution: The technological Revolution

The second Industrial Revolution conventionally took place between 1870 and 1914. This period was in general characterized by a great amount of inventions and technological advances in manufacturing technologies. Despite the start of second industrial revolution has been placed at 1807, many important inventions such the introduction of machine tools and the inventions of the Bessemer process for iron converting to steel, took place in the 1850s.

The second industrial revolution is usually identified with the standardization of pro-

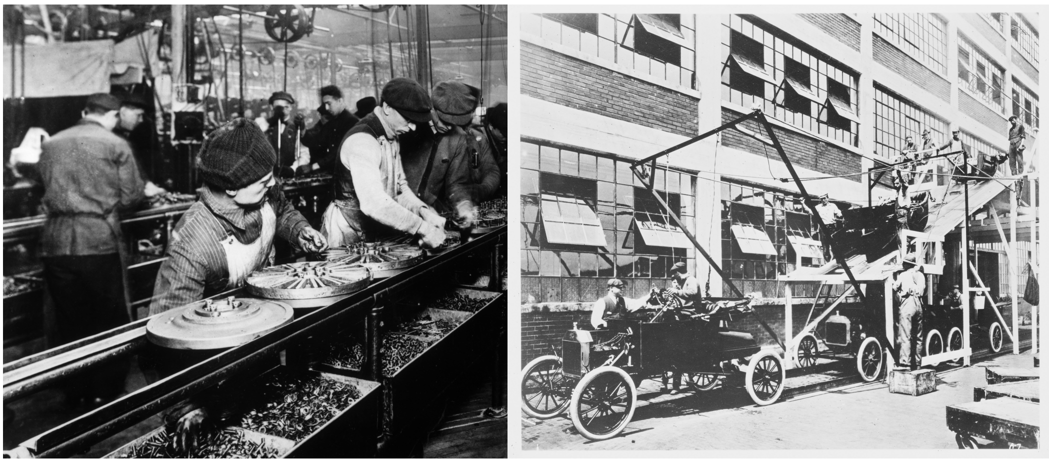


(a) Newcomen's Steam Engine (b) Watt's Steam Engine

Figure 1.13: Steam engines

duction and the introduction of methods and technologies for mass production such as interchangeable parts and assembly lines. The introduction of assembly lines, with the adoption of interchangeable parts, allowed an increase of the efficiency of production and consequently an increase of production rates and a reduction of production costs. Assembly lines has been adopted widespread by industries in different fields. Among the first examples of moving assembly lines are worth noting the Cincinnati Slaughterhouse, [35] which inspired Henry Ford for the introduction of assembly lines in his factory, and the portable steam engines assembly line in the Richard Garret & Sons factory, Leiston Works, located in Suffolk, England [88].

An invention which had a strong impact on 19th century's industries was the Bessemer process for steel-making. This new process increased the speed and scale of steel production, reducing the labour requirements, this enabled the mass-production of good quality steel. The process consisted in a controlled oxidation of pig iron in order reduce the excess of carbon and impurities. The oxidation is indeed an exothermic process so it raises the temperature of the iron mass keeping it molten without the need of fuel. The conversion of pig iron in steel was carried out in the so-called Bessemer converter, a cylindrical steel vessel lined with siliceous refractory. Near the bottom of the vessel some opening called tuyeres allows to blow an air-flow through the molten iron. This process had many advantages, such as the low cost (mainly due to the absence of external fuel needs) and the speed of production (the conversion of 5 to 30 tons of steel took approximately 20 minutes) however there were also some disadvantages mainly related to the chemical composition of the steel produced. With the Bessemer process, due to the acid lining of the converter was very difficult to reduce the content of phosphorous of the steels. In fact usually the phosphorous was eliminated by adding dolomites, magnesite or to the



(a) Flyweel assembly line (b) End of assembly line [17]

Figure 1.14: Ford moving assembly lines

molten iron but this was incompatible with the acid lining of the pot. To overcome this problem a lime-stone based lining was developed. Another chemical issue was represented by nitrogen, the use of air injection for the oxidation process imply that also nitrogen is injected in the iron, this leads to high percentage of nitrogen in the steel which can cause problems of brittleness, especially at low temperatures [12]. During the second industrial revolution many other process for steel conversion has been developed, among them there is the Martin Siemens Process which exploited the Siemens regenerative furnace for steel production. This process had some advantages such as the reduced exposure of molten steel to nitrogen and a better control on the chemical composition. The control of chemical composition of molten steel enabled the possibility to melt and refine large amounts of scrap steel, lowering the costs of production and allowing to recycle the waste material. The large availability of good quality steel at relative low cost allowed the development of metal-working industries which started to build larger bridges, railroads, skyscrapers and ships. Tanks to the advances in steel-making, new high tensile strength steel were available, this furthered the machinery industries which can built more powerful engines, gearboxes and other mechanical devices able to mange the increased power. This advances reflected also on defence industry with the improvement of naval ships, armoured fighting vehicles and tanks. Also telecommunications had great improvements with telegraph at the begin and after with telephone. Between 1856 and 1866 a first undersea telegraph cable was laid between Valentia, in Ireland, and Sunnyside (formerly Bay of Bulls), on the Canadian isle of Newfoundland. England noted the strategic importance of a good telecommunication network between the various English colonies around the world, the England government invested much on the development of a submarine cable system which dominated the world communication system until 1911.[49] Another significant contribute to communication came by Guglielmo Marconi which in 1897 patented a radio transmission system which enabled the communication between ships or aircraft and ground. In 1904 Sir John Ambrose Fleming invented and patented the vacuum tube or thermionic valve, a groundbreaking invention which influenced and enabled the development of modern electronics, communications and broadcasting. Finally the discovery of electricity played an important role in industrial development, the diffusion of electricity both for lighting and for powering machine tools and plant had a strong impact on industries development, facilitating the power distribution in the plants with a general reduction of costs.

Third Industrial Revolution: Digital Revolution

The start of the third industrial revolution can be dated back to the late 1970s. In these years, some great advances in electronics facilitated a great evolution of manufacturing industries. In 1968 Modicon released the first Programmable Logic Controller (PLC) which was invented by Dick Morley (Richard E. Morley)[36] for General Motors. PLC is essentially an industrial computer ruggedized and built in order to be highly reliable both for the physical part (extended working temperature range, immunity to electrical noise, resistance to vibration, etc.) and for the execution part. When GM asked for the development of PLC, the aim was to develop a rugged, flexible and programmable device to substitute the existing hard-wired relay logic system that were used in their factories. Hard wired systems were, in fact, very difficult to maintain and to alter in case of need of modifications in the automation process. A small modification in the automation process, with hard-wired logic would require many hours of the automation engineers, to re-design the circuits and to update the documentation, and a large amount of hours by the technicians to carefully re-wire the new circuits an to test the modifications. These were also very difficult to troubleshoot in case of failures as the technicians had to study the schematics and then try to find the defective components among many others. PLCs are built in a modular system which allows to build automations that can range from CPU with few I/O modules to an extensive system with many rack mounted CPUs with thousands of I/O networked with other PLCs.

Along with the development of PLC, also the programming language has been developed. The programming language needed to be user-friendly and with the minimum possible learning effort for the highly skilled technicians existing in the plants (e.g. maintenance engineers or electrical designer etc.). The very first language developed for the early PLCs were the so-called ladder logic. This is a graphic programming language which strongly resemble a schematic diagram of an electric plant with relays, contacts, lines and devices. This kind of language facilitated the transition from hard wired automation to PLC as the electrical engineer needed reduced training to be able to program PLCs as this would be essentially a transcription of the schematic diagram into the PLC program. In these years the development of electronics and IT and the increasing of PC reliability pushed the development and the diffusion of CNC machine tools. In the early 1970s, thanks also to the invention of the microprocessor which drastically reduced the cost of electronics for CNC machine tools, the CNC machines started their diffusion in the manufacturing realm. Concerning energy, the third industrial revolution is characterized by Nuclear energy, exploited for electricity production in Nuclear Power Plants. Despite the first commercial nuclear power station was connected to the English power grid in 1956, the proliferation of nuclear Power Plants started only after the 1973 oil crisis which in-


(a) The first PLC, Modicon 084 (b) Modern PLC *Siemens*

Figure 1.15: Ford moving assembly lines

duced the countries which were relying on oil for power generation to start building nuclear power plants.

Fourth Industrial revolution and Industry 4.0

As for the previous industrial revolutions , also the fourth industrial revolution can be characterized by on ore more disruptive technologies which had a tremendous impact in industries.

IOT and digitalization can be assumed as the technologies which started the 4^{th} industrial revolution, however, according to Martinelli et al. [63], industry 4.0 cannot be identified by an unique technology yet is better described by different technologies that are clustered and integrated together in order to build a comprehensive system, commonly called Cyber-Physical System [57]. Obviously these new technologies needs to be integrated with the existing machines and plants.

These technologies are generally called “enabling technologies” or “disruptive technologies” are:

- *IoT* Internet of Things includes a class of devices in which the internet enables advanced capabilities such as data acquisition and processing, self diagnosis, connectivity. The devices are connected together and with the rest of the world using standard connection protocols. IoT technology is largely used in industry 4.0 applications and in many others domains (domotics, building automation, automotive, health, smart cities, etc.). The application f IoT in the realm of Industry 4.0 are called IIoT, Industrial Internet of Things.

- *Industrial Analytics & Big Data* Are methods and tools to analyse and process large mounts of data in order to extract valuable informations for manufacturing, maintenance and supply chain management. The large amount of data coming from the field and their variety require innovative analytical approaches in spite of traditional statistical process control and similar techniques.

- *Cloud Manufacturing* Cloud Manufacturing involve the application of cloud technologies to manufacturing to support design and production processes, human resources and supply chain management. Cloud manufacturing applications spread from platforms and collaboration tools hosted in the cloud to the virtualization of physical resources (such as workstation).
- *Robotics* In this category are grouped bot classic robots (e.g Cartesian, SCARA, Anthropomorphic Robots etc.) and collaborative robots (also known as Co-bots). Collaborative robots are robots designed to share the workspace with human operators and to interact physically with them. Robotics and advanced automation enable innovative capabilities of production systems such as the improved ability to interact with the environment and between machines, self-learning, auto-diagnosis, use of vision and pattern recognition for continuous monitoring.
- *Artificial Intelligence* It deal with the techniques developed to make the machines able to mimic the human intelligence, or rather to make the machines able to work appropriately in their environment via forecast or reaction to exogenous phenomena. In industry, AI refers to a set of computer science-based technologies which are used to generate smart production devices, intelligent or virtual sensors, edge computing devices and other applications, also in conjunction with machine learning. AI is used also in the domain of Big Data in order to develop tools an algorithms for analysis and processing of large amounts of data.
- *Additive Manufacturing* Additive manufacturing is formerly known as rapid prototyping and today is also known as 3D printing. Additive manufacturing, in origin find its roots as a method to support the design process with technologies able to manufacture a model of the product in a rapid and relatively economic way. With the advances of technology and material-sciences these processes has been extended to actual manufacturing allowing to realize directly a product rather then prototypes. Additive manufacturing could be a valid support for repair and maintenance processes as it can be exploited to produce spare parts. The technologies included in additive manufacturing are defined by ISO in seven categories: Sheet Lamination, Photo-polymerization, Material Jetting, Binder Jetting, Material Extrusion,Powder Bed Fusion and Directed Energy Deposition.

These technologies are rapidly spreading in manufacturing industries, also thanks to many development projects initiated by different governments. The introduction of a combination of these technologies in industry may be a great opportunity to increase the overall efficiency or to improve and innovate products and production sites. However a particular attention need to be paid to the human part of the factory, the digitalization has to be a support for operators in their work, it cannot substitute them. Moreover technology shall not impede users in their everyday tasks.

Chapter 2

Development of advanced monitoring systems for industrial applications

Industry 4.0 technologies are rapidly spreading among the industries. Also in Italy, thanks to the development programs promoted by the government, many Industries faced the opportunity to adopt and integrate these technologies in their plants. Moreover the availability of advanced technologies pushed many manufacturer to start planning and developing digitalized product and to integrates industry 4.0 related technologies in their products. Universities and Research Center are often involved in these project as partners in order to support industries in their innovation journey providing the research methods and knowledges that sometimes are not available in industry, especially in SMEs. These collaboration between enterprises and Universities promote also a positive contamination which can facilitate the development of new economies.

Some research project conducted in collaboration between the University and local and international industries located mainly in northern east of Italy are presented in the following pages. The projects has been developed in quite different manufacturing areas both for products and for engaged tools, however all these projects share a common characteristic: they're all connected to the application of I4.0 principles and technologies to products or industrial processes. More specifically, the listed projects are all correlated with data collection, monitoring and data-logging from tools or products, also with tailor-made hardware.

2.1 Smart-Sawing machine

This research project, developed with a local manufacturer o metal processing machines, mostly pipes and metal sheets, whose products are sold internationally aimed to implement a comprehensive system for data-logging to be installed on an automated cutting machine. The system included data acquisition hardware and software both for data management and analysis.

The aim of the project was to design a system able to continuously monitor the cutting process through the collection and analysis of data coming from the PLC and servo-drives installed onto the machine together with the data collected by a set of sensors installed on the machines. Moreover the same data, obtained by a similar machine have to be used by a saw-blade producer to test their products in real working conditions. In this last use case the HMI had to provide functionalities to manage test sessions, such as a database for the storage of test sessions parameters and saw blades and workpieces characteristics. The automation system must allow the user to download a file containing the raw data collected during test sessions, together with related working parameters in order to allow off-line data analysis.

2.1.1 The cutting machine

The machine on which the system has been implemented is a an automatic cutting line. This machine is able to automatically cut to length metal bars of various shapes, following a recipe defined in the numeric control via the HMI or loaded remotely with adequate APIs. The Machine is moreover fully integrable with MES and ERP systems in order to allow remote programming and monitoring of the machine.

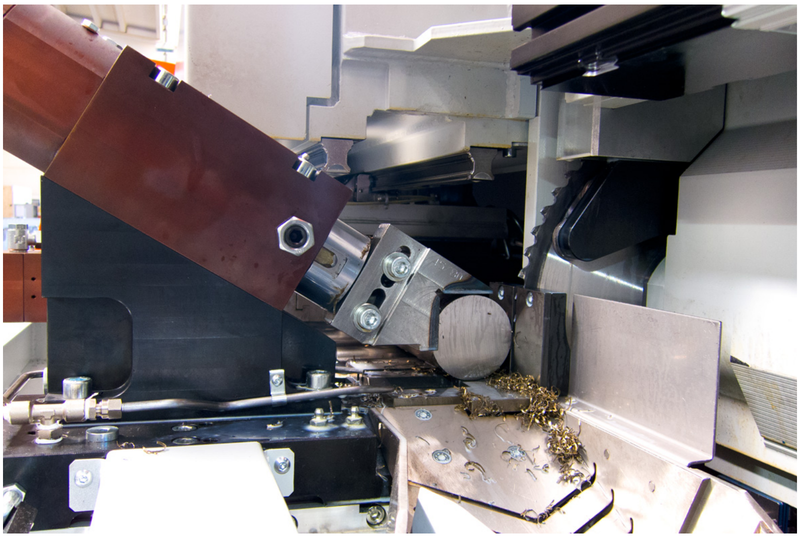


Figure 2.1: Example of cutting machine work-zone.

The machine is fully automated. Its structure can be divided in three zones:

- Loading Zone This zone is composed of a rack were bars bundles are loaded with elevators or cranes. Then a bar is sorted from the rack and loaded into the process zone.

- Process zone In this zone the bar is actually cut. Multiple automatic clamps, installed on linear rails and moved by linear actuators, allows to move the bar in order to feed it in the cut zone. A series of optical sensors enable the recognition of the presence of the bar and its begin in order to have a reference for the measurement of the pieces to be cut. The bar is clamped on both sides, before and after the blade in order to avoid issues due to unwanted movements of pieces during the cut. This machine uses a circular saw blade with Diamond, Ceramics or HM tooth specifically designed for high efficiency metal cutting. The blade is actuated by an induction motor controlled via inverter. The cutting head is installed on linear guides which allows to move the blade towards the bar for cutting.

- Unloading zone After the end of the cutting process, the cut piece is unloaded from the machine. This is done by using the movable clamp. This machines are usually provided with many containers in order to distinguish pieces with different length and in order to separate scrap pieces. In the unload zone are also collected the chips generated by the process, these normally are gathered under the process zone, in order to drain the coolant-lubricant fluid, and moved out of the machine, in an appropriate container, by an automatic conveyor.

The machine had also a series of auxiliary components such as hydraulic pumps and circuits for clamps actuation, pumps and circuits for coolant fluid, compressed air circuits, air-filtration systems and all is needed for an efficient and safe process.

2.1.2 System overview

The developed monitoring system is composed by various hardware and software parts in order to satisfy all the requisites. Concerning the hardware, the system will include, a set of sensors with related power supply, signal conditioning, and amplification devices, a data acquisition system, an industrial PC, and a touch panel. On the machine are installed three external sensors which were chosen as the most adequate for a punctual process monitoring. The sensor installed are:

- Triaxial Accelerometer installed on the cutting head, in the nearby of saw-blade hub. This sensor allows to acquire mechanical vibrations generated during the cutting in the frequency range from about 1 Hz to 15 000 Hz. In some working conditions (blade spinning without cutting) this sensor can be also used to detect issues or damages of the components of the cutting heads (bearings, gears, etc.).
- Ultrasonic Acoustic Emission Sensor. This sensors, based on piezoelectric sensing elements, is able to sense mechanical vibrations (surface and longitudinal waves) in the range from 50 kHz to 400 kHz. This class of sensors are able to detect the ultrasonic waves produced by mechanical deformations of metals, so they are particularly suited for monitoring in process which involve deformations of metals such as metal sheet forming, bending and shearing and similar processes and for machining.
- Inductive displacement sensor (Eddy Current) installed on the blade enclosure, this sensor is used to dynamically measure the axial deflection of the blade during the cut. The signal obtained by this sensor, combined with the signals coming from the above sensors can be exploited to identify undesired vibrations of the blade caused by a wrong set of working parameter which induce an instability in the process.

- Pyrometer. Installed on one side of the blade, it's used to estimate the temperature of the blade in order to analyze the amount of heat produced by the cutting process and eventually to prevent heat damages of the blade.

For the software part, the system, includes a custom software which is in charge of manage the data acquisition from the data acquisition system (for the sensors) and from the machine's PLC and the synchronization of the signals collected. For the connection with the PLC and with the data acquisition system, appropriate commercially available libraries and APIs has been used. The software includes also a kinematic simulator which, given the geometric characteristics of the machine, the characteristics of the blade, and shape and dimensions of the bar, and given the actual position of the cutting head, is able to calculate the geometry and the characteristic of the cutting zone (e.g. contact length, number of teeth engaged, average chip thickness.

The raw data recorded during the tests (if data logging is enabled) are stored on the internal storage of the industrial PC, while the synthesis parameters and indicators are stored in an SQL database which can be whether installed on the industrial PC or hosted by a cloud service.

The software will also provide an HMI to allow operators to visualize in real-time the data acquired from the machine and the status of the process and of the systems. HMI also provide forms for saw blades and bars characteristics management. Further parts of the software are devoted to off-line visualization and analysis of synthesis parameter calculated during the cutting cycles.

2.1.3 System Development

In order to develop an effective monitoring system, the first activity carried out in the development of this project has been an in-deep analysis of the machine and its control system in order to identify the dynamic characteristics of the system, especially the cutting head, and to determine the internal control variables to be acquired by the monitoring system. The analysis of the machine and of the process allowed also the definition of the more appropriate sensor to be installed on the machine in order to correctly monitor and describe the cutting process.

Then a first prototype of monitoring system, based on scientific data acquisition hardware has been set-up and installed on the machine. With the system installed on the machine, a series of test has been carried out in order to verify the proper operation of the acquisition system, particularly for the data exchange with PLC and the correct synchronization of the data collected by the two sources.

In this phase, also the software part has been developed and expanded to fulfil the requisites. Software development started with the kernel which includes the basic functions of communications with the PLC and the data acquisition hardware. Around the kernel all the other functions have been developed and expanded in order to implement all the planned functionalities. It's worth noting that in this phase, a kinematic simulator has been developed in order to have a real time simulation of the interaction between the saw-blade and the workpiece. The simulator parts is substantially composed by two elements. The first part is the calculation software which, basing on the geometric characteristics of the saw blade and of the workpiece and the actual position of the cutting head (read from the PLC) can evaluate some useful indicators of the interaction between saw and workpiece such as cut length, number of teeth involved in the cut, average chip thickness and other.

After the test, has been decided to move from a scientific data acquisition system to an industrial one, basing on reliability and resistance in harsh environment and implementation cost. After market research and analysis of several solutions proposed by different players in industrial automation, the hardware proposed by Beckhoff has been chosen. Among the advantages of such system there is the modularity, the data acquisition device i composed by a master unit, which is in charge of manage the communication between the Industrial PC and the other devices, ant a series of I/O modules with a range of different functionalities such as digital input/output, analog input/output, encoder reading, IEPE signal conditioning, small motor drivers and so on. This allows to build up a a system which can fit the requisites easily. For this applications, only analog input modules has been implemented, this modules include the oversampling functions which allow to acquire signals with a maximum data rate of 50 kHz per channel.

In order to control the new data acquisition hardware, a new piece of software has been developed, in fact, in order to manage the acquisition of the signals and to transmit them to the data-analysis software a soft-PLC is needed. The term soft-PLC means a PLC which didn't have a defined physical counterparts but it's hosted on a Windows industrial PC. The operative system of the PC has been properly modified by the provider of the hardware in order to ensure the real-time operation of the PLC and to enable the preemptive management of the CPUs.

2.1.4 Hardware structure

As explained before, in order to gather all the data needed for the monitoring of the process status the machine had two data sources, the first is the PLC which controls the machine functions and the second is the data acquisition hardware. Both this devices are directly connected to the industrial PC, which host the software for data acquisition and monitoring, via Ethernet cable. Machine's PLC is made by SIEMENS and is a PLC of S7 series which allow data exchange with third party devices via Ethernet using S7 protocol and an appropriate driver. The data acquisition device provided by Bechkoff is also connected to the industrial PC using an Ethernet cable, however the communication protocol is EtherCAT, an industrial communication protocol which uses Ethernet as communication media. The industrial PC is also connected to an industrial grade touch-screen panel which allows the interaction with the data acquisition software. For development reasons in the prototype machine the industrial PC and touch panel where integrated in an industrial-grade Panel PC added to the machine, however, if the machine already have a suitable panel PC or an industrial PC with a control panel, the software can be integrated onto this. The last part of the hardware system is represented by the sensors and related signal conditioning devices, as mentioned above, on the machine are installed a triaxial accelerometer, an ultrasonic acoustic emission sensor, an inductive displacement sensor and a pyrometer. Each of these sensors, in order to work properly needs a signal conditioning device which provide the sensor with the correct power supply and can receive, filter, amplify and convert the signal generated by the sensor in order to make it suitable for the data acquisition devices.

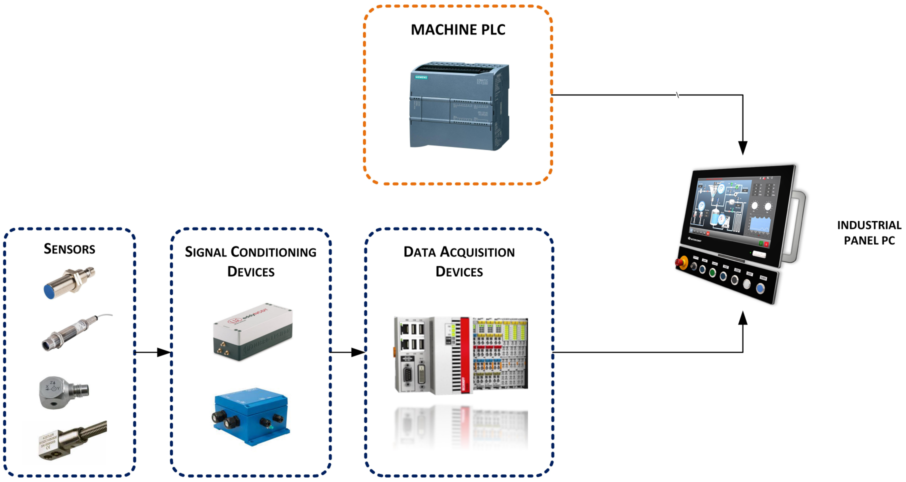


Figure 2.2: SmartSaw hardware scheme

2.1.5 Software Structure

The monitoring system is based on modular multi-threading software developed in C#. The core part of the software are the two threads which respectively receive data from the PLC and the data acquisition system. Both data sources had a proprietary communication protocol to be used for data exchange with third party software (S7 for Siemens PLC and ADS for Beckhoff), however .NET libraries for the implementation of these protocols are available for both systems. The whole data monitoring software is based on five threads:

- The first thread control the communication with the machine PLC. After receiving the buffer of data sent from the PLC, it convert them and fill the buffer for the statistics calculations and the buffer for the export of the raw data. In this case the software is a client of the PLC.
- The second thread manage the communication with the data acquisition devices. After a connection with the target PLC (the soft-PLC which manage the data acquisition) has been set-up, a link with a variable of the soft PLC is created (a boolean value which indicate the state of the buffer) and the software start monitoring the value of the variable and in case it changes from false to true, the software start reading the buffer from the PLC and collect the data which are then stored in the buffer for the statistics and in a queue for data export.
- The third thread manage the buffers used for the calculation of the process indicators and perform the data export on text files. To calculate the statistics an array for each variable has been set up, when new values of the variables arrive to the software,

these are copied in the respective arrays and, after a fixed amount of time, from each array are calculated the process indexes and then the array is emptied. For the data export two queues are set-up, the first for PLC and second for external data, and filled with the data coming from the device. The data queued are progressively written to disk and removed from the queue.

- The fourth thread is the kinematic simulator. When a new value of position (or a new type of blade or workpiece is selected) this thread starts and updates the simulation giving as result the data of saw-workpiece interactions. These data are merged with the data coming from the PLC and stored in the same file. Last calculated data are also stored in a specific structure for the update of the graphic representation of the process.
- The fifth thread control the GUI of the software, this piece of software is in charge of render all the pages and forms of the GUI an of updating process indicator charts and the graphic representation of process advancement.

The GUI of the software is composed by different forms and pages which allows different functions. The home page of the software allow the choice of the operating mode between process monitoring and session recording; Moreover the homepage allows the access to the pages for the management of blades and bars characteristics.

The monitoring panel allows the operator to select the shape of the bar and the type of blade installed and to train the system (executing one or more cutting cycles in nominal conditions), then the monitoring can be activated the software will display a chart with real-time data, or process indicator and the respective control limits, in case of one of the monitored signals exceeds the limits, an alarm is raised and highlighted in the GUI.

The session recording function is composed by different screens which allows he management of recording sessions and related tests. In session management, a tabular view shows all the performed recording sessions with date of creation, date of last recording and number of tests. User can create a new session or access an exiting one. Then session overview window. This form enables various functions through different panels, first panel give an overview on the data of the session and provides a link to the folder were session files are contained; second panel show a tabular view of the tests related to the session, for each test date of execution and number of cuts recorded are displayed together with the type of blade and of bar involved in the test. By clicking on a test the user can review real time data recorded in the test on an interactive chart. The third panel shows two scatter plots on which the user can select the process indexes to be plotted in order to roughly analyze the data collected. From the test overview, a new test can be recorded. Recording screen require the selection of blade and bar used for the test in order to allow recording to be started. During the recording on the screen are displayed a graphic representation of the current interaction between blade and bar, obtained by the simulator, and a chart panel. On the charts both process indicators an raw data can by displayed for all the signals acquired by selecting them from a drop down menu.

Data Acquisition PLC software The soft-PLC which is in charge of control and manage data acquisition hardware is developed and executed under the TwinCAT®environment.

The software is based on two buffers which alternates in reading and writing in order to have, at any time, a buffer which is being filled with new data (active buffer) and the other buffer which is being emptied by the consumer task (passive buffer). The communication between the PLC and higher level software is done by using ADS protocol, a proprietary protocol which allows the communication between different system. When the active buffer is full, a variable is changed in order to indicate to the consumer task that the buffer is ready for reading and the buffer is swapped in order to fill a new buffer.

2.1.6 Conclusions and future development

The project is concluded and the system is actually installed on a sawing machine in the research and development department of a manufacturer of saw blades for metal cutting. The machine is used as a test bench for products, some test cuts are performed and recorded, then the collected data are analyzed in order to evaluate blade's performances when changing some parameters. The project highlighted the interest in monitoring systems also from the industries which are currently using this kind of machines, which can take advantage of this systems , for example in predictive maintenance or for product quality prediction and assessment. Further development of this system would involve different approaches for monitoring, for example exploiting the availability of data at high rate from automation devices and motor drives which, in some cases, can be used in lieu of signals obtained from external sensors. An example of the data collected during a single cut are reported in figure 2.3. The signals obtained from machine's PLC (axis position, spindle current, and feed axis current) and simulator (contact lenght) are grouped in the left column charts while the data coming from the sensors installed on the machine are presented in the carts on the right column.

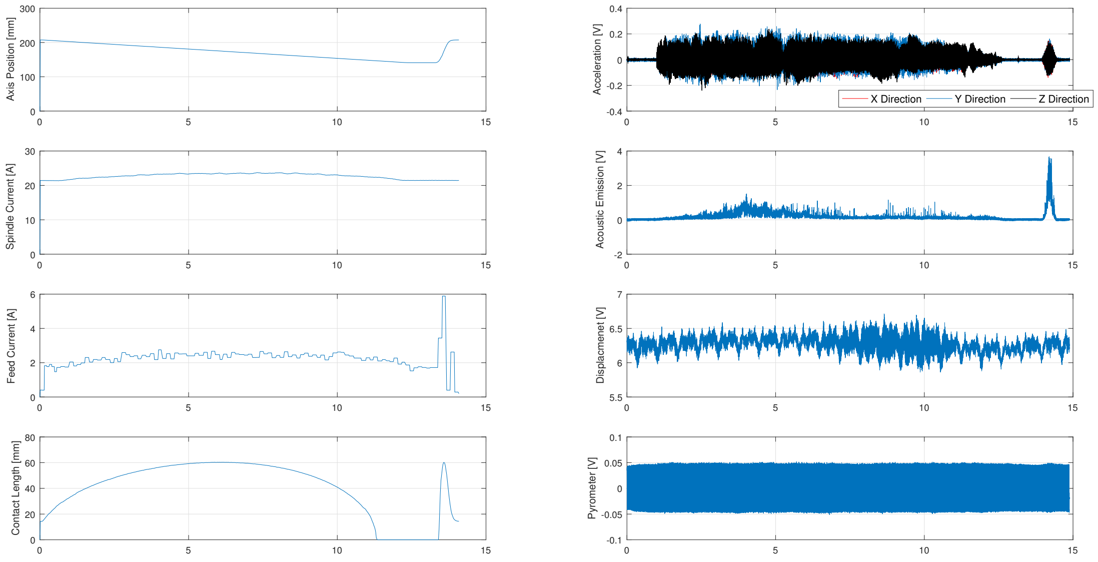


Figure 2.3: Example of data collected by the smart sawing machine during a test session.

2.2 Power Tool Monitor

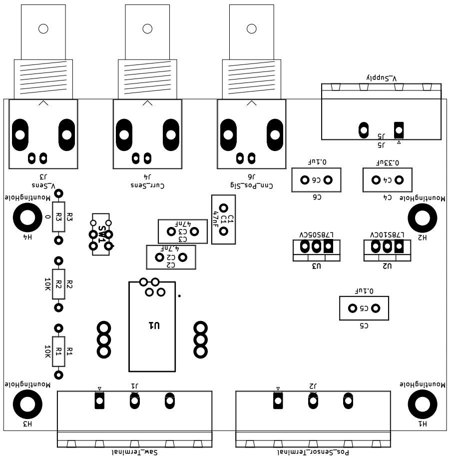
The aim of this project, was to design and build a PoC of a smart instrument for power consumption measures in cordless power tools. The device has to be user friendly and adaptable to power tools of different manufacturers. The device had to be integrated in a comprehensive portable system for data acquisition which had to provide also data management and export functions. Moreover the device installed on the power tool needed to be cordless in order to avoid mobility and usability issues. The development of the prototype involved different phases, in a first phase some power tools provided by the customer were disassembled in order to analyze the electrical circuit and find suitable point for the connection of the power measuring device. Some electrical tests were also carried out during this phase with the aim of evaluating the electrical characteristics of motor power signals. Then, based on customer's requirements and on the results of the preliminary analysis, a power tool to be used for the implementation of the system has been chosen. The selected power tool is a battery powered portable circular saw, employed mainly in construction sites. Before the development of the actual monitoring device, an in-deep analysis of the signals obtainable from the machine were required. Thus a series of test was arranged in order to acquire useful data for the subsequent phases. In this phase an high-end data acquisition system was utilized in order to avoid noise and other unwanted issues. All signals were sampled at about 20 kHz.The data acquired during these tests were:

- Position. The position of the saw was measured using a resistive position transducer installed between the tools and the test bench;
- Current. The current flowing from the battery to the motor were measured with a *LEM - HSLR 20 P* current transducer which converts a current in the range ±20 A in a voltage in the range 0 V to 5 V. The sensor also provide galvanic insulation between input and output;
- Voltage. The voltage is measured in parallel with the motor in order to measure the actual voltage provided to the motor. An additional voltage measures were taken in parallel with the battery in order to verify if there were appreciable differences in voltage between battery and motor. To make the voltage signal compatible with the acquisition device, the signal passed through a voltage divider before entering into the data acquisition device.

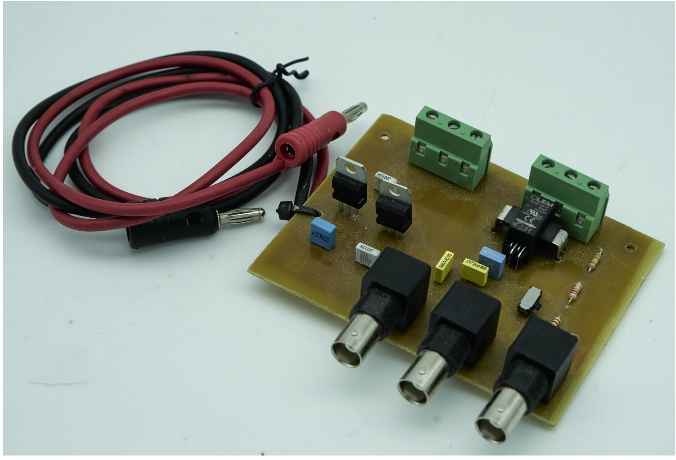
To simplify the wiring and to ensure stable connections between the sensors , the tool and the data acquisition device, a specific board was designed and produced in the laboratory. The board provided screw terminals for the connections with the power supply and with the power tool, and coaxial connectors type BNC for the connections with the data acquisition hardware. The circuit board is divided in four section, depending on the function or the signal involved.

- Power Supply

  In this section, the external power supply (in the range 12 Vdc to 28 Vdc) is firstly reduced and regulated to 10 Vdc, needed to obtain an output in the range 0 V to



(a) Board design



(b) Actual board

Figure 2.4: Data acquisition board

10 V from the resistive position sensor, and then reduced to 5 Vdc to properly power the current sensor.

- Position Measurement

  This sections had to provide the correct voltage supply to the sensor and to route the voltage signal coming from the sensor to the related BNC connector for the connection to the DAQ board. On the sensor side there's a three way screw terminal for **+Vdc**, **GND** and **OUT** signals which are respectively voltage supply, ground and output signal connections. On the data acquisition system side of the board there is a female BNC connector with 50 Ω impedance to ensure proper matching with data acquisition device.

- Current Measurement

This section involve the current sensor and the components required for its operations. The input of current sensor is connected in series with the motor of the power tool so that the current flows through the sensor. The output of the sensor is wired to the BNC connector in differential mode, with the *Vref* pin wired to the outer contact and the *Vout* pin connected to the center pin of the coaxial connector.

- Voltage Measurement

  This section contains the voltage divider required to reduce the power tool's battery voltage, 24 V, to a level suitable for the data acquisition hardware ±10 V. The voltage is measured in parallel with the motor terminals. The voltage divider can be isolated with a DPDT switch installed on the board if it's not required.

Several cutting test has been done with this board connected to the power tools and to a National Instruments data acquisition system and the resulting data has been recorded with the National Instruments' DiaDEM software. The tests involved cuts with three blades with different geometric characteristics executed on two different materials, MDF and laminated fir boards.

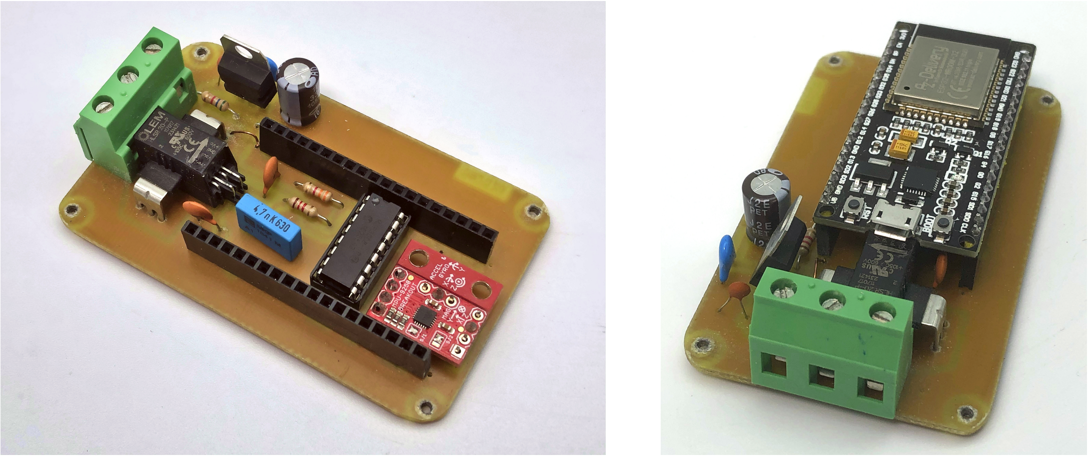
The analysis of the data collected during the test highlighted the influence of parameters like feed-speed and blade characteristics on the current absorbed by the motor during the cut. The relation between voltage, current and feed speed has been modelled through regression and the equations obtained on the same materials have been compared for the different types of blades in order to compare their performances. The in-deep analysis of current signals both in time and frequency domain revealed the possibility of evaluate the actual rotation speed of the blade.

2.2.1 Integrated monitoring device

Basing on the results of preliminary analysis and on the requirements of the customer, an integrated monitoring device has been designed an realized. The main requirements accounted during design were:

- Overall dimensions of the device compliant with the installation on the power tools without affecting user experience;
- The device has to be completely wireless, no cables for power neither for data exchange;
- Compatibility with different power tools;
- High sampling frequency, at least for current signals;
- Ability to perform real-time FFT of the acquired signals;

To develop a suitable solution which responded to all the requisites a custom system based on the Espressif's ESP32 SOC has been chosen. ESP32 is a well known system on a chip which integrates , in a compact package of approximately 32,00 × 18,00 × 3,50mm, all the function needed for the creation of smart electronic products such as CPU, RAM,



(a) Integrated monitoring device without CPU installed, ADC and IMU module are clearly visible.

(b) Integrated monitoring device complete, with CPU board installed

Figure 2.5: Data acquisition board

SRAM, memory, 2,4 GHz Wi-Fi and Bluetooth v4.2 with BLE. The device has an Xtensa® dual-core 32-bit LX6 microprocessor, with 240 MHz clock. The availability of two cores, together with the high performance of the CPU allows to develop real-time data acquisition devices with advanced functions.

The prototype device has been developed around a *ESP32-DevKitC-V4* board, this to facilitate the design, production, programming and testing as this board includes the circuits required to power the ESP32 and all the devices needed for USB programming and debugging of the micro-controller. The development of monitoring device involved several activities, especially for the analog data acquisition part. For this function two alternatives have been evaluated and compared, the use of the integrated ADC and the use of an external ADC. After some testing the external ADC solution has been selected for the implementation, basically due to some flaws in the management of dual channel high speed analog data acquisition with the ADC integrated into the ESP32. The external ADC selected for the application is a MCP3008 manufactured by Microchip, which provides eight single-ended channels with 10 bit resolution. The ADC has a maximum sample rate of 200 ksPs and and provides SPI interface for the communication with the micro-controller.

The communications between data acquisition devices and the gateway are based on Wi-Fi connection. Each monitoring device connects automatically to the gateway as, in this first version of the system, SSID and WiFi's connection parameters are hard-coded in the firmware.

The function implemented in the monitoring device are:

- Voltage measurement, performed by a voltage divider;
- Current measurement, executed using a *LEM - HSLR 20 P* current sensor;
- Three-axial acceleration measurement obtained with a MPU9250 Nine-Axis MEMS

MotionTracking$^{\text{TM}}$ Device which integrate in a 3 × 3mm package, a three-axial accelerometer, three-axial gyroscope and three-axial magnetometer;

- Motor speed estimation through real-time frequency-domain analysis.

Voltage and current signals are acquired with a sampling frequency of about 14 kHz while acceleration signals are acquired at about 1 kHz. These values of sampling frequency are a compromise choice between the needs for high sample-rate of the signals which are analyzed in frequency domain and the limits on memory available on the chips which indeed limits the dimensions of the buffers used for the calculations.

The device is powered by the battery of the power tool exploiting the cable used for voltage measurement. The input voltage from the battery is then divided in two branch, the first is directly connected to the voltage divider which routes voltage signal to the ADC while the second is connected to a *L78S05-CV* regulator which reduces and regulates the voltage of the battery (about 24 V in this case) to 5 V required for ESP32's power supply.

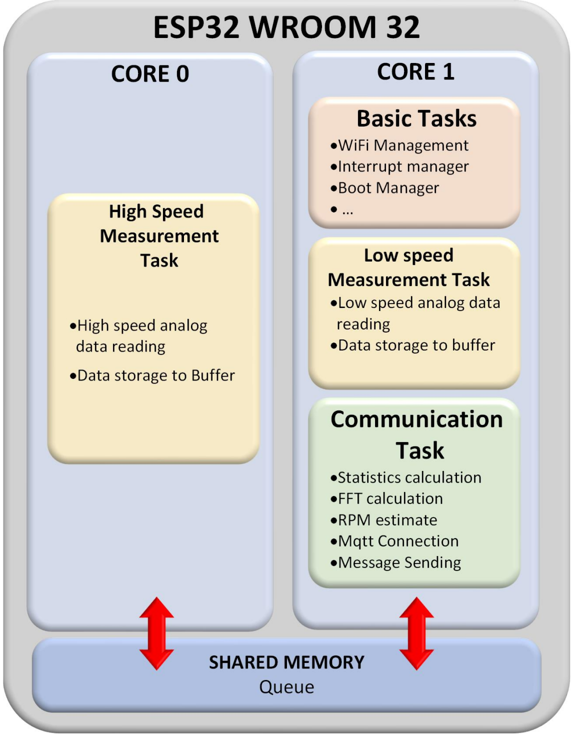


Figure 2.6: Block Scheme of Power Tool Monitor Firmware.

To consistently execute the measurements, the firmware exploits the dual-core architecture of the micro-controller using FreeRTOS methods and functions modified for ESP32 by Espressif in order to support symmetric multiprocessing [60]. One of the cores is fully devoted to the high speed data acquisition, this ensures to have no interruption in the data acquisition and a quite precise timing of the measurements. The second core performs all the remaining activities, such as low speed data acquisition, statistics calculations, communications management and basic micro-controller functions execution. Each of these functions is encapsulated in a task which can be launched at a definite time or after another task complete its work. In total four task plus one basic task are implemented in the micro-controller for this application each one with a specific function. Figure 2.6 describes the functional scheme of the firmware implemented in the monitoring device.

It's worth noting that monitoring devices exchange with the gateway statistics obtained from the raw data collected at high speed, this to reduce the bandwidth required for data transmission and also to reduce the amount of memory needed for data storage in the local storage device or in the remote storage.

Voltage and current data are digitalized and stored in temporary buffer created on purpose for safe data exchange between different threads also running on different cores. This type of approach ins required because if a simple array is used without taking into account the possibility of simultaneous access to the same memory allocation from different tasks, this can led to execution issues or failures. When a buffer is full the data analysis task is started. This task calculates the statistics for each signals and store them into an appropriate data-structure. This task also perform a Fast Fourier Transform of current signals and find the most relevant harmonic which is directly related to the rotation speed of the motor. The acceleration signals are also stored in buffers from which statistics are extracted at fixed time.

The statistics calculated for each signals are:

- Maximum value;
- Minimum value;
- Average value;
- Root Mean Square.

Then, the calculated statistics are packed into a JSON structure which also contains an unique identifier of the monitoring device which collected the data, the estimated rotation speed and a power ratio between spectral power of rotation related harmonics and the total spectral power. This last data is useful to establish if the estimated rotation speed is consistent or not.

The JSON structure is thus sent to the gateway using MQTT protocol over WiFi.

2.2.2 Smart Gateway

The smart gateway is the device which provides wireless connection to monitoring devices and collect the data coming from them. Data received from the devices can be stored in a local database hosted in the gateway or, if the gateway is connected to Internet with its Ethernet port, stored in a remote database. In order to build an autonomous portable monitoring system, the gateway provides many functions:

- SQL server which contains the database for the identification of recording devices and test sessions. The database contains also a table in which the last received data and status of recording device are stored and updated each time they change;

- Time Series Database which is used to store the actual time-series coming from the device monitoring, each measure is stored with its label, a time stamp, the id of the relate recording session and the id of the device which recorded the data;

- MQTT broker which manage the data exchange over MQTT protocol between the recording device s and the consuming task. This can be used also by third part application to read the packets coming from the monitoring devices;

- APACHE HTTP Server which provides the web server for the HMI web-application.

- Ingestion task which sets up a connection to the MQTT broker, as a client subscribing to a specific topic, and ,when new messages on the topics are received extract the data from the JSON structure, process them in order to verify the correctness and consistency of received data and, in case of successful verify, stores data in the TSDB and update the device status table accordingly.

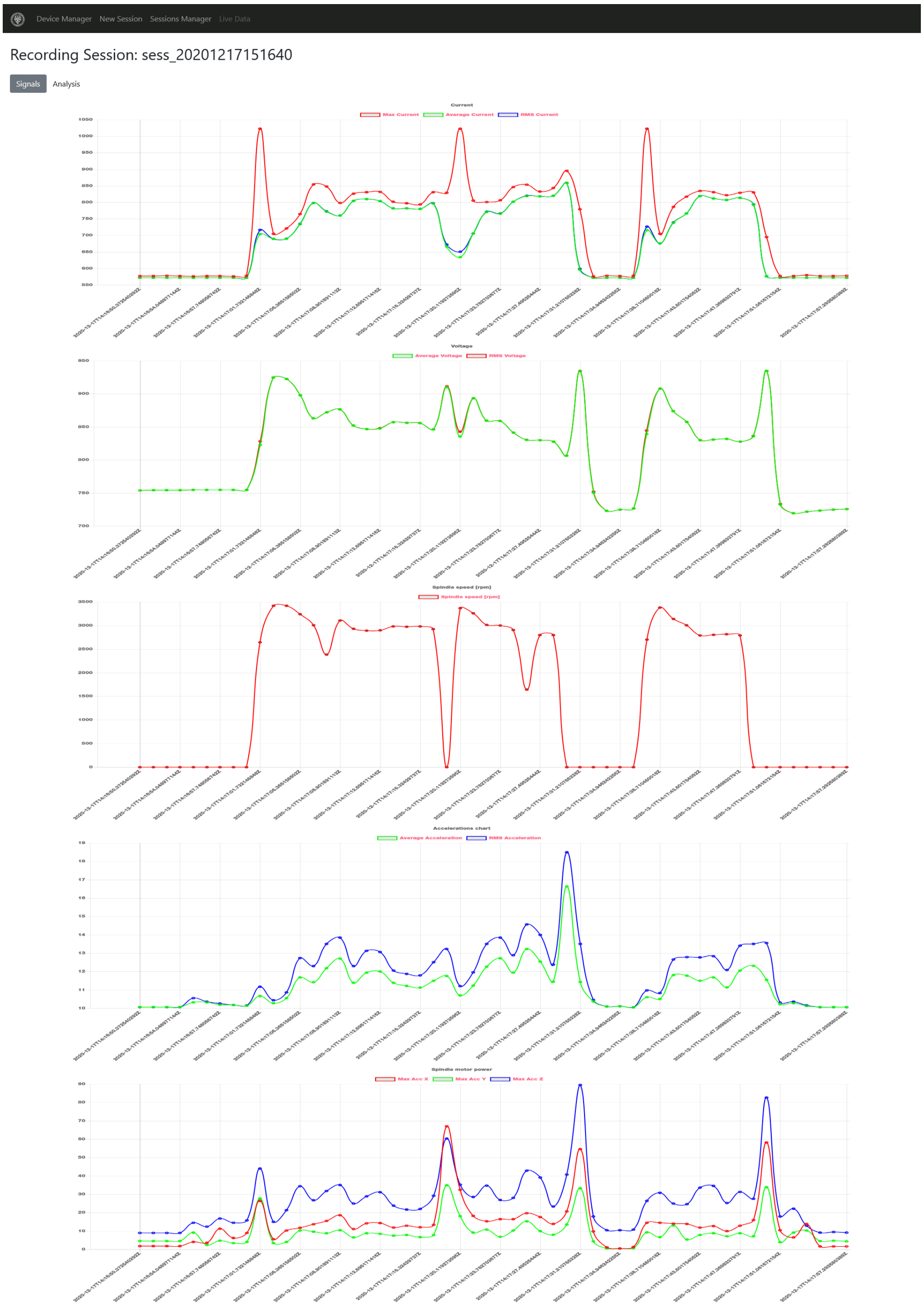
- Web Application for device and test sessions management. This application can be accessed connecting to the gateway by wireless or wired network and is compatible with a wide range of different devices and browsers. Several functions are integrated and can be accessed from the applications, such as management of recording devices (adding or removing a recording device, giving a name to a specific device etc.), recording session management (creation of a new recording session, list of existing sessions, recording start-stop etc.), real time data visualization for each active session, data visualization and download for past recording session.

A screen-shot of the web-application showing the data collected during a test session is shown in figure 2.7.

The gateway is powered at 5 Vdc via a microUSB port, this allow to power it both from wall adapter or USB power-bank with an appropriate capacity enabling a fully portable solution.

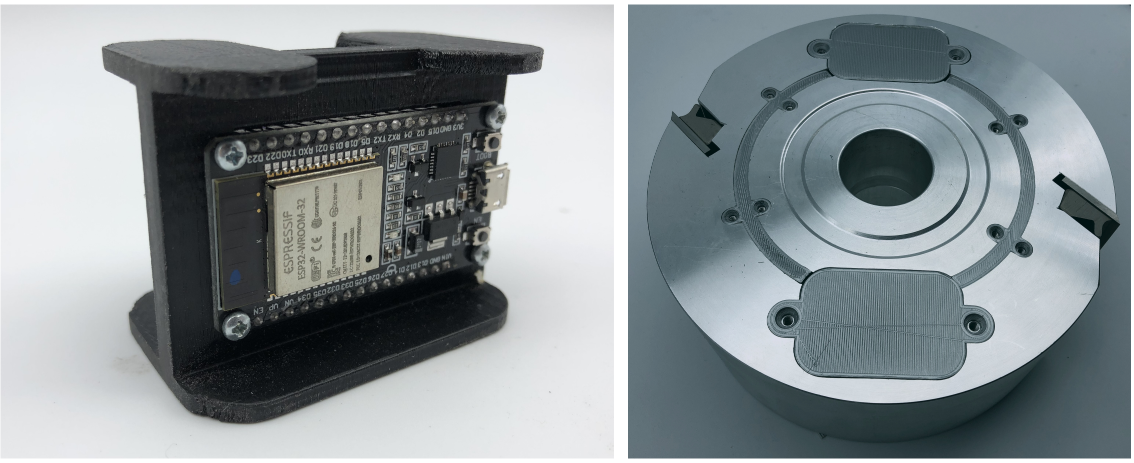
2.2.3 Conclusions and future developments

The system has been delivered to the customer which is using it in his R&D department for test on different types of wood-cutting blades with different power-tools. As reported by the customer the system is working flawlessly in any conditions and the data collected are useful for their analysis. The proposed system can have future developments both as a laboratory system for experimentation with power-tools or as a consumer product to be proposed as an addition to existing tools or integrated in new power tools to continuously monitor the status of the power tools, for maintenance and management purposes,and to collect long-term statistics on tool usage.



Recording Session: sess_20201217151640

Figure 2.7: Example of data collected by the system during a test session.



(a) Embedded data acquisition device with bracket.

(b) Modified cutting tool.

Figure 2.8: Smart Cutting Tool

2.3 Smart Cutting Tool

This project, developed in collaboration with a manufacturer of high technology and high precision cutting tools, even customized upon customer request, involved the creation of a proof of concept of a sensorized wood cutting tool. Thee tool has to be able to measure many parameters useful for process monitoring and to transmit the measures to an edge device in order to allow real-time visualization and recording of the collected data.

After some preliminary analysis on the data to be collected, the technologies to apply and all that could be useful for the definition of the smart device, the focus moved on the cutting tool. To build up a prototype with a good compromise between costs, degree of complexity and development time, the type of cutting tool on which the system will be developed was a crucial point; A too small tool require a great effort for the integration of the circuits and the electronics which will be costly while a too big cutting tool is costly by itself. After some evaluation a straight knife cutter heads has been chosen. The cutter head has an hardened alloy steel body with about 200 mm of outer diameter and 80 mm of height. The dimension of cutter body allows to machine it in order to create pockets where electronics and batteries can be inserted. The cutter body then has been modified creating two rectangular pockets of about $60 \times 30 \times 50$mm symmetrical with respect to cutter body axis to prevent unbalance issues. A circular slot, with a rectangular section has been created to connect the two pockets allowing cable routing between the devices. All slots and pockets are enclosed by plastic covers, manufactured by 3D printing, which are fixed to the cutter with screws.

The developed monitoring system is substantially composed by two parts, the embedded data acquisition device which is installed into the cutter body and an edge device which has to be installed on the machine tool. The data collected by the edge device are transmitted wirelessly to the edge device which can elaborate them eventually together with data collected from the machine tool and then retransmit them to the cloud storage service. Finally the cloud service can provide visualization and analytics tools.

2.3.1 Embedded data acquisition device

The main constraints for data acquisition device's design were represented by dimensions and power consumption, the device needed to have an overall dimension suitable to fit into the pockets into the cutter's body and, as the prototypes runs on batteries, the power consumption needed to be the less possible in order to maximize run time on a single charge. The device needed also to have enough computing power to ensure consistent data acquisition and pre-elaboration of acquired data. Some different solutions has been evaluated an finally the ESP32 SoC has been chosen for the development of the device. ESP32 is a System-on-a-Chip which groups in a single integrated circuit, a 32 bit dual core processor, ram, sram, memory and wireless connection system (2,4 GHz 6WiFi, Bluetooth 4.2 and Ble) ensuring energy-efficient operations. For technical reasons in this first prototype the only sensor which has been installed is a triaxial MEMS accelerometer but future versions will include also thermocouple sensors installed close to the knives in order to monitor their temperature during the process.

The firmware installed on the device exploits the availability of two separated processing cores to enable high-speed data acquisition from the accelerometer. In fact, using the FreeRTOS libraries provided by the chip manufacturer, which enables parallel computing on the two cores. The firmware is composed by three tasks, the first is the base task which executes all the fundamental functions of the MCU such as energy management and wireless connection control. The second task is in charge of communication, this task receive a buffer full of measured data and process it in order to obtain the statistics which are then sent to the edge device using MQTT protocol. The last task runs on a a dedicated core and is in charge of measurement, it periodically (each 500 µs) reads the data from the accelerometer and store them in a buffer, When the buffer is full it is sent to the communication task.

2.3.2 Edge Device

The edge device, which can be installed on the machine tools or near to it performs several functions. The primary tasks of the device is to provide a wireless connection for the connection of smart tools and to receive and process the data coming from the cutter. The edge device may also acquire data such as rotation speed and power consumption of the spindle from the machine tool on which it's installed, these data combined with the data coming from the cutting tool can be useful for process monitoring.

The prototype of the edge device has been developed using a RaspberryPI 3B+ board. This single board PC offers, in a compact form factor, a flexible development system for many applications. The board features a quad core processor with a maximum frequency of 1,4 GHz, 1 GB of RAM, dual band Wi-Fi, Bluetooth 4.2 and 40 GPIOs which can be used for connecting external devices. The board uses a Debian derivative, called Raspbian, as operative system which runs on SD card and can be deeply customized by the user.

The egde device integrates many functions such as an MQTT broker for data exchange with the smart cutter, the data ingestion process, data acquisition from the machine tool, data processing and storage in cloud space. For the prototype system the databases and data analysis service has been integrated into the edge device for demonstrative purposes, in order to have a fully working system also in absence of internet connection.

The cloud part of the system includes a time series database (TSDB) in which are stored the data coming from the devices and a dashboarding web application, the system will include also a web application for data management and visualization.

2.3.3 Conclusions and future development

The presented system has been presented to the customer and tested in his application laboratory. The cutter heads with the electronics installed has been firstly balanced with a dedicated machine in order to compensate the weight difference between the battery pack and the circuit board, then the cutter has been installed on a moulder and some cutting tests has been performed. Both during the balance and the cutting tests, the system collected and recorded acceleration data. In figure 2.9 an example of the data collected during the cutting test is represented.

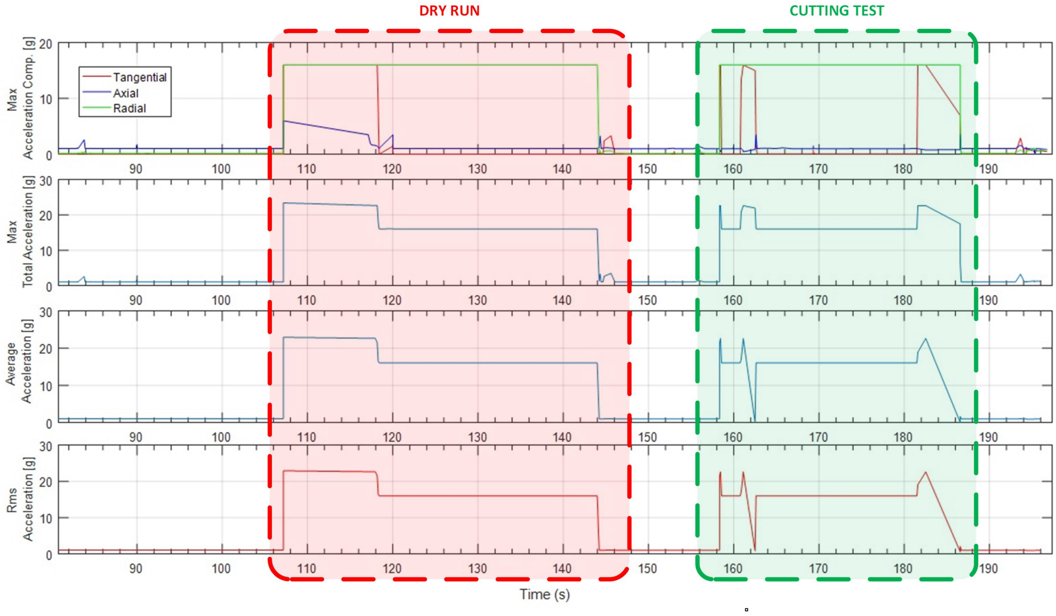


Figure 2.9: Example of data collected by smart cutter

The analysis of the data collected during the test revealed the possibility to describe the state of the cutting process by using the data coming from the cutter. This potential can be greatly increased collecting also data coming from the machine tool and analysing all the data together.

The system highlighted great potential and in future it could be integrated in high end product series of cutting tools. Future developments of the system would include a study for the reduction of sizes of electronics in order to allow the integration of the system in smaller cutting tools.

2.4 Machine tools monitoring system

This project developed with an international group specialized in high precision mechanical parts production aimed to developing a comprehensive system for data collection from existing machine tools with minor modification to the machine. As the system has to be installed in production environment in need to e reliable and with suitable certifications. To satisfy these requisites an industrial data acquisition system has been chosen.

The system is based on Beckhoff hardware, which provides flexibility both for the CPUs and for the data acquisition devices. The adopted system is modular and provides several different I/O devices which allows the acquisition of different types of signals and the connection to the main industrial fieldbus systems.

2.4.1 Edge device

In order to enable data acquisition from existing machines which, usually, doesn't have integrated sensor or the possibility to exchange data with plant IT infrastructure, a modular edge device has been designed. The device is based on a Beckhoff din rail mounted industrial PC of the series. On the IPC are then connected the expansion modules which allows to connect different types of sensors and to acquire several types of signals.

The proposed prototype represent an example of the device that can be installed of a typical machine tool to measure vibrations and power consumption of the main spindle during machining. The prototype is based on a CX8190 IPC that provides Ethernet connection on two ports which supports many communication protocols, and EtherCAT connectivity (one E-BUS) for the connection of the expansion modules. The IPC has a ARM Cortex$^{\text{TM}}$-A9 CPU with 800 MHz and 512 MB or RAM memory, the storage is provided by a 512 MB industrial-grade microSD card. The operative system of the IPC is Windows Embedded Compact 7. For the data acquisition are installed, on the E-BUS connector of the IPC, two EL3632 *2-channel, IEPE/Accelerometer analog input*, for the connections of a triaxial acceleromter, and a EL3702 *2-channel,* ±10 V *Voltage analog input* for the connection of ultrasonic acoustic emission sensor and power sensor.

2.4.2 Data acquisition and elaboration software

Data acquisition and processing tasks are carried out by a softPLC which runs on the IPC. Signals are acquired at 5 kHz, then the resulting data are stored in dedicated structures from which statistics are calculated every 500 ms.

PLC software is quite simple and rely on two parallels programs and some user-defined function blocks, functions and data types. Some variables, used for configuration of the system, for the configuration of MQTT connection and for the links between data acquisition hardware and virtual objects, are defined in the so-called global variable list or GVL. The variables which needs to be valid locally, only for the program or function in which are used, are instead defined in variable defining part of the program or the function.

Th first program is the MAIN, this is the principal program of the PLC and is the program which is executed cyclically by the PLC. In the variable definition part some instances of the FB_ STAT function block are created, once per channel which is acquired.

Figure 2.10: Edge device configured for the demonstrative system

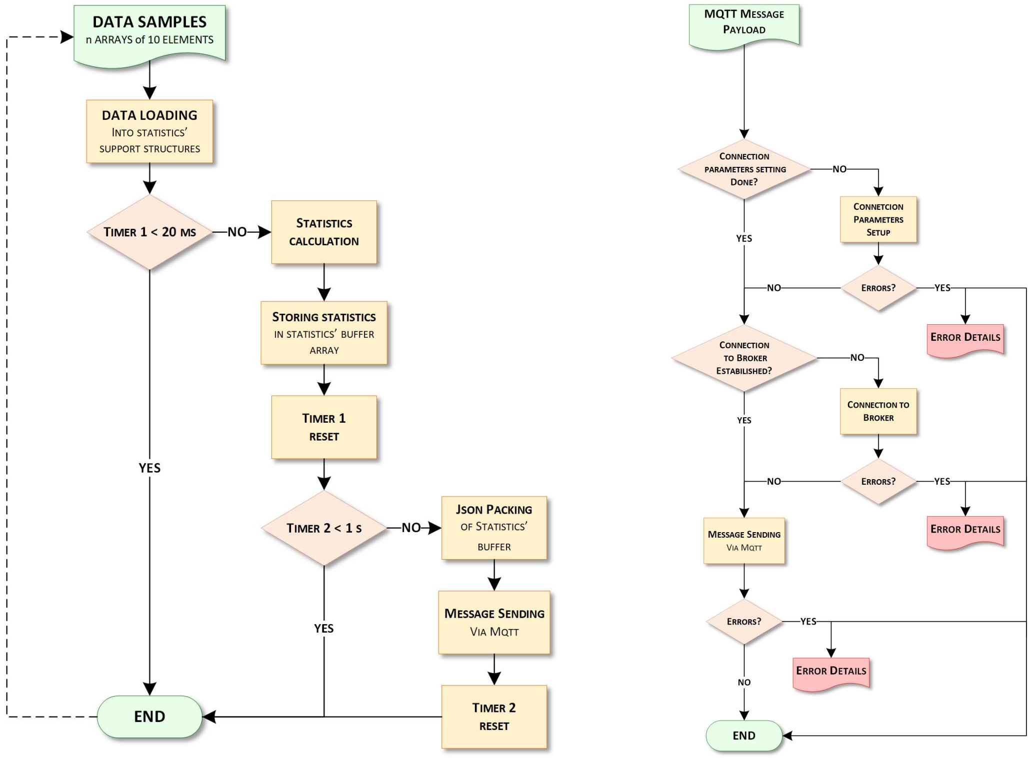
Then a Timer which controls the calculation of statistic is instantiated and initialized. Also a set of support variables such as counters and indexes are initialized together with an array of structures ST_ Payload which will contain the payload of the MQTT message.

The program starts setting the timer then, a for cycle extract the data coming from the acquisition hardware and store the values in their respective structure. When the timer triggers, the statistics, for each channel, are extracted from the data structures and queued in the payload structures array. The data structures are emptied and the timer is reset. When the programmed number of statistics is calculated the payloads structures array is packed into a JSON structure using an appropriate function which add also packet tracing and identification informations such as unique machine identification code, time-stamp packet dimension and other useful informations. Then the second program is started, this program will set an MQTT connection with the programmed broker and if the connection is successfully established it will send the message containing the JSON structure with the data.

2.4.3 Demonstrative system

In order to perform a demonstration of the system, a prototype of the whole system has been set up. The prototype included the edge device with a CX8190 industrial PC plus an EL1008 *8 channel, Digital input module* and two EL3632 *2-channel, IEPE/Accelerometer analog input*. To the input modules were connected, two push buttons which simulates the digital input and a triaxial accelerometer Kistler 8764B050BB.

To simulate the server system in a development environment without the need for a



(a) Main program

(b) MQTT connection and publishing management

Figure 2.11: Flowcharts of edge device program.

remote server, a Reaspberry Pi 3B+ has been configured as a server. Thus allowed to realized a fully working portable prototype of the system which can be used, for demonstrative purposes or even for monitoring of stand alone machines with a plug and play system. The Raspberry has been configured to work as a router both on the wired and wireless connection, so a DHCP service has been installed. On the board are also installed a Mosquitto MQTT broker to which the edge device and other clients has to be connected in order to send and receive MQTT messages, a SQL database (MariaDB) on which are stored events and relevant data, a time series database (InfluxDB) to store the received data. Finally the "server" includes also an MQTT client that reads the messages coming from the edge devices and stores the data in the databases, and a web server which provides a dashboarding web application for data visualization and analysis (Grafana).

2.4.4 Conclusions and future developments

The prototype system presented to the customer highlighted great potential for the monitoring of existing machine tools with relatively low expenses and efforts. Machine tools monitoring is becoming increasingly important in manufacturing plants, especially in case of manufacturing of millions of pieces of medium and small dimension with high throughput, were a problem on a machine if not recognized promptly can produce huge quantity

Flow readings

time	flow1	flow2	flow3
Jun 7th, 2021 14:46:16	50%	50%	50%
Jun 7th, 2021 15:01:16	49.4%	44.9%	49.2%
Jun 7th, 2021 15:16:16	45.3%	47.5%	53.9%
Jun 7th, 2021 15:31:16	47.9%	52.9%	59.3%
Jun 7th, 2021 15:46:16	51.4%	58.5%	56.0%
Jun 7th, 2021 16:01:16	54.3%	61.9%	58.5%
Jun 7th, 2021 16:16:16	56.0%	63.3%	65.3%
Jun 7th, 2021 16:31:16	56.7%	66.9%	59.6%
Jun 7th, 2021 16:46:16	56.1%	59.5%	59.1%
Jun 7th, 2021 17:01:16	58.3%	57.0%	65.7%

Figure 2.12: Example of dashboard for visualization of acceleration data *Source grafana.com.*

of scrap pieces. Future developments of this project would involve the realization, in collaboration with a system integrator, of a pilot application, on an actual machine,of this system and after a test period, the large scale implementation of the system on the plants.

2.5 Door Monitoring System

This unusual project, developed as a POC of a bigger project which involved an international manufacturing group, aimed to develop an electronic system for tracing and monitoring the usage and the status of a door and of its components which can be affected by wear.

The plan was to equip a door with a system which has to be able to:

- Measure the position of the door along its stroke;
- Identify the current status of the door (open or closed);
- In case of moving door identify if it's an opening or closing movement;
- Measure accelerations of the door both during movements and in steady conditions for maintenance and safety purposes;
- Control external devices such as an electric lock.

The device had also to be able to send the collected data to a server which will store them for further analysis. The power for the devices come from a cable routed into the door's frame.

The system has been developed using an ESP8266 SoC as main processing unit. In order to measure the position of the door and its accelerations, an IMU (*Inertial Measurement Unit*) has been installed on the door and connected to the ESP826. The IMU integrates a triaxial accelerometer, a triaxial gyroscope and a triaxial magnetometer and allows to measure with very low uncertainty, the position of the door by combining magnetometer's and gyroscope's measurements. External devices can be controlled directly using one, or more, dedicated digital output which are available on the board or, in case of high current or voltage, using a relay connected to the board.

As the ESP8266 has only one processor, continuous measurements at high datarate cannot be performed, so in this case the device is programmed in order to sample the data for a defined time (about one second) storing the data collected in a structure. At the end of the sampling period some statistics are calculated from the data in the structures. The statistics are written in a JSON structure which become the payload of an MQTT message which is sent to the server.

The incoming messages such as the messages for external devices controlling are received and processed by a dedicated process which is automatically triggered when a new message is received.

2.5.1 Conclusions and future developments

The system is still installed on the door of the laboratory and is still collecting data. The data acquired from the device are stored in a time series database and will be used in future for wear analysis on the door and its components and for a long-term analysis on user habits. It's also possible to analyze these data together with the user declaration to try to build an AI algorithm which recognize the user by its habits when using the door.

2.6 Conclusions

Many case studies regarding the digital transition of manufacturing have been presented. The case studies involved different aspects of manufacturing, from tools to plants, however a common guideline can be found. As well different technologies and device has been employed in the development of the case studies, ranging from custom designed devices, to consumer electronics, to industrial devices.

Some of the advantages of the implementations of these technologies in industry has been presented together with some possible future developments of these projects in terms of industrialization and distribution of the proposed solutions.

Chapter 3

Advanced machining sandbox

Research and development in in advanced control strategies for machine tool, could greatly benefit from having a completely open system to use as a sandbox. Test and implementation of advanced algorithms on commercial numeric control can be very difficult, in fact many numeric controls are closed-source, mainly for safety related issues, and even get data from them can be very difficult if not impossible. In order to develops and test their algorithms and machining techniques, research centres have two alternatives, to develop their own numeric control system or to collaborate with numeric control manufacturer which can adapt the NC to the research requirements. It's also worth noting that testing a new control algorithm can be risky, especially if it involves low-level controls on drives, because in case of failure it can result in crashes or damages to the machines or its components. Thus the ideal testbed for the development an test of advanced numeric control algorithms and control techniques would be a lightweight machine with limited power drives for the axis and an "open" numeric control which allows to extract all the relevant data and act on the basic logics of the control. The testbed must also allow enough flexibility in order to enable different types of test and experiments with reduced effort in system modification and reconfiguration.

In literature there are many works regarding the design of manufacturing testbeds for the development test and analysis of cutting-edge manufacturing technologies. For example Kovalenko et al. [52] presented an innovative manufacturing testbed which integrate both virtual and physical manufacturing systems. The testbed is composed by three cells connected by conveyor and includes three robots and four CNCs retrofitted with modern CNCs an PLCs in order to obtain easy access to real-time and historical data. All the devices in the testbed are connect and can exchange data. On the contrary, Vogl et al. [94] developed a very specific testbed of a machine toool's linear axis in order to develop ant test axis health status assessment algorithm to be implemented on an actual machine tool. As for the numerical control, Onwubolu et al. [73] developed a customized numeric control and PC-based frontend for an automatic drilling machine, in order to integrates and tests several innovative technologies and control algorithms.

In order to have a suitable machine tools for experimentation, development and testing purposes a flexible machining platform has been realized and is presented in this chapter. The base for the construction of the experimental machine tool is a *Personal Machine 3D*, a small-sized three axis milling machine with moving gantry structure. As the numerical control and axis drives were outdated, the machine has undergone a complete retrofitting to update the control to modern principles, in order to be able to integrate smart functions on the machine and to enable the communications between the machine and the IT infrastructure of the Laboratory.

Retrofitting of existing machine tools in order to enables smart functions and to make them connected and compliant with Industry 4.0 principles[62][39] is a trending research topic; in their review, Jaspert et al. [44] show that since about 2010, when the concept of Industry 4.0 was announced in Germany, the number of papers regarding retrofitting of machine tools raised drastically. Retrofitting is an efficient way for extending the useful life of a machine, in an efficient way both from time and costs point of view, which enhance the sustainability of the plants [42] [28].

Figure 3.1: Milling machine subject to retrofit.

3.1 The milling machine

The milling machine on which the testbed has been implemented is a *Personal Machine 3D* built around the first 2000s. This machine, designed and built by an Italian manufacturer, was originally designed for very-light milling works. The main purpose of these class of machines was the machining of foams and resins for production of orthotic and orthopedic devices. The machine have an aluminium structure and the axes are in a gantry configuration with double screw and motor for the movement of the *Y axis*. The frame of the milling machine is made by structural aluminium profiles while the working table and the axes structures are made by machined aluminium parts. All the axes are guided by supported hardened steel guide bars and related linear ball bearings. All axes are actuated by ball recirculating screws with 5 mm of pitch. The Z axis is balanced by two gas springs so that no brake is required on the axis to prevent it from falling when the drive motor is switched off.

The original numerical control of the machine was made by *PROMAX*. The NC needed to be connected to a PC, with the related software and drivers, in order to work and to enable machining. The axes were driven by open-loop stepper motor, so there wasn't any feedback about the rare position of the axes. The spindle, a 750 W triphase induction motor, was, as well, controlled in open loop by a variable frequency drive. The stepper motor were controlled by stepper drives which received direction and step signals from the numeric control. The two main disadvantages in this system were the impossibility of modifications and access to data on the numerical control, this was caused mainly by the type of numerical control and by the lack of documentation, and the open-loop axis drives, these didn't ensure the precision of the positioning of the machine and didn't give a feedback of the actual position of the axes. Moreover it was impossible to get data, such as torque, programmed speed, acceleration, and similar, from the axes drives.

A first, very light retrofit of this machine was done in 2017 when the numerical control was removed and was replaced by a customized ones built on an *Arduino DUE*®development board. The whole control logic was programmed from scratch, including advanced motion profiles, and some simple prototypes of adaptive numeric control were built and tested on this system [10]. The results of these tests and the interest on these topics from some numerical controls and automations manufacturer encouraged the development of a full retrofit of the machine in order to implement advanced control and monitoring strategies on industrial numerical controls.

3.2 Retrofitting project

Before to start planning the retrofit, an analysis of the structure of the machine tool and a study on the desired characteristics of the "new" machine were required. From the analysis of the actual machine emerged that the only electric part which was convenient to maintain was the electro-spindle which needed indeed and encoder in order to be able to measure the actual speed of the machine. Also the size of the new motors to be installed on the machine was decided after the analysis of the machine. For the new testbed, after some research and evaluations, the subsequent requisites were formulated:

- Flexibility, the system had to be flexible in order to adapt it to different kind of works, the machine has to provide the possibility to install auxiliary devices near the spindle or to easily substitute the spindle with another end effector (e.g laser head, welding torch, plasma torch etc.) in case of need;
- Feedback, the motor had to be controlled in closed loop, to increase the positioning precision and to be able to measure the real position of the axes and other useful informations such as following error;
- Interchangeability of numerical control, the machine is a testbed for numerical control so it's fundamental to be able to easily swap the numerical control from different manufacturer or with self-developed custom numerical controls;
- Connectivity, the machine had to be able to exchange data with the IT infrastructure of the laboratory as well as to allow the implementation of M2M communication among the machines which are and will be installed in the laboratory;
- Data access, the automation system had to allow the access to all suitable data from the devices, such as status of the devices, actual voltage and current signals from the motors, real speeds and so on;
- Scalability, the project can be considered as a base for the scale-up of the principles of smart retrofit and of the developed control on bigger production machines;
- Safety, the machine had to implement all the basics safety features such as emergency stop buttons, interlocked access doors and inhibition of drives and spindle in case of "intrusion" in the working area;
- Cost, the total cost of the project had to be maintained in a reasonable price, also considering further development and potential of the machine.

These requisites has been the base for the development of the project.

The solution which has been implemented has been chosen between different solutions proposed by the main players in the realm of industrial automation. During the evaluation of the proposals, many aspects has been taken into account in order to find the solution which best fitted the requisites.

Then the selected solutions has been developed in a collaboration between the manufacturer of the automation devices, the system integrator and the University in order to develop a comprehensive integrated automation system. The selected automation device provider is Beckhoff, while the chosen system integrator is SAIEE srl.

The project has been divided in three parts:

- Automation hardware selection and supply, carried out by the University together with the supplier, this part of the projects concerned the selection of the hardware to be integrated in the machining system basing on the characteristics of the machine, the requisites and planned system architecture.

- Electric plant retrofit. This part of project includes the ideation, the design and the construction of the electrical parts of the test platform. These tasks were developed by the system integrator with the guidance of the University and the advice of an expert who assisted in the planning of the system.
- Mechanical retrofit, some parts of the machine need to be modified in order to allow the installation of new devices. This tasks were carried out directly by the University which designed and realized the modifications to the structure of the machine. This retrofit didn't included substantial modifications to the machine structure but some new parts were designed and manufactured to realize suitable mountings for the new motors.

3.3 Automation system architecture

While planning the retrofit, a particular attention has been paid to the design of the automation system as it is crucial for the fulfilment of the requirements. Even though the machine is small and cannot be considered as a production machine, the electrical cabinet is quite complex and implements all the system which can be found in a modern machine tool. The automation system is substantially composed by five sections which are clearly identifiable in the electrical cabinet plus the HMI.

- Drive Assembly. This first section is devoted to the controls of the servomotors and of the spindle. In the machine is installed a modular drive system which includes components from the AX8000 motion control products manufactured by Beckhoff. This series of motion control devices includes all the components required for a comprehensive drive system such as power supplies, single or dual channel drives with different rated currents and auxiliary modules such as power recovery module. Each axis in the group can be controlled via EtherCAT and provides a sets of variables which can be read by the other devices connected to the fieldbus. The system is designed to drastically reduce the mounting and wiring effort by using a mounting system with integrated contacts for motor power supply, logic power supply, and fieldbus. Also the motors are connected with a single cable which includes both power and encoder signals.
- PLC. This component is in charge of the control of all the basic functions of the machine. To the PLC are connected, using adequate I/O modules, all the signals which are used for the regular function of the machine such as switches, push-buttons, leds, and limit switches . The PLC controls also the main contactors which interrupts the power supply to the drive assembly as well as the relay which controls the auxiliary functions. PLC is also directly connected to the safety PLC and exchange some variables, such as system status, with it. In the main fieldbus the PLC is seen as a slave device with its own process image and its own variables while in its own subnetwork, the PLC is the EtherCAT master of the devices connected to him.
- Safety PLC. The main task of the safety PLC is to controls and manage all safety-related devices, it is composed by a dedicated CPU and some dedicated I/O modules.

The safety devices are easily identifiable and can be distinguished from regular I/O devices thanks to their yellow case. Safety PLC executes a dedicated program and is under stricter rules if compared to regular PLC, such as password protection of the program and CRC control. Safety logic provides a restricted set of functions as each function implemented in safety PLC has to be certified.

- Numerical Control. Numerical control is the core of the machine as it's in charge of the control of all the devices on the machines. The machine is realized in a way that allows to swap the numerical control with a relatively reduced effort. In the base configuration the numerical control is soft-NC based on TwinCAT software. The numerical control is hosted on a Beckhoff CX2042 Din rail mounted Industrial PC. The numerical control act as master of the principal EtherCAT bus and is directly connected to the PLC, the data acquisition devices and the axes drive assembly.
- Auxiliary devices. To complete the automation system, a series of auxiliary devices are installed in the control cabinets. These devices provides power supplies for power and logic circuits, protection for all circuits and allows the control of power supply to some devices. Among the auxiliary devices there are also an Ethernet switch, to allow the remote connection to the PLC and to the IPC for management purposes and a signal converter for the connection of the HMI to the IPC via USB.
- HMI. The HMI is based on a 19,5' touch display with a CN extension that provides multiple programmable push-buttons, switches, and trimmers with indicator leds as well as an emergency stop-button. The HMI is connected to the IPC via DVI while touch-screen, buttons and leds are connected through USB. The Emergency stop button is obviously connected to a digital input but its state is also transmitted via the same USB connection of the others buttons.

3.3.1 EtherCAT bus topology

The EtherCAT filed-bus is the backbone of the automation system, all the informations between the different components of the system are exchanged through the field-bus which connects all the system. EtherCAT allows great flexibility in the bus topology as it allows to build line, tree, star or daisy-chain networks. Many different types of bus topologies can coexists in the same system without problems. EtherCAT allows also to build loops and redundant networks [38]. In this application the EtherCAT topology is quite simply, mainly due to the limited dimensions of the machine, however there are some things which are worth noting. The figure 3.2 represents the topology of EtherCAT network as was planned for the implementation in the test-bed's control cabinet.

The network is substantially a linear network which starts from the master device, the IPC that hosts the numerical control and ends with the last drive in the drive assembly. In the figure can be seen four different devices clusters connected to the EtherCAT fieldbus using Ethernet cables. The first device, in the top part of the figure is the numerical Control's industrial PC which is also the EtherCAT master, the device which manages the state of all the devices connected to the network and is in charge of the generation and reading of the EtherCAT datagrams which are sent in the network. An hardware license

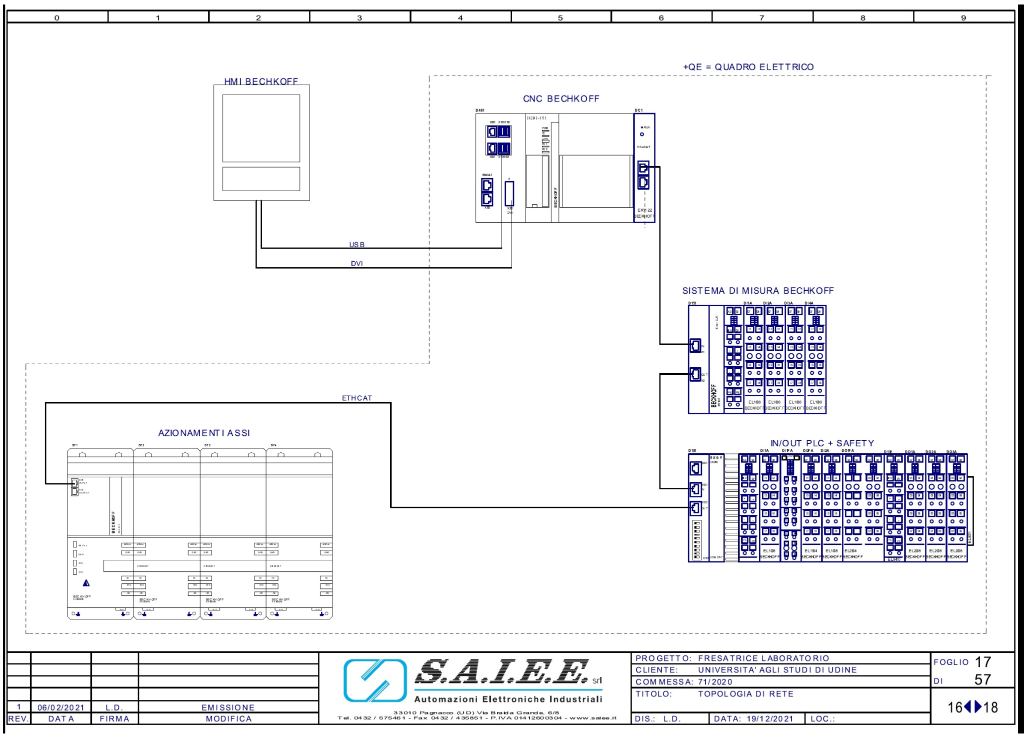


Figure 3.2: Ethercat Network Design

dongle and an adapter are connected via E-bus to the IPC, then a CAT 5 Ethernet cable connect the IPC to the next device in the network, the data acquisition cluster. This second device is composed by an EK1100 bus coupler to which are connected, via E-bus, a series of modules which allows the acquisition of analog signals from the sensors installed on the machine such as accelerometer and ultrasonic acoustic emission sensors. Then the network continues to the PLC, based on a CX8110 din rail mounted industrial PC. This device is quite singular as it act, at the same time as EtherCAT master, for the devices connected to the E-bus on its right, and as EtherCAT slave, for the network connected to the two RJ 45 ports on its left side. The two EtherCAT network are independent, the data exchange between the master and the slave side is guaranteed via the process image which can contain up to 512 bytes or 256 variables divided in input and output variables [31]. Finally, the EtherCAT network is connected to the axes drives assembly. The Ethernet cable is connected to the AX8620 - Power supply modules which extends the network to other connected drive modules through a dedicated bus.

As said before there is also a secondary EtherCAT network whose master is the PLC. This network connects various devices which are related to the functionalities of buttons, end-stops, leds, and locks on the machine as well as relays and contactors. It's important to highlights that in this network are also included the devices related to the safety PLC, in particular a safety digital output module, EL2904, and two safety digital input modules, EL1918 and EL1904, are installed. EL1918 is a eight channel safety digital input that integrates the safety logic function so it can be used as a safety controller.

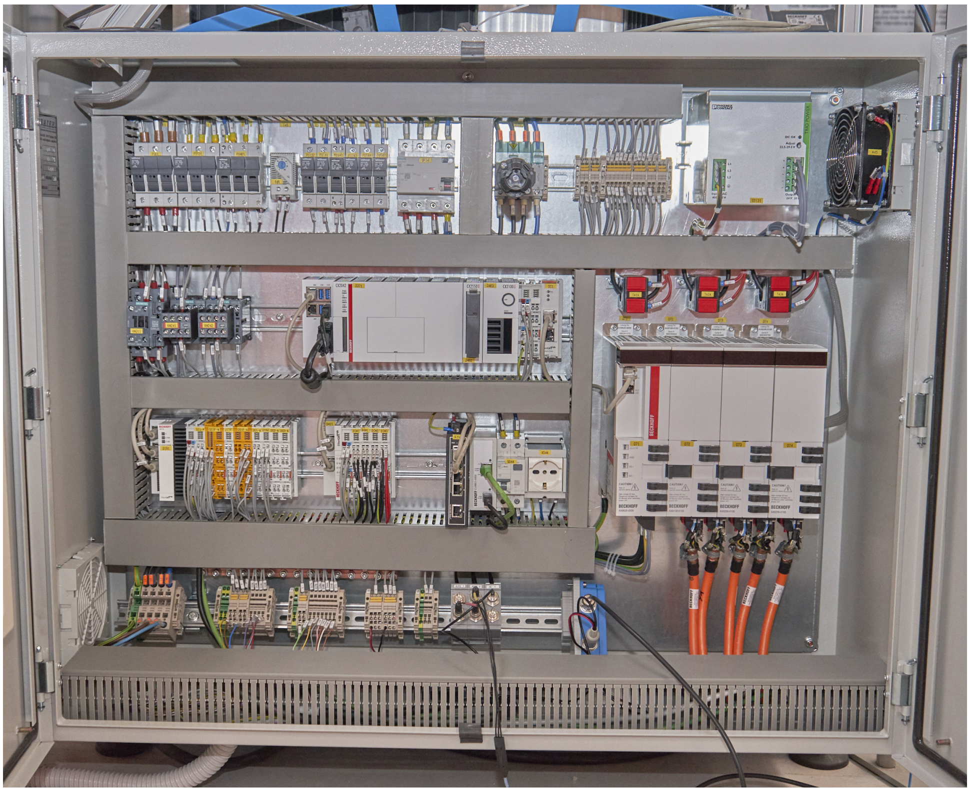


Figure 3.3: Machine electrical cabinet after retrofit.

3.3.2 Numerical Control Structure

The machine is controlled by a soft-NC, a numerical control based on software, this means that the numerical control doesn't have a dedicated hardware but can, theoretically, be executed by a normal PC that satisfies the requirements and can execute a real-time kernel operative system. Practically, for industrial applications, as high reliability of the system is required, only industrial PCs are used. An industrial PC is a PC which is designed in order to withstand the harsh industrial environment. So this PCs are usually are certified to work in an extended range of temperature and the circuits boards are designed in order to increase the immunity the electro magnetic interference. Some industrial PCs are also certified IP68 or more, this means that they can resist water and other liquid splashes.

The Soft-CNC is quite complex as it can controls simultaneously 64 axes or spindles that could be interpolated or they can be dislocated on different machines. To simplify configuration, operation and maintenance of the system, the CNC has a tree structure which includes different levels of organization entities such as channels and axes.

CNC software structure

CNC software is indeed composed by three main tasks, which are devoted to specific purposes and are executed with different timing. These tasks are closely related to the correct functioning of the CNC. The three tasks are:

- **GEO** This tasks runs with the interpolation cycle. It generates the inerpolation points according to the calculated motion profiles;
- **SDA** This is the NC program decoder, this tasks calculates also the correct motion coordinates for the rule in use, This task also calculates the maximum velocity of the axes considering the physics of the system and the limiting parameters;
- **COM** This task executes the communication between the CNC and the HMI.

Channel & Axis

The CNC organization structure is based on two main objects, channels and axes. A channel is a representation of a motion unit (e.g. a machine or a part of a complex machine). A channel can holds up to 32 axes, of which a maximum of 6 can be spindles, simultaneously. A CNC configuration may contain multiple channels and, of course, a channel contains many axes. A CNC project can groups up to 12 channels and a maximum of 64 axes with 12 spindles. An axis can be dynamically associated with a channel, this allows to programmatically move one axis from a channel to another, allowing also the synchronization and the interpolation in the new channel. Each object of the CNC project is described by a parameters list in which is possible to set all the properties of the object. Some properties of higher level objects can be inherited by the lower level elements, however it's also possible to override the inherited parameters for a specific object.

Each axis in the configuration usually have its physical counterparts, however in complex and modular machine this is not always true, so it's possible to manage different configuration of a machine with minimal program changes.

CNC packets enables several cinematic transformations which can be applied to a channel in order to align the virtual axis configuration to the actual machine configuration reduced effort as for the most diffused machine configuration is still present the related cinematic transformation.

Axes can be configured as single axes or gantry axes in master & slave configuration, this last functionality allows to synchronize two machine drives in order to move synchronously the two devices. The physical alter-ego of an axis can be connected to the CPU through many different fieldbus protocols both for axes interface and for the integrated I/O system.

3.3.3 Actual machine tool configuration

The actual experimental machining testbed in its base configuration has four axes organized in a single channel as their are referenced to a single motion units and needs to be synchronized and interpolated. The configuration includes also a spindle which is controlled directly by the CNC.

The real configuration of the CNC system, with the related tree structure is represented in the figure 3.4. As can be seen from the figure, the motion element contains a CNC configuration which is composed by many items. In the tasks container, there are the

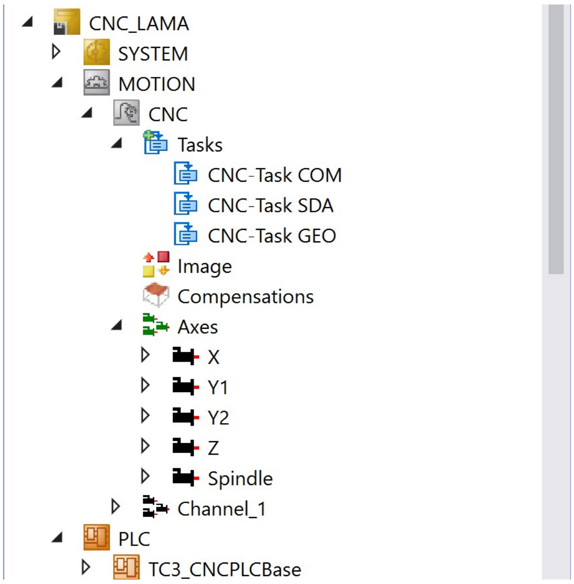


Figure 3.4: Actual CNC configuration in TwinCAT

three tasks needed by the CNC. The compensations containers group all the eventual volume compensation tables needed by the machine in order to reach high precision. The axes tabs comprises the four axes and the spindle. Each axes has an inputs and an output image in which are contained the related inputs and outputs variables defined during drives commissioning. The axes elements allow the link between the virtual element and the physical drive. In the axis configuration, can also be selected the channel in which the axis is connected. Then there is the channel element, also this elements provides inputs and outputs images which are configurable. Each one of these last three elements (axes group, axis , channel) has a parameters list which can be edited during the commissioning of the machine in order to enable the drives to fulfil the application's requisites.

The TwinCAT Engineering environment allows the user to control all the aspects of a complex automation projects using a single software which integrates, in a Visual Studio® shell, all the tools needed for the management of various aspects of the automation projects, from PLC project, to I/O supervision and configuration, including the management of tasks priorities and timing. The software allows also the creation of the so-called "Measurement project" which are substantially virtual oscilloscopes which allows the user to configure different types of graphs on which selected variables can be plotted in real time and recorded. This kind of projects are useful both for commissioning and configuration phases and during normal operations of the machine. During the start-up phase, the graphs simplify the tuning of drives regulator parameters as enables the technician to see how cinematic parameters (position, velocity, acceleration ,torque) vary when changing control loops parameters. During the normal operation these projects can be used for process monitoring or diagnostics on the machine or its components.

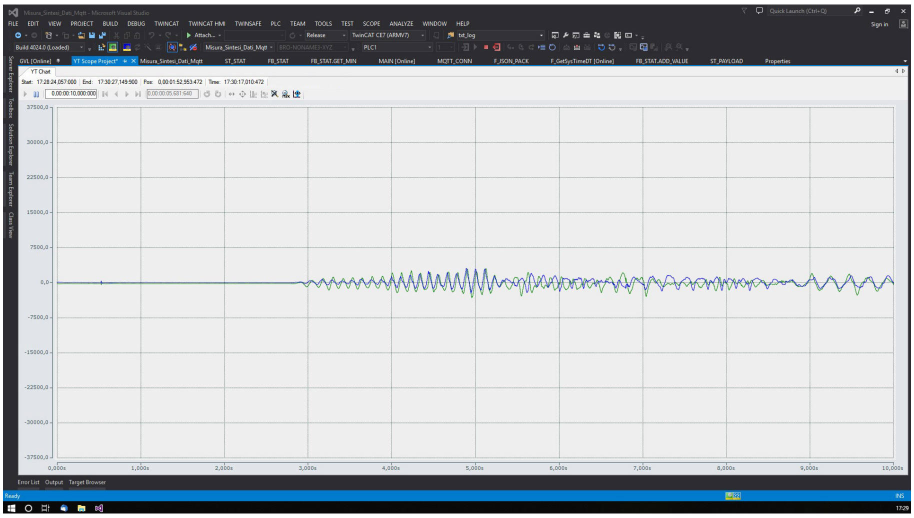


Figure 3.5: Example of measurement project, scope view.

3.4 Machine Start-up

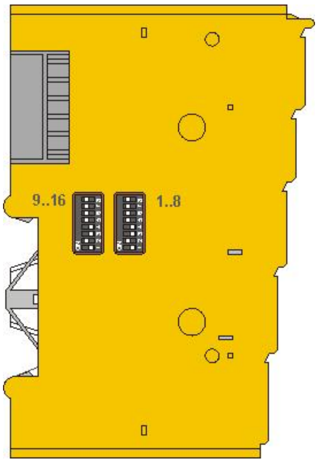
After the completion of hardware building and testing, the configuration commissioning and start-up phases started. These phases involve configuration of the IPC, programming of the safety PLC, programming of the machine's PLC, creation of the CNC configuration, commissioning an tuning of the drives. As the automation system is entirely based on Beckhoff hardware, all these software configuration are carried out in the integrated development environment provided by the manufacturer.

3.4.1 EtherCAT Networks Configuration

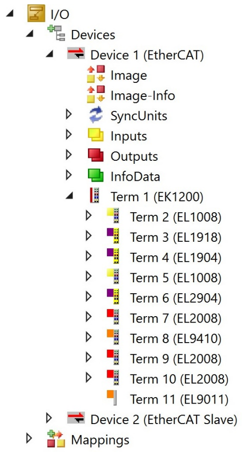
The very first task to perform when starting for the first time a new machine is the configuration of the fieldbus networks. This configuration is needed as it enables the user to link the variables created in PLC programs to the corresponding physical channels and is also important because allow the operator to test the network and to verify that all the devices installed are correctly connected to the fieldbus and are correctly working. As said above, the machine has two "independent" EtherCAT networks, the first is the main network, mastered by the CNC, which connects the CNC to the machine PLC, the data acquisition I/Os and the drives. The second network is a sub-network mastered by the IPC which controls a series of I/O modules as well as the safety modules. The configuration of the networks start with the sub-network to proceed with the main network.

Sub-network configuration

The first network to be configured is the sub-network. This network is quite simple as it's developed on a single branch and is all located directly on the E-bus provided by the IPC. However there are some operation which are crucial to allow the correct configuration of the other components of the system such as the assignation of the address to the safety modules. Unlike normal modules, safety modules, are equipped with a dip-switch array for the setting of the address of the module. The hardware address has to be unique in the network and need to be set before starting the software configuration, otherwise the system won't recognize the module.



(a) Safety Module dip-switches array. *Beckhoff*



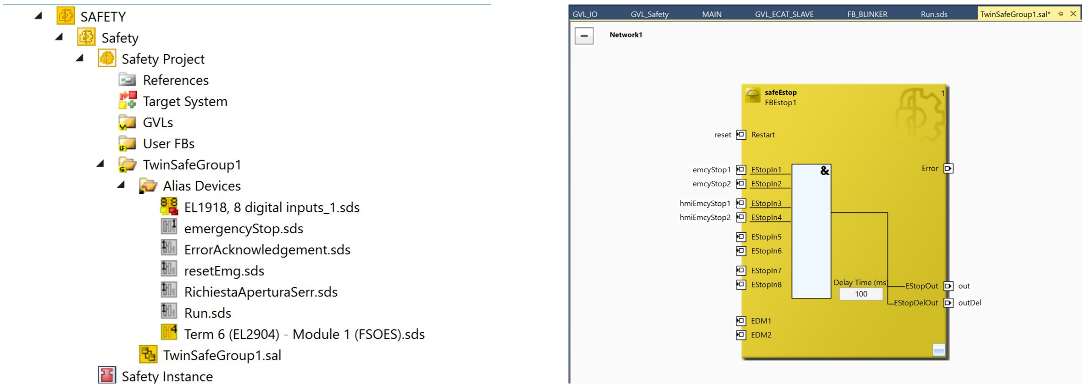
- I/O
  - Devices
    - Device 1 (EtherCAT)
      - Image
      - Image-Info
      - SyncUnits
      - Inputs
      - Outputs
      - InfoData
      - Term 1 (EK1200)
        - Term 2 (EL1008)
        - Term 3 (EL1918)
        - Term 4 (EL1904)
        - Term 5 (EL1008)
        - Term 6 (EL2904)
        - Term 7 (EL2008)
        - Term 8 (EL9410)
        - Term 9 (EL2008)
        - Term 10 (EL2008)
        - Term 11 (EL9011)
    - Device 2 (EtherCAT Slave)
  - Mappings

(b) Sub-network hardware configuration

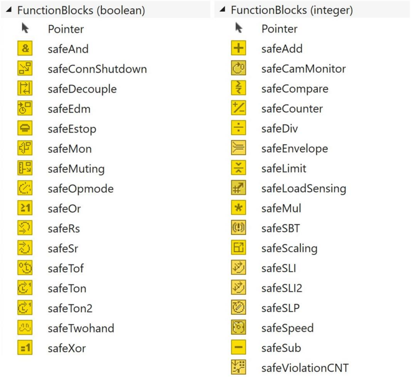
Then, the hardware configuration can be imported in the TwinCAT software configuration by performing a scan of the network. This procedure, available only when the system is in *Config Mode* allows the operator to easily discover the devices connected to the fieldbus and add them to the actual configuration. In the CX8110 EtherCAT network there are nine devices. Two of them are digital inputs modules *(EL1008)* which are connected to the buttons and switches installed on the machine. Then there is a digital output module *(EL2008)* which controls the signal lamps. In this network are inserted the safety devices, two input modules *(EL1918, EL104)*, one of whom with integrated safety logic, and a safety output module *(EL2904)*. At the end,is installed a power supply module *(EL9410)* which allows the control of the supply of two digital output modules *(EL2008)* that can be used for auxiliary functions. After the scan and the identification of the connected devices, they are ready foe their configurations and for the link between PLC variables and physical devices.

Main network configuration

The configuration of the main network is done using similarly to what done for the sub-network. In this case there are quite many device connected as this network includes all the devices installed on the machine. The network is composed by four clusters of devices with a total of fifteen devices. The master of the network is the CX2042 IPC on which is installed the CNC. The first two devices are installed directly on the IPC. These are an hardware license dongle and a *EK1122*. This last device allows the continuation of the E-Bus on Ethernet cable providing two RJ45 ports. Then, the network proceed via cable to the next device, an *EK1100* fieldbus adapter, this convert the Ethernet to E-Bus and provides power to the connected devices. In this segment are grouped all the devices related to analog signals acquisition, in particular there are two IEPE compatible, 16 bit analog input modules *(EL3632)*, a 16 bit voltage analog input module *(EL3702)* and a power monitoring module *(EL3773)*. All these modules are compatible with distributed clocks and oversampling, this allow to acquire analog signals with precise timing with a sample rate up to 50 MHz. The next device in the network is the CX8110 industrial PC that hosts the machine PLC. In this context the IPC act as a slave device and exchange the data defined in its process image. The last group of device in the network is composed by the drives and the auxiliary devices. The first device in this group is the power supply module *(AX8620)*, this module is directly connected to the EtherCAT bus via Ethernet cable, to the 24 V logic power supply and to the 380 V tri-phase power supply for the motors. The module then routes the EtherCAT bus and the logic power to a specialized bus which connects the various axes installed. It also converts the tri-phase power to a suitable voltage to feed the DC bus for the motors. Three axis drives with different characteristics are installed on the machine, one single axes drive with a nominal current of 8 A, which controls the spindle, and two dual channel axes drive which can provide a maximum current of 6 A per channel, that are connected to the four servo-motors which drives the machine's axes.


- SAFETY
  - Safety
    - Safety Project
      - References
      - Target System
      - GVLs
      - User FBs
      - TwinSafeGroup1
        - Alias Devices
          - EL1918, 8 digital inputs_1.sds
          - emergencyStop.sds
          - ErrorAcknowledgement.sds
          - resetEmg.sds
          - RichiestaAperturaSerr.sds
          - Run.sds
          - Term 6 (EL2904) - Module 1 (FSOES).sds
        - TwinSafeGroup1.sal
    - Safety Instance

(a) Safety PLC Project Tree (b) Safety PLC Project Network


FunctionBlocks (boolean)
- Pointer
- safeAnd
- safeConnShutdown
- safeDecouple
- safeEdm
- safeEstop
- safeMon
- safeMuting
- safeOpmode
- safeOr
- safeRs
- safeSr
- safeTof
- safeTon
- safeTon2
- safeTwohand
- safeXor

FunctionBlocks (integer)
- Pointer
- safeAdd
- safeCamMonitor
- safeCompare
- safeCounter
- safeDiv
- safeEnvelope
- safeLimit
- safeLoadSensing
- safeMul
- safeSBT
- safeScaling
- safeSLI
- safeSLI2
- safeSLP
- safeSpeed
- safeSub
- safeViolationCNT

(c) Safety PLC Function Blocks

Figure 3.7: Safety PLC Configuration

3.4.2 Safety PLC configuration

An important task to fulfil when starting the new machine was to program the safety PLC in order to read the status of the emergency-stop buttons an to appropriately control the status of the outputs connected to the main contactors that energize the drives and some I/O modules.

Safety PLC project are configured, compiled and managed in a purpose-built development environment called TwinSAFE, which is integrated in the TwinCAT distribution [30].

Programming of safety PLC requires to firstly define a target system on which the safety program will be installed [32]. This could be a dedicated controller or a I/O module with integrated logic. Then the creation of virtual alias of the physical devices is needed in order to correctly link the physical devices with the corresponding variables. Then the actual safety-PLC program is created. In this case only graphical programming (with function blocks) is allowed. For safety PLC programs, only certified functions and function blocks can be used as they have to be certified for safety use and there are some limitations on the types of inputs and outputs variables which are allowed. The users has a library of available function block for boolean and integer variables Each function block has a precise function [33].

The basic safety configuration of the machine is quite simple as it involves a single FB which is devoted to the control of the EStop buttons. In figure 3.7a the actual TwinSAFE network is represented. On the right side of the function block are located the inputs, as can be seen there are two emergency stop buttons (*emcyStop* and *hmiEmcyStop*) installed respectively on the machine and on the HMI panel. Each button has two normally closed contacts which are connected to two different digital inputs and obviously to two inputs of the safeEstop FB. There is also a “Restart” input which is connected to the reset variable which is linked to the corresponding reset buttons on the machine and on the HMI panel, this signal is used to acknowledge and clear an emergency stop. On the right side there are the outputs. The EStopOut is connected to a PLC variables in order to signal the emergency status while the EStopDelOut is linked to a channel of the safety output I/O module which is connected to the contactor coil. It is possible to see a delay for the second output in order to enable the PLC to execute some emergency-related task before acting on the contactor.

3.4.3 Machine PLC Configuration

The PLC running on the CX8110 IPC is in charge of the management of the basic functionalities of the machine, together with the safety PLC. The IPC installed on the machine provides two EtherCAT ports in addition to the E-Bus. These two additional ports enable the IPC to be inserted as a slave device in an EtherCAT network. In order to enable data exchange, the creation of variables in the process image of the EtherCAT slave is needed. This can be done simply by opening the EtherCAT slave in the device manager and adding the variables in the input or output image by right-clicking on it and choosing the type and the name of the variable. In the actual configuration, ten inputs variables and ten output variables of type byte has been created. The created variables are linked to two corresponding byte arrays of ten elements created in a dedicated global variable list in the PLC project. The PLC project has also two other GVLs called *GVL_ IO* and *GVL_ Safety* in which are grouped respectively the variables linked to physical I/O signals (i.e. buttons, switches and LEDs), and the variables related to the Safety PLC and devices. Finally, there is a *MAIN* program in which the status of the buttons and switches installed on the machine is read cyclically and the status of the outputs is set consequently.

3.4.4 CNC configuration

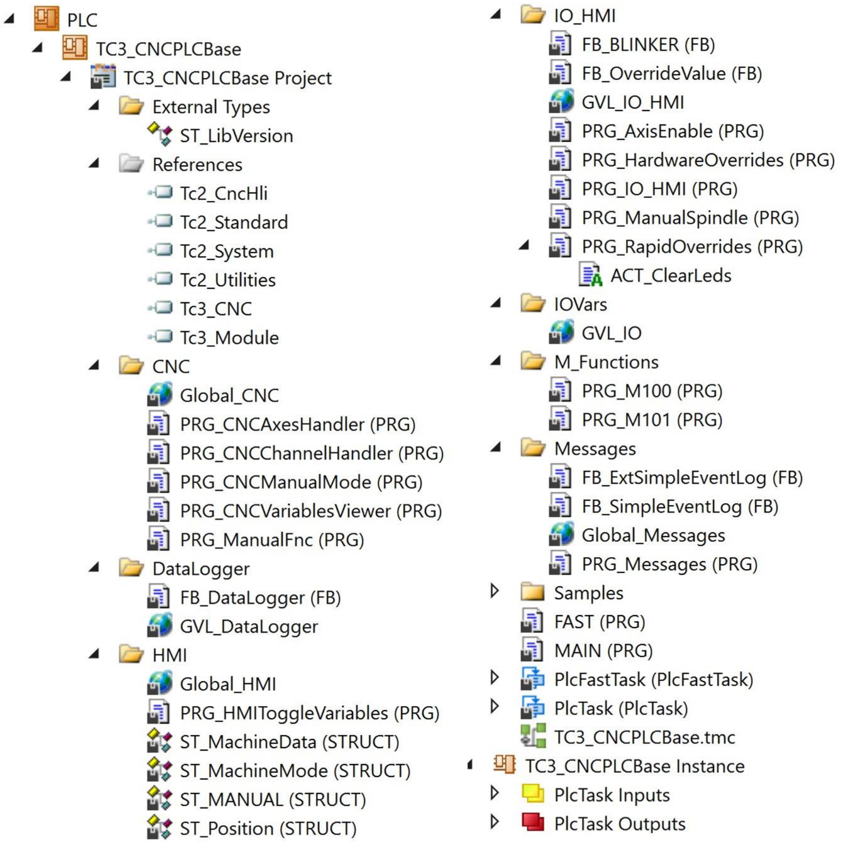
In order to start the CNC configuration, is required to add an appropriate object in the software configuration. It's then necessary to add the CNC project under the motion group, this will create different object in the configuration included the three tasks needed for the CNC to execute. Is then possible to add the axes and to link them to the physical axes of the machine. On this machines there are five axes called *X*, *Y1*, *Y2* (the machine has a gantry structure with dual motor on the Y axis), *Z* and *Spindle*. At least one channel needs to be created in order to groups all the axes of the machine in a unique motion unit. Once the axes and the channels are created is possible to associate the axes to the corresponding axes and to program the drives writing the appropriate parameters in the parameters list. Each parameter list is downloaded on the drives each time the configuration is activated. Also channels have many parameters lists which describes the general behaviour of each channel and its characteristics.

3.4.5 CNC PLC Configuration

To enable the machine to work properly a PLC is required together with the CNC configuration. The PLC has many functions such as the control of the axes, the control of the spindle and other CNC-related tasks. The PLC is based on a standard library provided by the manufacturer. This library includes all the function blocks required to build a CNC application. The manufacturer provided also a basic PLC program to be used as a starting point for the machine configuration. This program can be extended and modified in order to fit the application requirements. The PLC allows the user to add functionalities to the machine such as custom M/H codes, tools tables and auxiliary functions. The PLC program provided by the manufacturer can interface directly with the HMI program provided as an unsupported utility by Beckhoff.

3.5 Machine tool modelling

In order to have a comprehensive knowledge about the machine tool behaviour a set of experimental test has been carried out. The tests aimed to develop models the principal components of the machine and the whole machine. These model are useful because allows to distinguish the contributes of the machine by the contributes of the machining process during the next experiments. As well, some of the data collected during this tests are used to build a “snapshot” of the initial status of the machine and its components which can be used afterwards for machine health status assessment for maintenance purposes.



- PLC
  - TC3_CNCPLCBase
    - TC3_CNCPLCBase Project
      - External Types
        - ST_LibVersion
      - References
        - Tc2_CncHli
        - Tc2_Standard
        - Tc2_System
        - Tc2_Utilities
        - Tc3_CNC
        - Tc3_Module
      - CNC
        - Global_CNC
        - PRG_CNCAxesHandler (PRG)
        - PRG_CNCChannelHandler (PRG)
        - PRG_CNCManualMode (PRG)
        - PRG_CNCVariablesViewer (PRG)
        - PRG_ManualFnc (PRG)
      - DataLogger
        - FB_DataLogger (FB)
        - GVL_DataLogger
      - HMI
        - Global_HMI
        - PRG_HMIToggleVariables (PRG)
        - ST_MachineData (STRUCT)
        - ST_MachineMode (STRUCT)
        - ST_MANUAL (STRUCT)
        - ST_Position (STRUCT)
      - IO_HMI
        - FB_BLINKER (FB)
        - FB_OverrideValue (FB)
        - GVL_IO_HMI
        - PRG_AxisEnable (PRG)
        - PRG_HardwareOverrides (PRG)
        - PRG_IO_HMI (PRG)
        - PRG_ManualSpindle (PRG)
        - PRG_RapidOverrides (PRG)
          - ACT_ClearLeds
      - IOVars
        - GVL_IO
      - M_Functions
        - PRG_M100 (PRG)
        - PRG_M101 (PRG)
      - Messages
        - FB_ExtSimpleEventLog (FB)
        - FB_SimpleEventLog (FB)
        - Global_Messages
        - PRG_Messages (PRG)
      - Samples
      - FAST (PRG)
      - MAIN (PRG)
      - PlcFastTask (PlcFastTask)
      - PlcTask (PlcTask)
      - TC3_CNCPLCBase.tmc
    - TC3_CNCPLCBase Instance
      - PlcTask Inputs
      - PlcTask Outputs

Figure 3.8: CNC PLC structure.

To build a model which can describe many aspects of the machine, two types of tests has been conducted:

- Pulse testing, to analyze the static and dynamic behaviour of the machine tool's structure;
- Axes and spindle free-run tests, to analyze and model the characteristics of the axes and the spindle when moving (or rotating) without loads applied.

3.5.1 Pulse testing

Pulse testing is a technique for the evaluation of dynamic characteristics of structures. It was originally applied, by aircraft industries, for the evaluation of aircraft dynamic characteristics [9]. Afterwards this methods has been extended to other industrial fields such has machine tools and mechanical structures. Pulse tests allows to measure the FRF of a dynamic system by applying an input to it (*input command or disturbance*) and observing the resulting response of the system. Both the input and the output signals need to be recorded and used for the computation of the frequency response function of the system.

Measurement system

Pulse tests can be executed on a very broad range of structures with different experimental setups, however, in general, all variants has in common three devices [25].

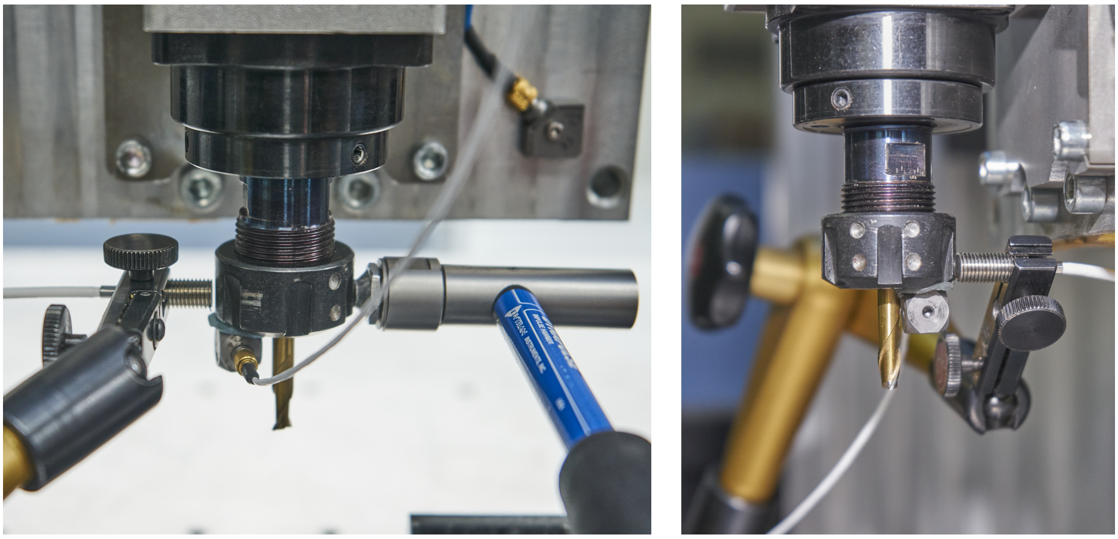
- Excitation mechanism, the device which generates the input signal, it can be automatic (such as electromagnetic shakers) or manual (hammer). In case of automatic excitation mechanism, there are also a source for the excitation signal and a power amplifier.
- Sensors to measure the input signal applied to the structures and the output signals generated by the structure. The input signal is usually measured by a force transducer (load cell) installed between the structure and the excitation mechanism. In case of manual excitation the input sensor is usually integrated in the hammer tip. The output signal can be measured with a variety of sensors, depending on the characteristics of the system which is analyzed and of the signals to be measured. Accelerometers are widely used for this kind of test, however in certain cases a non contact measurement method need to be used in order to avoid excessive system perturbation, such as inductive or laser sensors for displacement measurements or microphones.
- Recording and analysis system to control the sensors, filter and record the data coming from them. The recorded signals are then analyzed in order to extract the useful information and evaluate the FRF which can be then presented on a Bode-Plot or in a Nyquist diagram.

Actual Experimental Setup

For the identification of the dynamic characteristics of the machine tool's structure, manual pulse tests has been conducted using an instrumented hammer (*Dytran 5800B*) as input source and a triaxial piezoelectric accelerometer (*Kistler 8763B050A*) and an eddy current displacement sensor (*MicroEpsilon eddyNCDT*) as output measurement transducers. Al the signals has been measured directly on the machine using appropriate Beeckhoff input modules and a TwinCAT measurement project. All the analog signals are acquired at a sample rate of 25 kHz. The force has been applied on the spindle's collet nut while the accelerometer was mounted with wax, under the spindle collet, and the non-contact displacement sensor, held by an hydraulic support, was placed facing the spindle's collet nut at the opposite of the force application site. In figure 3.9 the experimental setup for pulse tests in X (3.9a) and Y (3.9a) directions.

Design Of Experiments

Due to the geometrical characteristics and the configuration of the machine's structure, in order to build a model which can describe the dynamic behaviour of the structure in different positions, the test has been conducted with the axes in different positions. So for each axes three test positions has been defined, a position near the minimum end stop, a



(a) Pulse Test experimental setup - X direction

(b) Pulse Test experimental setup - Y direction

Figure 3.9: Pulse tests experimental setups

position in the middle of the stroke and a position near the maximum end stop. All the combinations of the positions have been tested along the X and the Y direction in the machine coordinate system. Basing on the results of a preliminary pulse test conducted in a reduced sets of points, the Z directions has been excluded from the DOE, since its contribution to the dynamic behaviour it's not so important. In table 3.1 are listed the three position levels for each axis. The DOE counts a total of $3x3x3x2 = 54$ tests.

Axis	Min Position [mm]	Med Position [mm]	Max Position [mm]
X	0,00	312,50	625,00
Y	2,00	200,00	400,00
Z	0,00	85,00	170,00

Table 3.1: Position levels for each axis.

Data Analysis

During the tests all the signals has been recorded in a TwinCAT measurement project. The TwinCAT development interface provides an effective instrument for the visualization and recording of the signals collected or produced by the devices (physical or virtual) connected to the project. Once registered, the signals, can be saved into a file. The recording system provides many options regarding file format. In this case CSV has been chosen for its flexibility and compatibility with different operating system and programming languages.

The data analysis has been done in Matlab so each data file has been imported and converted from CSV to a Matlab structure, this to save memory (a .MAT file is about the 10% in size respect to the corresponding CSV) and to speed up the analysis process as these files are charged faster than normal text files. Each data file is then processed in order to extract only the useful part of the signals. The pre processing function scans the data and selects only the transients with a good signal to noise ratio and without saturation problems. The selected transients are then packed in signal arrays which are saved for the next elaborations. This allow a further reduction in file dimensions as only the useful part of the data is kept. Then the transient are analyzed to evaluate the frequency response function of the system. As for the tests two output sensor has been used, two FRF are calculated, one for each output sensor, together whit the related coherence function. The two FRF function are then combined with a weighted average using the coherence function as a weighting parameter. The results of data analysis are reported, for two different test points in X and Y directions, in figure 3.10. As can be seen from the charts, the averaged FRF (cyan curves) fits quite well the FRF obtained from the displacement signals obtained from the accelerometer signals (red curves), and the displacement signals obtained from the eddy current sensor (black curves). Coherence functions curves are also reported for the measured signals. This procedure is repeated for all the test points and the results are saved in appropriates data structures.

FRF model

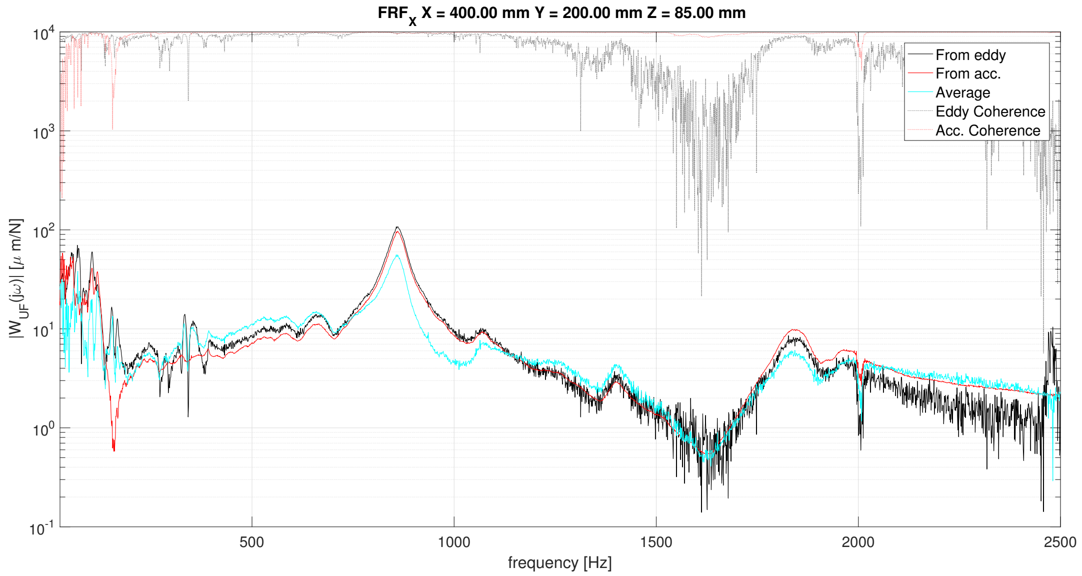
In order to enable the possibility to evaluate the Frequency Response Function, and in particular the static deflection and the resonance frequencies of the machine's structure in all the positions of the working volume with an acceptable precision. The model is built basing on the results of the previous experiments. The calculated frequency response functions has been inserted in a Matlab structure together with the positions of the machine and the direction of measurement. Then for each frequency value between 0 Hz and 10 kHz (the signals were acquired at 25 kHz sampling frequency), with a resolution of 1 Hz, two arrays with the real and the imaginary parts of the response function has been created. These arrays were then used for a regression based on the *X, Y, Z* coordinates of the machine and their combinations. For each frequency is then obtained a model of the type:

$$\begin{aligned}\Re(W_\omega) = A_{\omega,0} + A_{\omega,1}\cdot X + A_{\omega,2}\cdot Y + A_{\omega,3}\cdot Z + A_{\omega,4}\cdot X\cdot Y \\ + A_{\omega,5}\cdot X\cdot Z + A_{\omega,6}\cdot Y\cdot Z + A_{\omega,7}\cdot X^2 + A_{\omega,8}\cdot Y^2 + A_{\omega,9}\cdot Z^2\end{aligned} \quad (3.1)$$

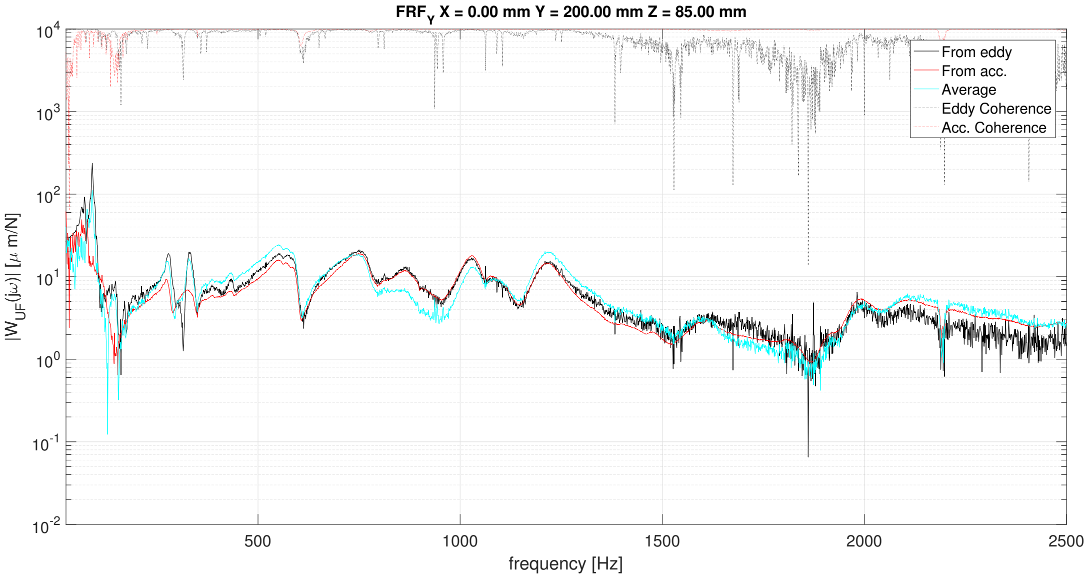
for the real part and,

$$\begin{aligned}\Im(W_\omega) = B_{\omega,0} + B_{\omega,1}\cdot X + B_{\omega,2}\cdot Y + B_{\omega,3}\cdot Z + B_{\omega,4}\cdot X\cdot Y \\ + B_{\omega,5}\cdot X\cdot Z + B_{\omega,6}\cdot Y\cdot Z + B_{\omega,7}\cdot X^2 + B_{\omega,8}\cdot Y^2 + B_{\omega,9}\cdot Z^2\end{aligned} \quad (3.2)$$

for the imaginary part, where $\Re(W_\omega)$ and $\Im(W_\omega)$ are respectively the real and the imaginary parts of the frequency reponse function W calculated at the frequency ω, $A_{\omega,0} \ldots A_{\omega,9}$



(a) X direction



(b) Y direction

Figure 3.10: Measured Frequency Response Functions

and $B_{\omega,0} \dots B_{\omega,9}$ are the regression coefficients of the real and the imaginary parts of the FRF at the ω frequency, and X, Y, and Z are the coordinates of the position, in mm, in which W is calculated.

The regression coefficients calculated are stored in two matrix, one for the real part's coefficients and one for the imaginary part's coefficients. Each row of the matrix correspond to a frequency step of the FRF. This procedure has been repeated for both the X and the Y direction in order to enable the estimation of the FRF in both interest directions.

For a given position $\hat{x}$, $\hat{y}$, $\hat{z}$ the corresponding frequency response function can be then evaluated as:

$$\begin{bmatrix} A_{11} & \dots & A_{19} \\ \vdots & \ddots & \vdots \\ A_{m1} & \dots & A_{m9} \end{bmatrix} \times \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \\ \hat{x} \cdot \hat{y} \\ \hat{x} \cdot \hat{z} \\ \hat{y} \cdot \hat{z} \\ \hat{x}^2 \\ \hat{y}^2 \\ \hat{z}^2 \end{bmatrix} + i \begin{bmatrix} B_{11} & \dots & B_{19} \\ \vdots & \ddots & \vdots \\ B_{m1} & \dots & B_{m9} \end{bmatrix} \times \begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \\ \hat{x} \cdot \hat{y} \\ \hat{x} \cdot \hat{z} \\ \hat{y} \cdot \hat{z} \\ \hat{x}^2 \\ \hat{y}^2 \\ \hat{z}^2 \end{bmatrix} = \begin{bmatrix} W_{11} \\ \vdots \\ W_{m1} \end{bmatrix} \tag{3.3}$$

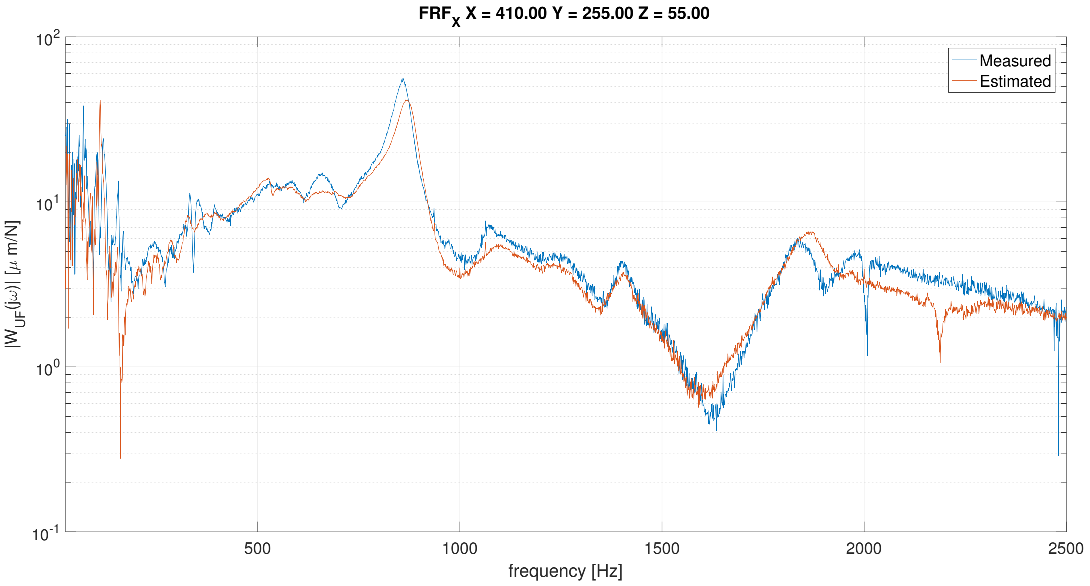
$$A \times X + iB \times X = W \tag{3.4}$$

Where A is the $m \times 9$ matrix of the coefficients of the real part of the FRF, B is the $m \times 9$ matrix of the coefficients of the imaginary part of the FRF, W is the $m \times 1$ complex array of the FRF, X is the 9×1 array of the coordinates and their linear combinations.

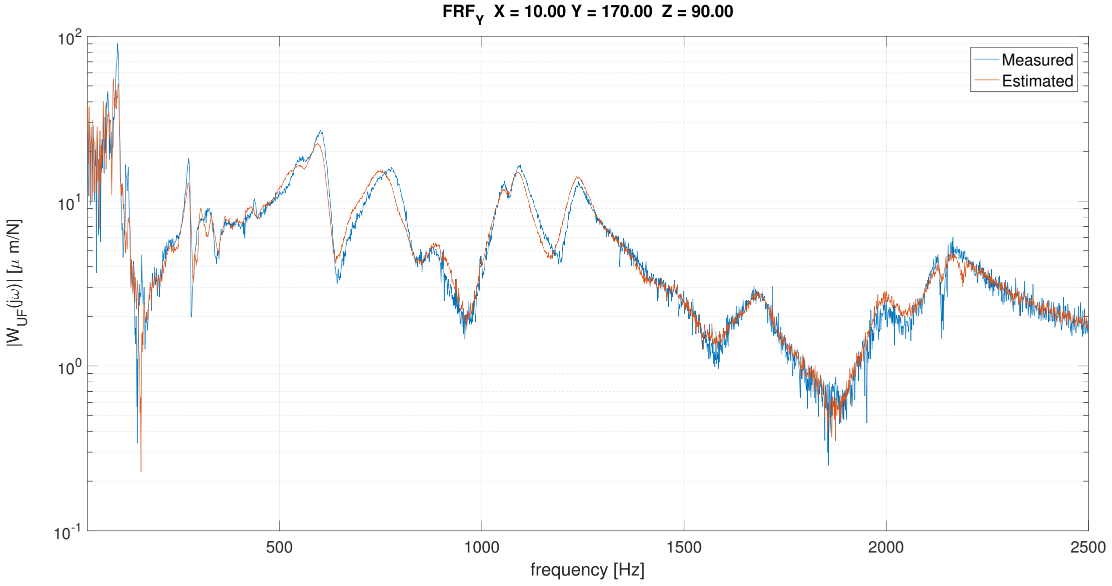
The number of elements in the array m depends on the frequency limits and resolution of the model.

Model validation

In order to evaluate the performance of the model and its correctness, a validation process has been carried out. The validation process has been divided in two phases. in the first phase the model has been used to estimate the FRF in some of the positions of the previous DOE, then the estimated FRF were compared with the measured one. These first validation tests aimed to find errors in the model construction; the results of these preliminary test were positive. The second validation phase consisted in the reconstruction of the FRF in an arbitrary position of the machine, using the model. Then the evaluated FRF had been compared with the data obtained by the evaluation of the FRF based on the data obtained by a pulse test executed in the same position (3.11). As can be seen in the images the FRF estimated with the model described above (red curve in charts in figure 3.11) is quite similar to the FRF measured in the corresponding axes positions (blue lines in charts in figure 3.11). These tests has been repeated in many different positions and the relative error between the estimated and measured FRF has been evaluated. For



(a) X direction



(b) Y direction

Figure 3.11: Model-estimated Frequency Response Functions VS Measured Frequency Response Functions

all the test point the relative error was acceptable in the frequency range of interests for the applications.

3.5.2 Axes and spindle models

An important aspect to be studied and analyzed when approaching a new machine tool, is the characteristic of the axes and the spindle. In particular is fundamental to investigate the behaviour of the components of the machine when no load or external disturbances are applied. These data can be useful during the subsequent research activities because allows to distinguish between the base contributes of the machine from the "disturbances" related to the cutting process or other external forces acting on the machine. This models can be obtained substantially in two ways, analytically or empirically, by experiments.In bibliography there are may examples of analytical modelling of machine tool's axes. For example in [4] and [24], the authors propose an analytical model of a ball-screw actuate machine tool's axis, other examples of analytical models of machine tool's axes can be found in [97], where the authors present an hybrid approach for the modelling of the behaviour of a machine tool's axis under different conditions, or in [93] that present a collection of mathematical models for the description of lead screw systems. However most of these models are developed and applied on test benches or single axes. For the discussed application a non-parametric model has been chosen. The reasons for this choice are mostly related to the characteristics of the machine. in fact the machine on which the model is developed has some construction features that heavily affect the axes behaviour making very difficult to obtain a reliable analytic model. The protective bellows that cover the axes protecting the linear rails and the screws from dust, chips, and other contaminants which can harm the components, for example, cause a strong dependence of the torque with the position of the axis. The gantry configuration of the Y axes, for example causes, for both Y axes, a torque contribute needed to keep the axis in position and to maintain the machine aligned; this contribute is not constant and depends on many variables some of which are not controllable. Another "disturbance" can be found on the Z axis where two gas springs are mounted as counterweight to balance the weight of the axis assembly and of the spindle avoiding any movement of the axis when the motor are de-energized.

Design of Experiments

The data required for the construction of the model were obtained by a set of tests on each axis of the machine. The tests consisted in a series of runs along the full stroke of the axis with different speeds. The values of speed were chosen in order to ensure the analysis of a wide range of speed in accordance with the limits of the machine. For the X and Y axes 19 speed levels, ranging from 100 mm/min to 10 000 mm/min has been set, while on the Z axis, due to the limited stroke, 14 speed levels, ranging from 100 mm/min to 5000 mm/min. At each speed level the axes were moved (one at a time) along the full stroke in both the positive and the negative directions. For the spindle the tests, conducted after a warm-up cycle, consisted in running the motor at a fixed speed for a fixed time period. Spindle's test counts 16 speed levels from 100 RPM to 24 000 RPM.

Data Analysis

Axes Data

The dataset collected during the tests carried out on each axis has been, first of all, converted from CSV to a Matlab structure in order to save memory and to reduce the time required for the data loading during the elaborations. Then, since the tests were saved on many files, from each files the useful data has been extracted and packed into a structure which contains all the data related to the tests of an axis. Once prepared a data structure for each axis, the actual data analysis started. After loading position, velocity, acceleration, and torque data collected during the experiments on the axis, the parts of the signals containing useful data were identified. In particular, a purpose-developed algorithm selected the signal portions in which the following conditions on position were fulfilled:

- The position was inside a pre-defined interval, in order to exclude the portions near the limits of the axes;
- The axis is not still (i.e. $V \neq 0\mathrm{m\,min}^{-1}$);
- The axis is moving at constant speed ($A = 0\mathrm{m/min}^2$).

Then, to build a suitable data-set for the development of the model, each data portion (corresponding to a speed step) has been discretized in position segments of 5 mm of length, for each segment the average position, speed, and torque has been calculated. For the torque signal, also the standard deviation has been calculated. So the model has been calculated using regression. Given that the torque depends on position and speed but there is not cross-correlation between position and speed, the model has been evaluated in two steps. It's also worth noting that, since some contributes depends on the direction of movement (i.e. sign of speed) while others torque contributes are direction independent, two different model has been developed for the movement whit positive speed and with negative speed.

In the first step the models speed-torque has been evaluated for each position value obtaining two models in the form:

$$C_{i+} = A_{0+} + A_{1+} \cdot V + A_{2+} \cdot V^2 + A_{3+} \cdot V^3 \tag{3.5}$$

for the torque with positive speed, and

$$C_{i-} = A_{0-} + A_{1-} \cdot V + A_{2-} \cdot V^2 + A_{3-} \cdot V^3 \tag{3.6}$$

for the torque with negative speed, where C_{i+} and C_{i-} are the torque values, at the $i-th$ position calculated respectively for a positive or a negative value of speed, $A_{0\pm} \ldots A_{3\pm}$ are the regression coefficients, and V is the speed value in mm/min;

The obtained regression coefficients were stored in two $n \times 4$ matrices A_+ and A_-.

The second step involved the estimation of the model which connects torque and position. The model has been obtained by the regression of the previously obtained coefficients on the position. Each of the eight coefficients' array (four for the positive torque model and four for the negative torque mode), has been taken as observation of the dependent variable and the positions (and its powers) as regressors. This process produced eight models in the form

$$A_{m\pm} = B_{0,m\pm} + B_{1,m\pm} \cdot X + B_{2,m\pm} \cdot X^2 + B_{3,m\pm} \cdot X^3 \tag{3.7}$$

Where $A_{m\pm}$ is the $m-th$ coefficients of the positive or negative torque model (with $m = 0 \ldots 3$), $B_{0,m\pm} \ldots B_{3,m\pm}$ are the four regression coefficients, and X is the axis coordinate in mm.

The obtained coefficients were stored in two 4×4 matrices.

This process has been repeated for all the four axes of the machine (three physical axes with one gantry of two axes.) obtaining the model for all them.

Spindle Data

The data recorded during the spindle test has been imported in Matlab and converted from CSV to native Matlab data format to reduce the storage memory usage and to reduce the time required for data loading and elaboration by the next processes. Then the signals related to the spindle, in particular speed and torque, has been extracted from the structure, properly scaled, and stored in arrays. Spindle acceleration has then been calculated from the spindle speed signal by differentiation. After that, the portion of signals in which the spindle is rotating at constant speed has been identified and extracted. Then for each speed value the the average torque is calculated together with the standard deviation. In this case, since the torque - speed characteristic has a complex shape, an interpolation function which covers the whole curve hasn't be calculated. However a function which given spindle speed values constructs an interpolation function on the k-nearest points and evaluate the corresponding torque value has been realized.

Model validation

Then all the models has been validated. As done with the FRF model, also these models has been validated in two steps. The first step o validation, carried out just after the model creation, consisted in the application of the model to the at a set used for its creation. Then the data estimated with the model has been compared with the registered data. The second step of validation involved the selection of some arbitrary levels of axes or spindle speeds at which some tests were carried out. Then the torque was calculated applying the models and the value obtained was compared to the value registered during the test. In figures 3.12, 3.13, 3.14, 3.15 the comparison between the extracted torque model (represented by the surface) and the measured points is shown. As can be seen the model fits very well the experimental points and is able to take into account both the correlation between torque and speed and the correlation between torque and position.

3.6 Conclusions

An introduction on machine tools retrofitting process has been outlined. The reasons and the requirements for the retrofit of a machine tools has been discussed.

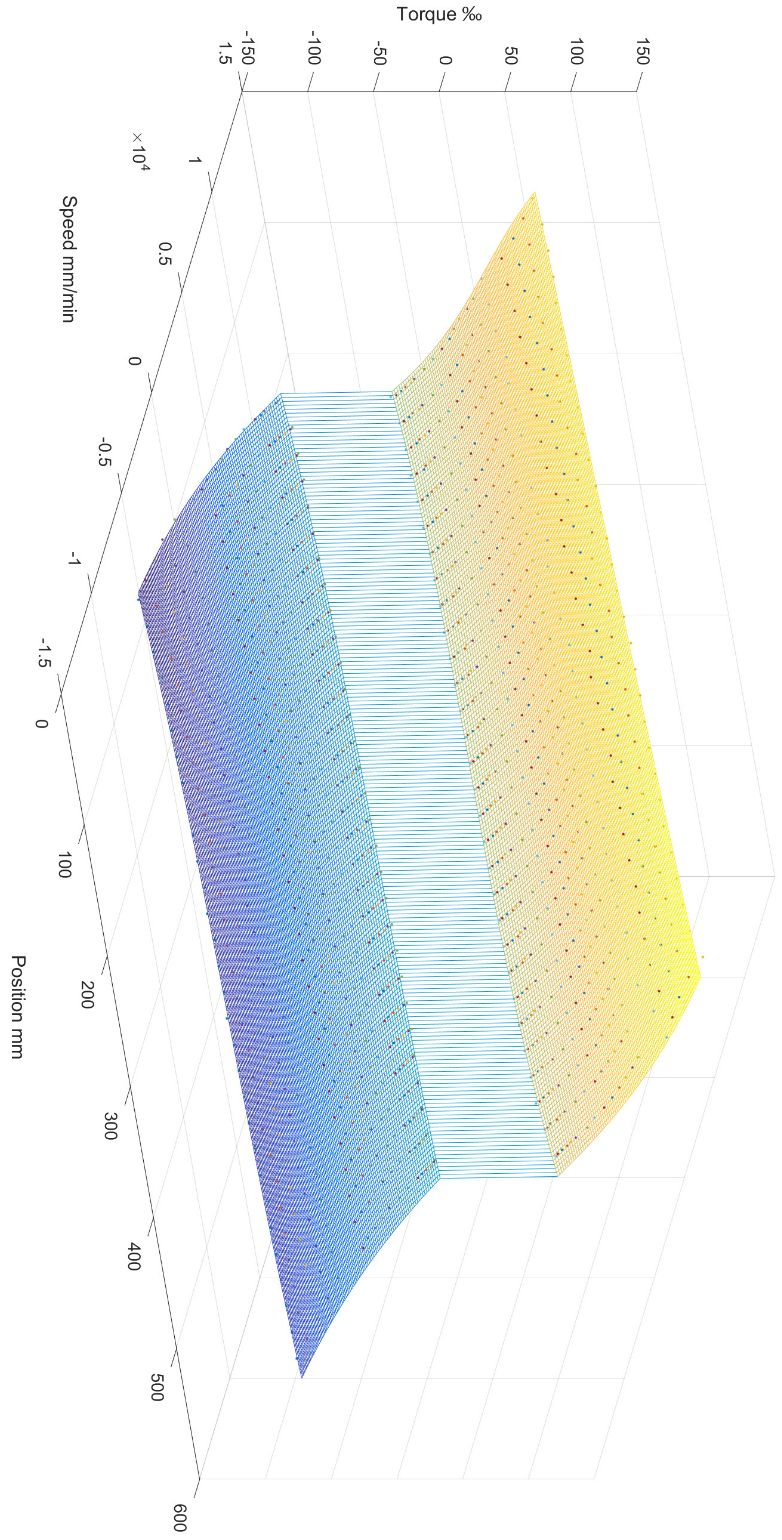


Figure 3.12: Measured torque points and torque model: X axis

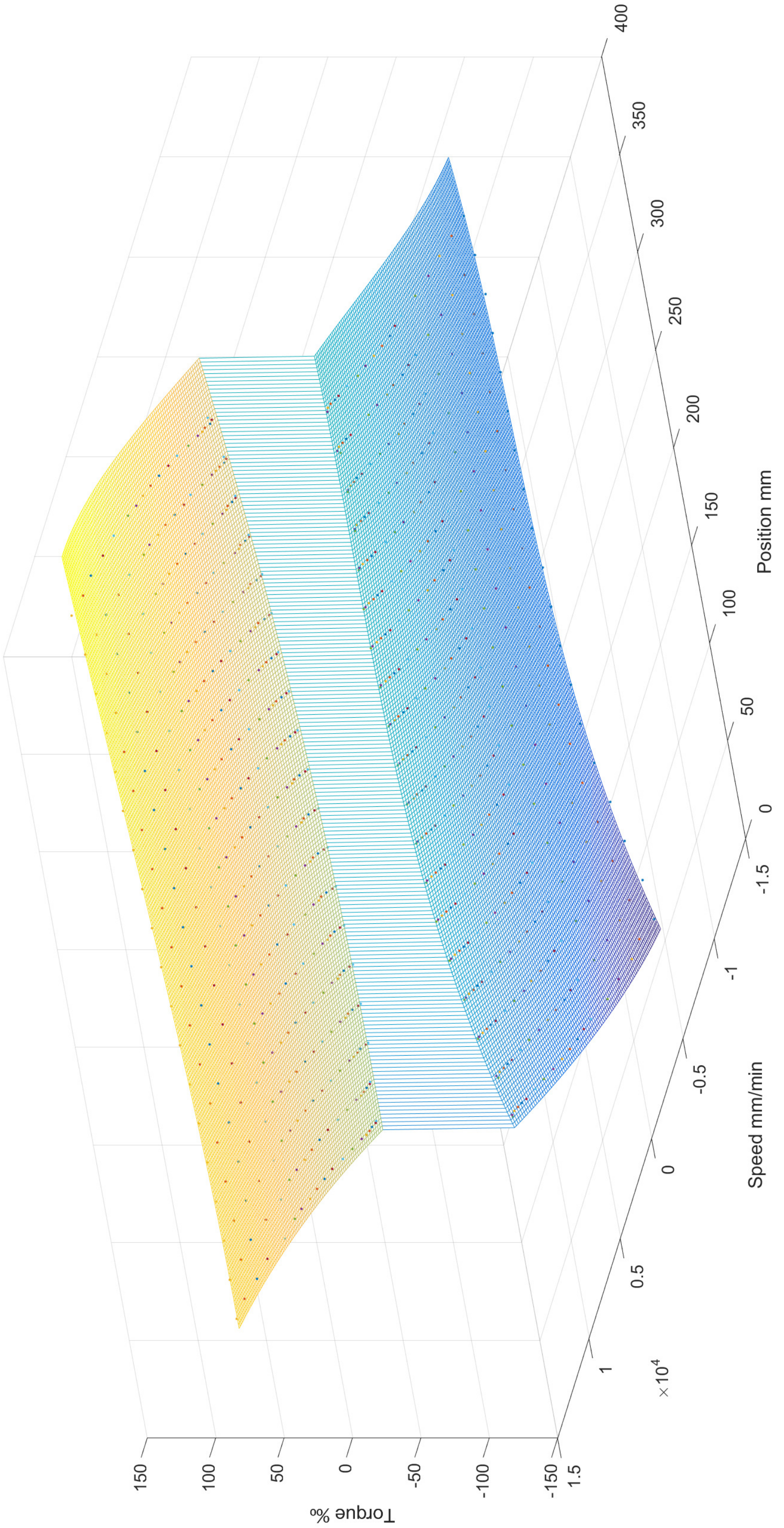


Figure 3.13: Measured torque points and torque model: Right side Y axis

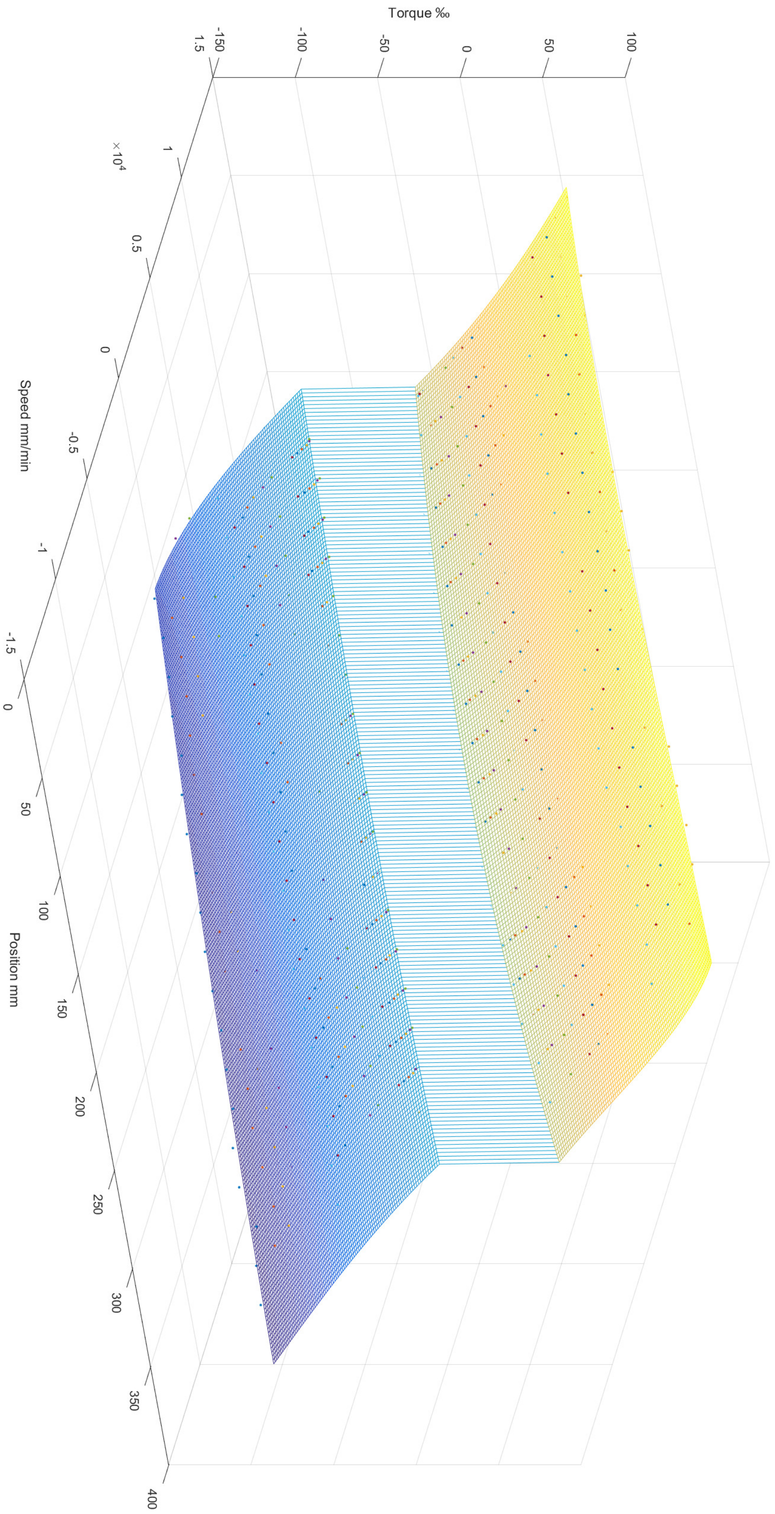


Figure 3.14: Measured torque points and torque model: Left side Y axis

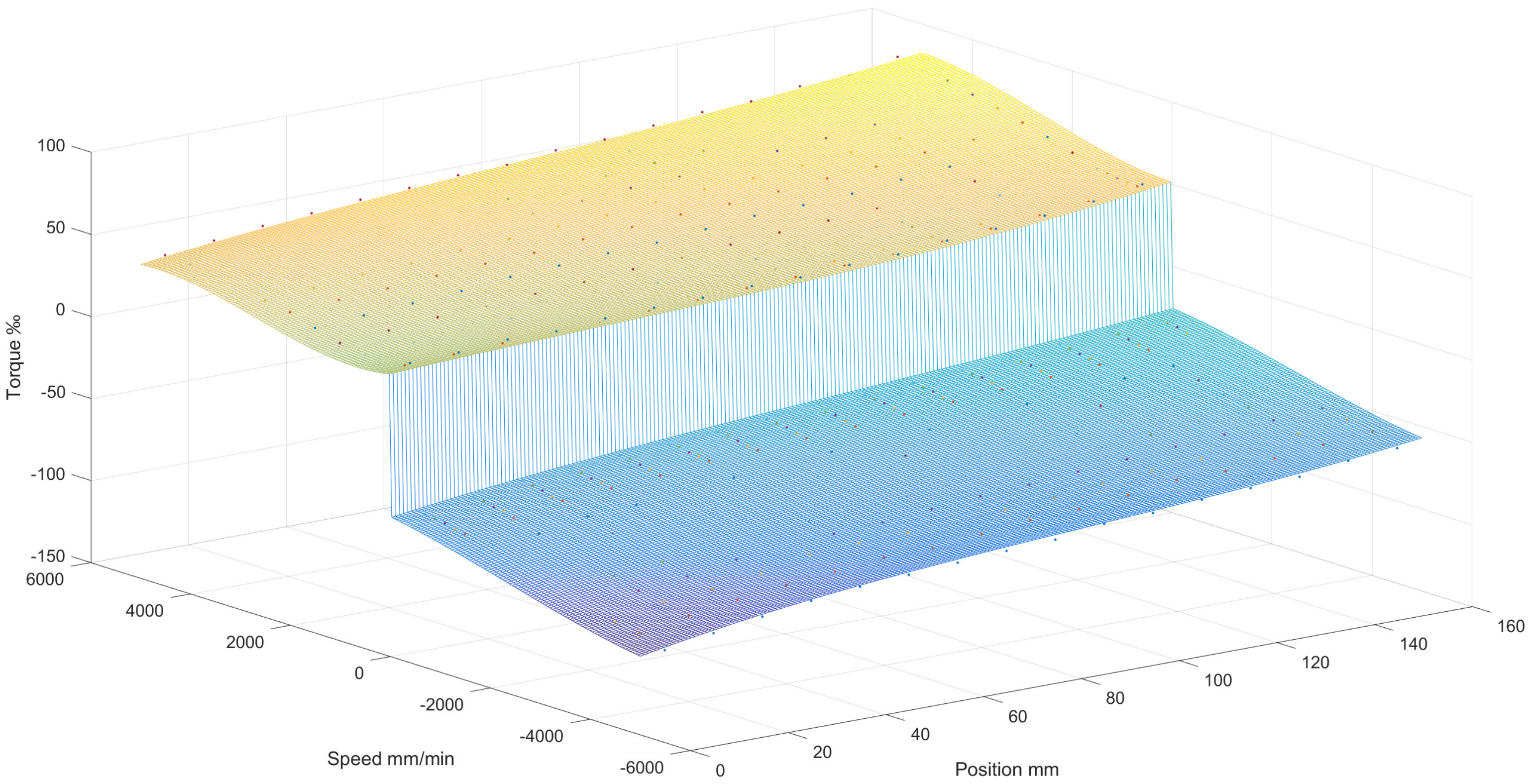


Figure 3.15: Measured torque points and torque model: Z axis

Then an example of a machine retrofitting in order to obtain a machining testbed has been described discussing the requirement of the specific application and the design choices. The general architecture of the designed automation system has been introduce with particular attention to the description of the various elements composing the automation system and their characteristics.

The actual configuration of the machine after the retrofit has been presented , focusing on the high technology parts of the project. The general structure and the working principles of the CNC installed on the machine has been presented and discussed highlighting the high flexibility and modularity of the system.

The activities carried out for the start-up and configuration of the new machine has been documented in order to build a knowledge base for eventual future use.

Then the machine tool analysis and modelling process has been described. First the dynamic response of the machine's structure has been studied using pulse testing techniques. A model to evaluate the frequency response function of the machine in any point of the work-volume has been created from the data gathered during the experiments. The model has been validated with other dataset collected in arbitrary machine positions.

Finally, the correlation between axes torque and speed has been studied and modelled. For each axis of the machine a model which allow the evaluation of average torque, given the actual speed and position, has been created using the data collected during a series of experiments carried out on each axis. All the created models has been validated with data collected at arbitrary axis speed and in arbitrary positions b the comparison of the evaluated average torque and the measured torque. Also for the spindle, the relation between torque and speed has been investigated experimentally and a function which allows the estimation of average torque at a given spindle speed has been created. Also this function has been validated by comparison of the torque measured at an arbitrary spindle speed with the torque estimated by the model.

Chapter 4

Milling Machine Condition Monitoring

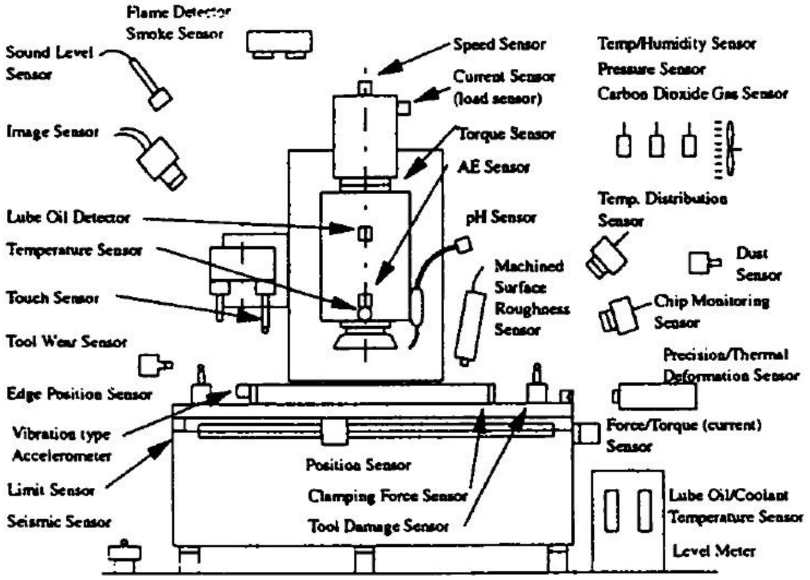


Figure 4.1: Sensors for machine tools monitoring. [13]

From the second industrial revolution, the increasing automation of machines and production plants allowed the increasing of production efficiency and of the products quality. However the introduction of automated machines led to a gradual reduction of the production staff. Since automated machines were able to produce autonomously, one operator was able to control many machines as he had to operate on them only in case of issues or for adjustments. Soon it was evident that, to enable an efficient unmanned machining and to detect eventual failures which can affect the product quality or damage the machines, a sensing system able to continuously monitor the process and to warn the operator in case of issues was needed. Then the research centres of the most industrialized countries started to analyze and design this systems. In their paper published in 1983, Tlusty et al. [89] analyzed and reviewed the sensor systems commercially available, or in advanced research status that can be applied for machining process monitoring. It's worth noting that already from the first '70s there were research center engaged in the development of sensors and system for process monitoring. The first proposed systems were quite complex put oriented to a lows implementation cost, Horváth et al. [40], for example, proposed a system for the monitoring ow tool wear and for the detection of tool breakage through measurement of spindle motor current and direct measurement of the tool's geometry using proximity sensors. An advance to this system was proposed by Ruiz et al. [81] which extends the system, adding the measurement of the feed axis current through the insertion of shunt resistor on the motor feed lines.

In the last years, with the advances in electronics and sensing technologies which enabled the diffusion of sensors with good performances and relatively low cost, many monitoring system has been developed with different approaches. Möhring, for example proposed a monitoring system based on sensors integrated in the workpiece fixture [67]. The proposed system is based on a modular clamping system in combination with a zero point tooling system. In the clamping elements has been integrated a strain gauge, a micro temperature sensor, and a mems accelerometer. The signal processing unit is embedded in the base of the clamping system. The zero point mounting system provides power, connection to the CAN-Bus and an optical communication line to the sensing devices. The sensors can be also installed on the spindle of the machine which is usually more accessible and allows easier installation of sensors. In this case the most used sensors are accelerometer and ultrasonic acoustic emission sensors as well as current sensor on the spindle feed line. In [14] an example of the usage of an accelerometer installed on the spindle, and an hall effect sensor for spindle feed current measurement used for the development of a data-driven digital twin of a milling machine. Finally, thanks to the advances in drive technologies and the availability of advance field-buses, the so-called sensorless monitoring is emerging.In this last case there are no sensors added to the machine and the monitoring of the machine and the process is carried out using the data already available from the automation systems, such as signals from the drives (actual position, speed ,acceleration, following error, torque, etc.), or signals from the numerical control (active line, active tool, interpolation mode etc.) or signals fro the auxiliary of the machine. These data can be used as-is or analyzed and combined to build a virtual sensor which can simplify the interpretation of the data. For example in [6] the spindle motor current commands coming from CNC are used to detect chatter during milling operations.

Many author proposed also common frameworks and approaches for the implementations of monitoring systems on machine tools [23, 34, 58, 59, 82].

The next pages of this chapter will be devoted to the presentation and discussion of three milling machine monitoring system designed and developed in order to fulfil specific requisites, also some results obtained from the elaboration and analysis of the data obtained by these system will be discussed.

4.1 SMART NC

This project, developed in collaboration with a manufacturer of hardware and software for numerical control and machine automation, aimed to develop an advanced numerical control, with integrated condition monitoring systems, able to perform process diagnostic and machine tool status assessment.

The developed monitoring system has to be capable of data acquisition from different sources such as the numerical control, the components of the machine such as axes drives and PLC, and from the sensors eventually installed on the machine.

The project included also an experimental validation of the developed algorithms which were carried out on an industrial milling machine.

System Structure

The proposed monitoring and diagnostic system includes both hardware and software components, developed on purpose in order to be easily installable on existing machine tools equipped with the numerical control of this manufacturer. From the hardware part the system involves the following parts:

- Sensors, eventually installed on the machine to monitor specific parts or specific signals which are not observable with the equipment already installed on the machine. Today's machines are usually provided with some sensors already installed (e.g accelerometer on the spindle housing for condition monitoring and maintenance), however many times these sensors are installed for other reasons than process monitoring (e.g spindle bearings monitoring) so the data acquired could be inaccessible to the user or the measured signal could be useless for process monitoring. The installation of a sensor in a production machine is often a trade off between cost, sensing requirements and production requirements. In fact some sensors could be very expensive if compared to others, alternatively, the installation of a sensor may require heavy modifications of the machine in order to work effectively and many times these modifications don't comply with the production specifications;

- Fieldbus bridge, a device which enables the communication between the components of the machine and the numerical control. The bridge is connected to the industrial pc that hosts the numerical control via EtherCAT and allows the connections of various devices with analog protocols, field bus or other communication protocols. The bridge provides also high precision analog input with ±10 V range for the connection of externals sensors.

- Data logging system, is a piece of software, integrated into the CNC which allows to capture the data coming from the EtherCAT bridge and from the CNC. The acquired signals are stored in specific binary files to be used for the successive analysis.

- Diagnostic Algorithm, a set of algorithms for the analysis of the data coming from the machine. The first prototype of Smart NC has been developed for off-line data analysis, however the data elaboration algorithms are developed in order to be applied in real-time during machining. Depending on the functions enabled, the algorithms are classified in two categories:

  - Basic algorithms. These algorithms are quite simple and involves only basic mathematics functions without the usage of specialized libraries. These algorithms are mostly based on the definition of thresholds of the signal and the search of threshold crossings. The threshold could be either fixed or adaptive, depending on the application. These algorithms are also used as functions for the construction of the advanced algorithms.
  - Advanced algorithms. In his category are grouped algorithms that realizes advanced functions, also using specialized libraries. Among the advance functions there are the precise estimation of spindle speed (for machines without spindle encoder), the estimation of axes (or spindle) torques, identification of current machine status, and chatter identification. This algorithms are supported by a set of auxiliary functions.

- Diagnostic dashboard, built with particular attention to ergonomics and usability in order to allow all users to easily understand the status of the machine and its components as well as to promptly identify process issues.

- CNC a software CNC composed by the usual modules, part program interpreter and interpolator. However the trajectories generated by the interpolator are filtered with a notch filter winch eliminates the harmonics nearest the resonance frequencies f the machine in order to avoid resonance of the machine. The CNC integrates also a kinematic simulator to perform a check of the resulting motion of the machine in order to avoid excessive acceleration or inaccuracy in position due to kinematic effects.

- Axes Drives, which receiving trajectory informations by the CNC, elaborates the information received and generates commands for the motors, monitoring its behaviour in order to ensure precision movements.

4.1.1 Diagnostic system

The diagnostic system, as explained in the above overview is composed by a set of algorithms used for the analysis of the data coming from the machine. As said before, the first implementation of this system has been done for off-line data analysis, so the following discussion will discuss the analysis of data stored in log files, however the presented algorithms are developed to work also in real-time (or quasi-real time). All the proposed algorithms has been developed and tested in GNU Octave.

The cornerstone of the diagnostic system is a decision tree classification algorithm. An overview of algorithm's working principle can be found in the flowchart in figure 4.2. This first function, starts loading the log files by means of a specific module. Then the content of each file is analyzed, with particular attention to the data coming from the axes drives and for the analog data. Then, in the signals, the transients are distinguished from the steady conditions. In the portion of signals were the machine is in steady condition, using

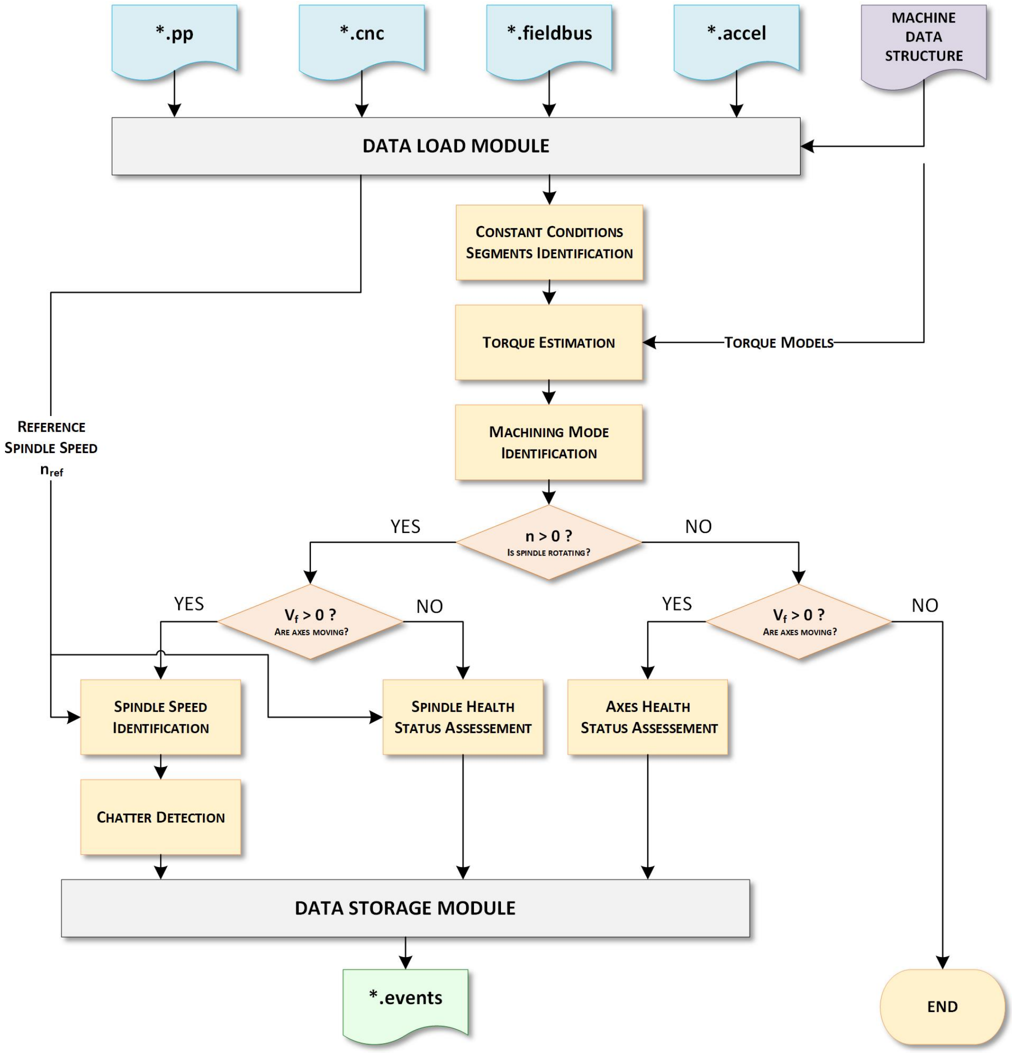


Figure 4.2: Flowchart of classification algorithm.

the models stored in a data structure, the nominal torque of the axes and of the spindle (if are moving) is estimated. So the data are passed to a decision tree classification algorithm which starts verifying whether the spindle is moving or not, after, each axes is analyzed in order to check if there's any axis moving. Each possible combination led to a particular machine status and enables one ore more specific diagnostic algorithm. Each diagnostic algorithm carries out a specific diagnostic task and returns a data-structure called event to the main process. Once the diagnostic algorithm complete its execution, the main process stores the generated data structures to a results file. In the next paragraphs the most interesting diagnostic algorithms will be presented.

Spindle Speed Estimation

This function has been created to obtain a precise estimation of the spindle speed on machines which aren't equipped with speed feedback on the spindle motor (encoder or tachogenerator), since for certain algorithms is fundamental to have a reliable value of the actual spindle speed in order to work properly. This algorithm is, obviously, activated only when the spindle is rotating. Spindle speed estimate starts with loading of axes' signals, in particular torque signals of each axis are loaded by the algorithm. Then, depending on the signal to noise ratio) one of the signals is selected among the available signals. An FFT transformation is then applied to the selected signals to switch to the frequency domain. So, the ratio between the energy related to rotation speed harmonics E_r and the "aperiodic" energy E_a (called Correlation Index) has been evaluated in a range of the nominal rotation frequency. The frequency which maximizes the Energy ratio corresponds to the rotation frequency of the spindle. The flowchart representing this algorithm can be found in figure 4.3.

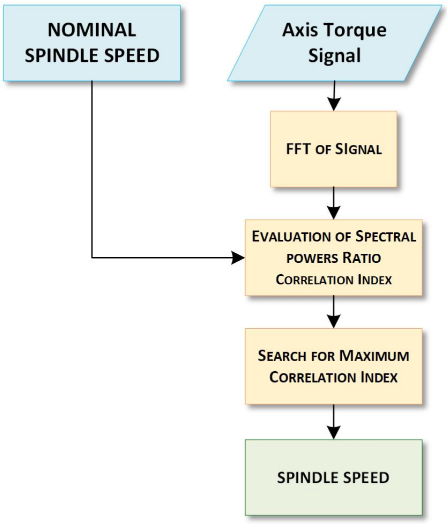


Figure 4.3: Flowchart of spindle speed estimation algorithm.

Axis Health Status Assessment

This algorithm allows the operator to verify if there are problems or damaged components within the mechanical parts of the machine axes, such as gears, bearing etc. The algorithm is activated when a axis is moving while the spindle is still, or during the standard test cycle which is implemented in the CNC. The standard test cycle consist in moving each axis along all the available stroke at different levels of speed. During the tests the data logging system record the signal coming from the machine. The resulting data are then analyzed with the algorithm that also compare them with the fingerprint of the axis captured during the start-up phase of the machine. As can be seen in the flowchart in figure 4.4 the function take as input the torque and speed signals of the axis, then, using the model created during the start up phase, the torque ideally needed to move the axes is estimated. The estimate and the measured values of torque are then compared an if the difference exceeds the tolerance range, a non conformity event is generated. The algorithms performs also a space-domain analysis of the signal, in this case the torque signal is analized in relation to the position. The position is expressed as linear position along the axis or as angular position of the motor or of the screw. Also in this case the trend of the signal is compared with the fingerprint of the components.The function integrates also a frequency-domain analysis in which the spectrum of the measured torque signal is compared with the spectrum of the initial torque in order to check i there are differences in harmonics of the signal. The frequency domain analysis allows also, in case of issues with an axis part, to identify the damaged components by looking at the frequency of the disturbance. In case of issues is detected, the function generates one or more events with the indication of the probable cause of the issue, and the information regarding machine status, time of the event, and positions to which the issue has been detected.

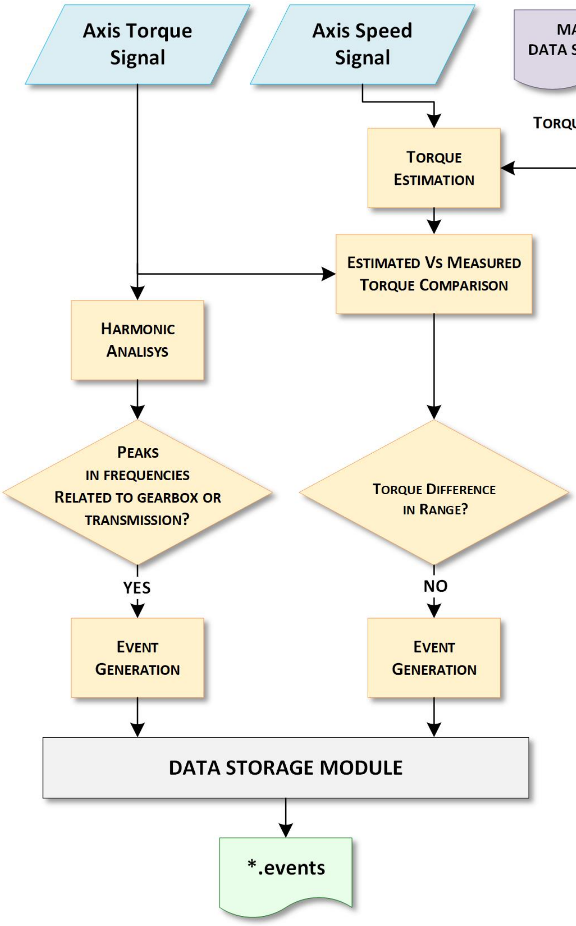


Figure 4.4: Flowchart of axis health status assessment algorithm.

Chatter Detection Algorithm

This function enables the recognition of undesired vibrations during milling operations. Chatter is an undesired vibration, generated, during cutting operation, by the dynamic response of a machining system subject to external aperiodic exciting force generated by the interaction between the workpiece and the cutting tool. This phenomenon has been studied since 1907 [87], as it heavily affects surface quality, dimensional precision and tool duration.

The developed algorithm uses torque signals from axes and spindle to detect chatter during milling operations using the Energy Ratio Chatter indicator ER_{ci} which, in frequency domain can be evaluated as [54]

$$ER_{ci} = \frac{E_{chatter}}{E} = \frac{E - E_{periodic} - E_{noise}}{E} \tag{4.1}$$

$$0 \leq ER_{ci} \leq 1$$

In order to distinguish the harmonics related to the TPE (tooth pass excitation) from the other harmonics (noise and chatter), is fundamental to know, with the lowest uncertainty possible, the actual value of spindle speed (which sometimes can differ substantially from the nominal speed). The actual spindle speed is estimated beforehand by the previously presented algorithm and then feed as input parameter to the function.

For each axes the corresponding ER_{ci} is calculated, then the maximum of the four calculated value is compared with a threshold value. If the calculated value is under the threshold, the operation is stable otherwise the operation is affected by chatter.

If, during a machining operation, chatter is detected, the algorithm creates an event in which the information related to the machining phase and the type of problem are stored. In figure 4.5 the chatter detection algorithm is represented.

4.1.2 System testing on industrial milling machine

The developed monitoring system has been tested on a four axis industrial milling machine made available by the manufacturer in his showroom. The machine has a cantilever structure with fixed bed and moving column, with tilting spindle. All the axes are moved by a rack and pinion mechanism actuated by servomotor through a planetary gearbox. On the machines was installed the bridge to whose were connected the axes drives (via EtherCAT), the spindle inverter and the sensors used for testing phases.

Before starting validation of the monitoring system, some preliminary tests, useful for the preparation of the following steps, has been conducted on the machine. These tests included modal analysis of the machine structure and spindle and axes characteristic identification. The modal analysis allows to estimate the resonance frequencies of the machine structure which can cause issues during the data analysis. The test on axes and spindle allowed the creation of the models needed for the monitoring algorithms.

After the preliminary tests, the actual validation of the monitoring system started. For the tests, has been installed on the machine, near to the spindle, two sensors, a triaxial accelerometer Kistler 8764B050BB and an ultrasonic acoustic emission sensor

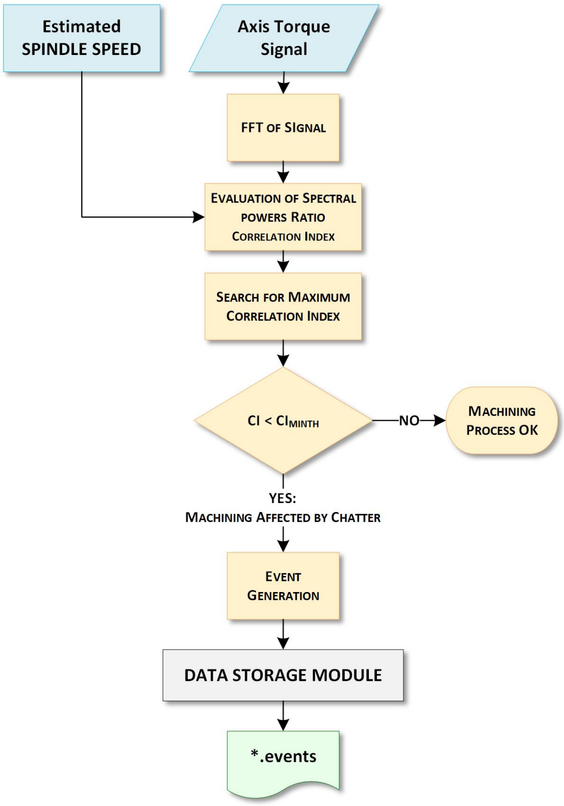


Figure 4.5: Flowchart of chatter identification algorithm.

Kistler 8152C1. These additional sensors can be useful for for the monitoring of the cutting process and their reduced size simplifies the installation on the machine.

In order to test the performances of all the implemented monitoring algorithms a set of tests has been designed and executed such as cutting tests in different conditions and axis damage simulations.

Cutting Tests

To test the chatter identification algorithm, some cutting tests on an aluminum hollow square profile similar to those who are normally machined on these machines has been carried out. The tests involved two clamping configuration, the first set of tests was conducted with the workpiece installed between two clamps while the second set of test was conducted with the workpiece overhanging, so clamped on only one side while the other side was free, this allowed to have a workpiece with varying compliance to test the chatter identification algorithm. The tests consisted in a slot milling done using a single tooth flute mill. The first set of tests, involved a DOE on the cutting parameters, the investigated factors were depth of cut a_p, feed-rate f_z, and cutting speed V_c. Each factor was set on two levels. The second set of experiments was done at fixed cutting speed and feed-rate, the only factor investigated was the overhang distance between the clamp and the axis of the slot which was varied on eight levels. Both test were carried out using a sharp and a wear tool with the same characteristics in order to verify the possibility to estimates the wear status of the tool. During the cutting tests the monitoring system was activated and it has demonstrated to be able to correctly detect the operations affected by chatter. The data collected during the tests were also exported and analyzed in Octave in order to compare the results obtained by the monitoring system, which uses torque signals, with the results obtained using the data coming from the sensors installed on the head of the machine. The comparison demonstrated that in most of the cases, the torque signal is sufficient for chatter detection. In figure 4.6 the results of the data analysis is shown. The photos on top of the image shows the actual workpiece after tests. The workpiece is clamped on the right side while the left end is left free. As said the tests of the second set, has been performed with the same machining parameters, except for the position. As can be seen from the photo the surface finish of the part is getting worse as the distance between the working point and the clamping point increase. This is due to the reduction of workpiece stiffness as the overhang increases. The green circles in the photos identifies a stable operation while yellow triangle represents a marginally stable milling and red square represent unstable or hardly-unstable operations. The first chart in figure 4.6 shows the results of chatter classification algorithm applied to the data collected by the tri-axial accelerometer and ultrasonic acoustic emission sensor mounted on the spindle. The red dashed lines represents the limit between stable and unstable machining, this is defined experimentally beforehand. Blue circle markers represent the ER_{ci} evaluated using the ultrasonic acoustic emission signal as a base. Red squares are the datapoints obtained by evaluating the ER_{ci} on the Y components of the acceleration, which is the direction parallel to the working direction. Finally the green triangles represents the ER_{ci} evaluated using the data coming from the Z component of the acceleration, which is the vertical direction in the machine reference system. As can be seen the ultrasonic acoustic emission signal is not so reliable for chatter identification in this case. However the two acceleration signals are quite reliable, so they can be used as a base for the evaluation of chatter index. The second chart in the figure is similar to the one above but all the indicators are evaluated using the torque signals coming from the axes drives. Also in this case the red dashed line represent the threshold between stable and unstable operations, the points well below the line represents a stable operation while the points well above the line represents unstable operations. The points nearby the line are usually related to marginally stable machining operations. As can be seen from the chart, torque signals are quite reliable for chatter detection in milling. It's also worth noting that not all the signals can offer the same performance in chatter detection. In this case, for example, it's clear that the torque related to the X axis and to the Z axis performs better than the torque related to the Z axis. The choice of the signal on which rely for chatter detection depends strongly on the type of machining operation and on the characteristics of the machine, however advanced algorithms such as artificial intelligence or sensor fusion techniques can be adopted in order overcome this issue [55].

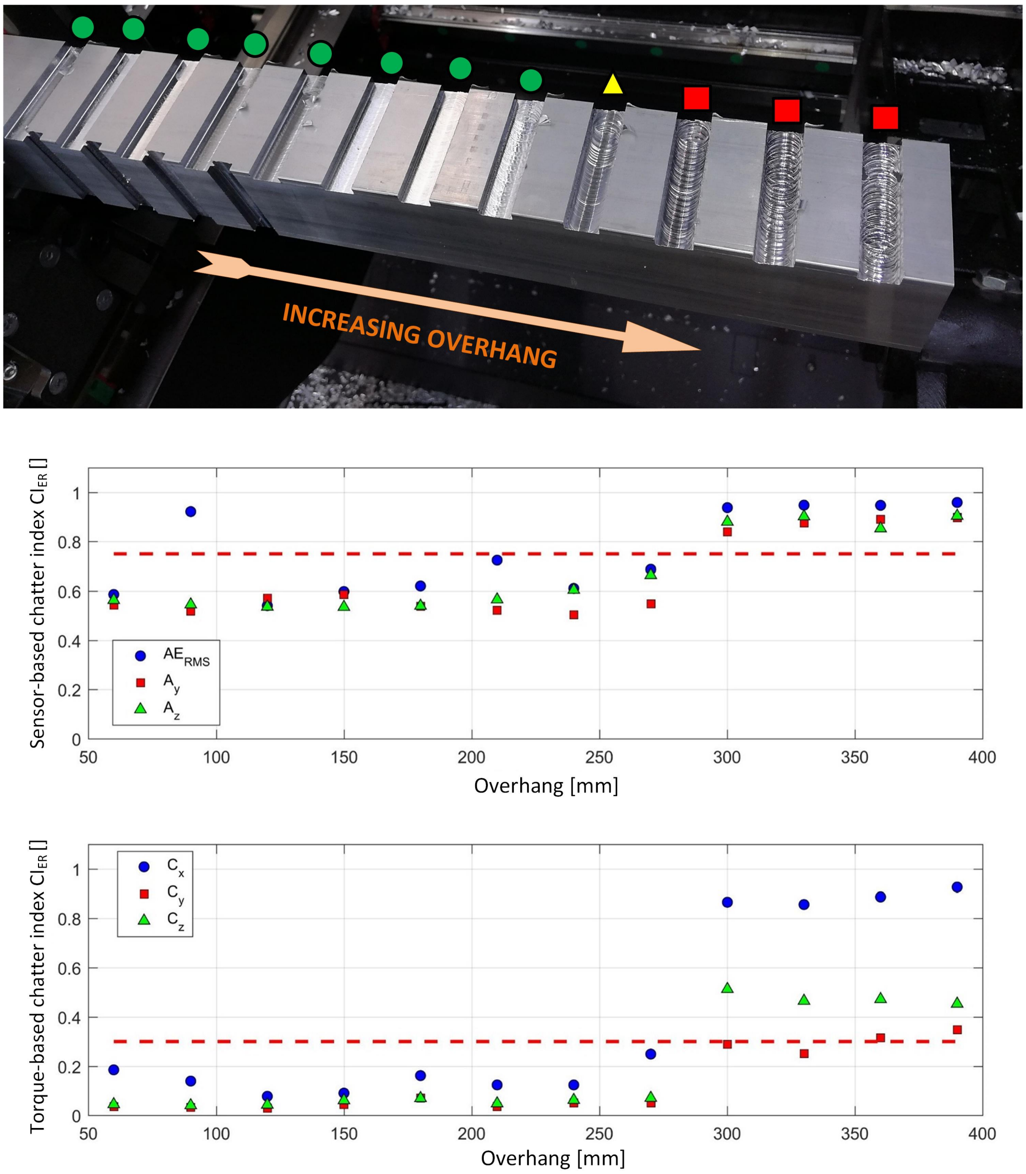


Figure 4.6: Results of chatter detection during cutting tests.

Simulated Axis Damage

The axes health status assessment algorithm was verified by simulating a damage on the rack and pinion or on the rails of an axis and moving it in order to check if the algorithm was able to identify the defect. The tests were performed on the X axis of the machine, the axis on which moves the column, because it was more accessible and allowed to simulate the damage easily. Obviously the tests had to be completely reversible and cannot cause permanent damages on the machine. Moreover it wasn't possible to perform damage test on the planetary gearbox or on the bearing because even if damaged components were available, the time required for their installation on the machine was too long and incompatible with the time available for the tests.

Three types of damages were then planned with the qualified technicians, simulation of a small entity localized damage realized by some aluminum chips put on the rack and fixed with grease, a damage which involves a sector of the rack simulated by the application of a sheet of paper on the rack and a simulation of a localized damage on the linear guides by the application of a small amount of glue on the top part of the track.

The data acquired during the tests were analyzed directly by the monitoring systems and with Octave and the obtained results were compared in order to verify that the events generated by the monitoring system corresponded to actual issues. In figures the signal corresponding to undamaged axis(figure 4.7), axis "damaged" with aluminum chips (figure 4.8b) and with paper sheet (figure 4.9b) are depicted. In the chart on the left side of the figures, there is an overview of the signals acquired during the test, while on the left side there is a detail on the signals in the zone highlighted in red in the position overview.

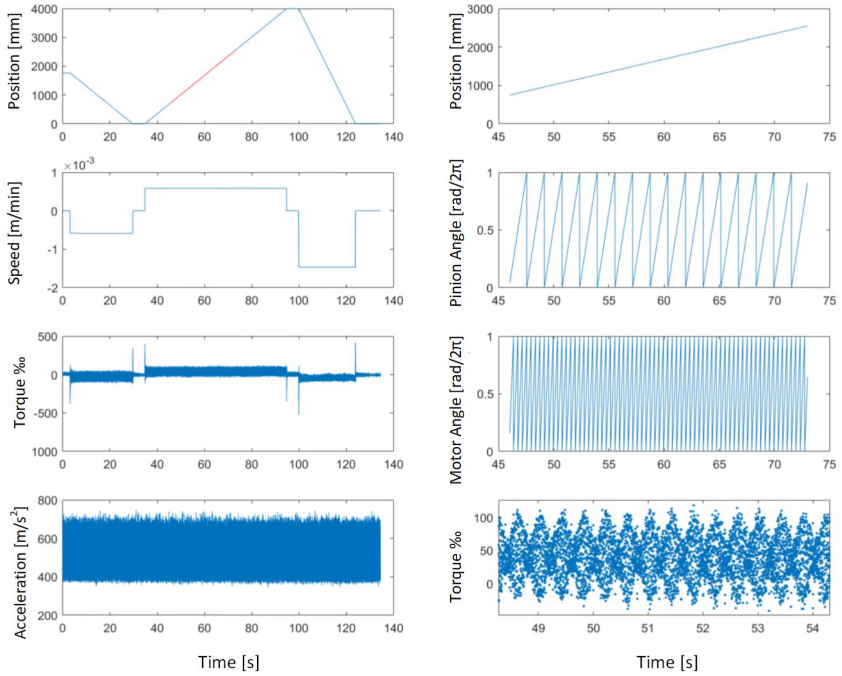
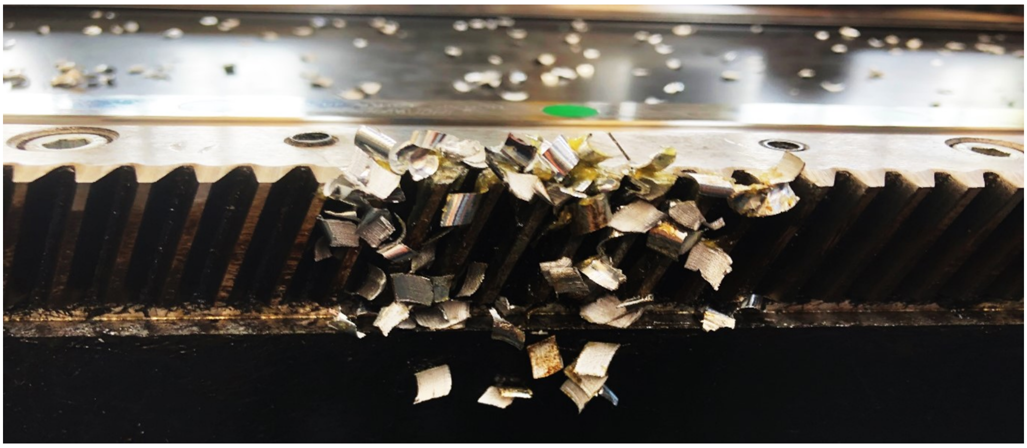


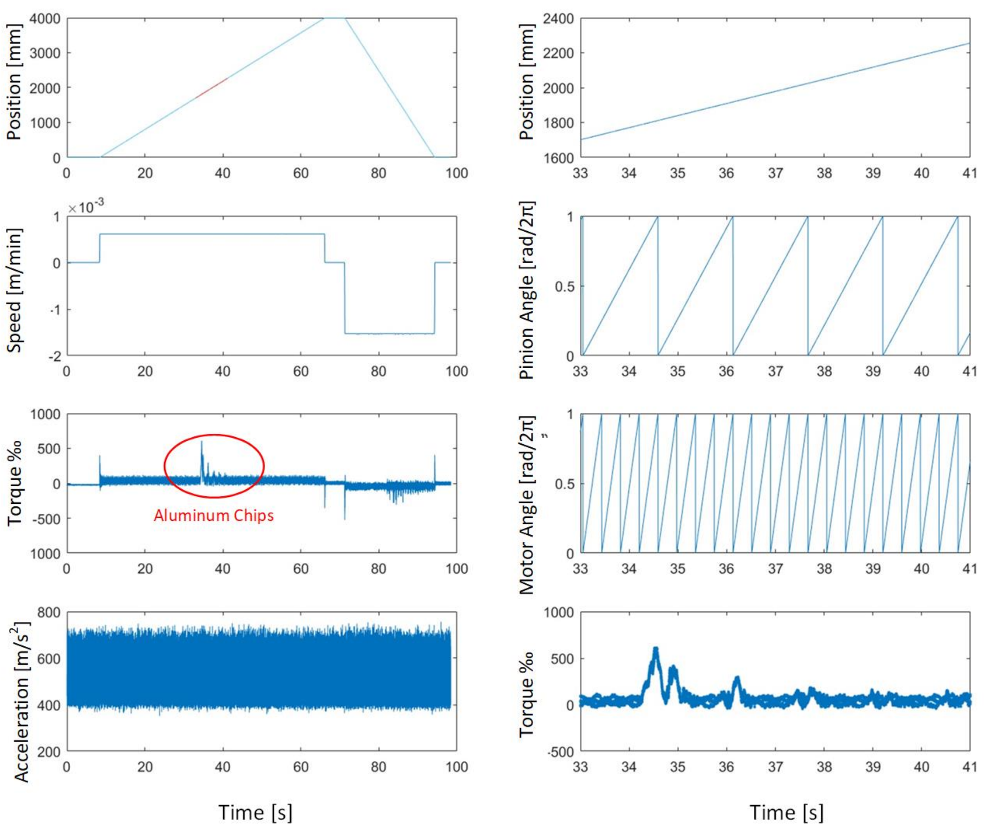
Figure 4.7: Data collected from undamaged axis.

4.2 Plug-in monitoring system

This monitoring system has been developed to be installed on a HAAS VF-2 TR Milling machine installed at Laboratory for Advanced Mechatronics LAMA FVG in Udine. This machine is equipped with a proprietary numerical control which doesn't provide advanced data exchange protocols, also the auotmation system communicates with the numerical control through serial bus with a proprietary protocol so there is not a suitable way to



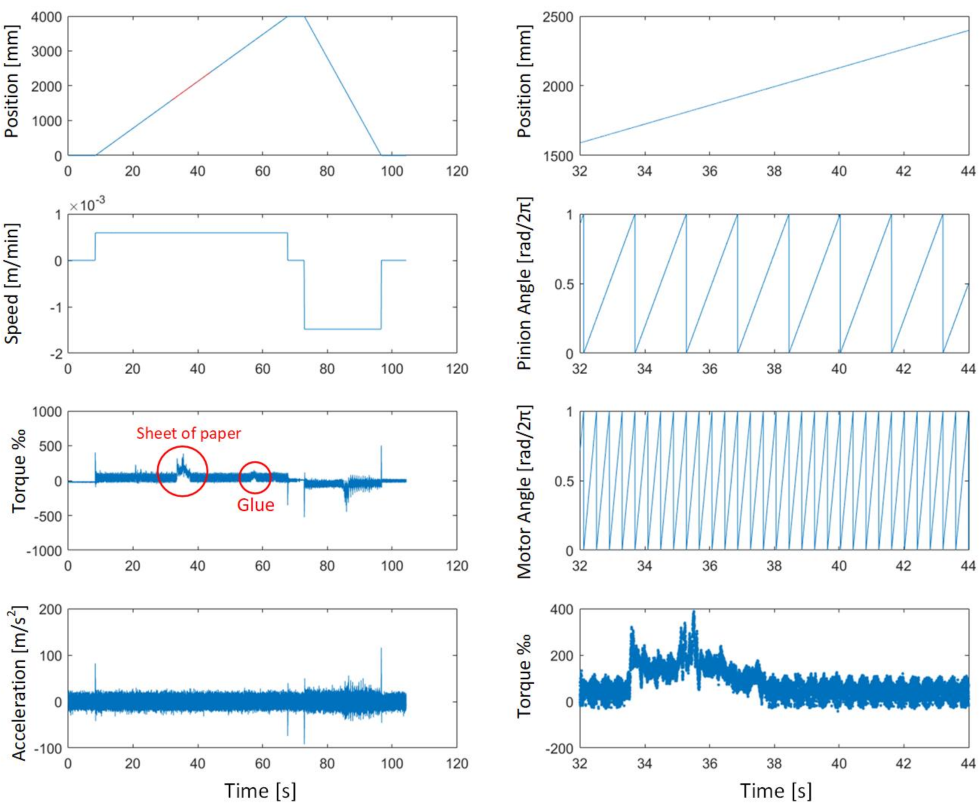
(a) Detail of the rack with aluminum chips applied.



(b) Data collected during the test.

Figure 4.8: Damage simulation with aluminum chips.

(a) Detail of the rack with paper sheet applied.



(b) Data collected during the test

Figure 4.9: Damage simulation with a sheet of paper.

obtain high-bandwidth data from the machine. The only available communication means is a RS232 port which allows to exchange data with the machine at a very low speed, about 1 packet for second depending on the amount of data requested. So, in order to effectively monitor the process, the installation of external sensors and a data acquisition system are required. The monitoring system installed on the machine will constitute a demonstration of digitalisation of existing machine at a relatively low cost avoiding a retrofit. In addition to the demonstration purpose, the system will be useful also for research purposes as it enables the acquisition of data at up to 50 kHz with a fully customizable system. The data collected from the system are being stored on a server and could e used for long-term research in the realm of big-data analysis, digital twins and artificial intelligence.

An accurate evaluation of the sensors to be installed on the machine is required, in order to minimize the impact on the machine and to obtain the best quality of the signals without affecting the process. In this case, according to the characteristics of the machine, the sensors chosen for the installation are a *Montronix PS200-DGM* power sensor, a *Kistler 8763B100A* triaxial piezoelectric accelerometer, and a *Kistler 8152B111* ultrasonic acoustic emission piezoelectric sensor. The power sensor will be installed on the spindle feed line, while the two piezoelectric sensors will be mounted on a purpose made bracket installed under the spindle, near the spindle nose (figure 4.10).

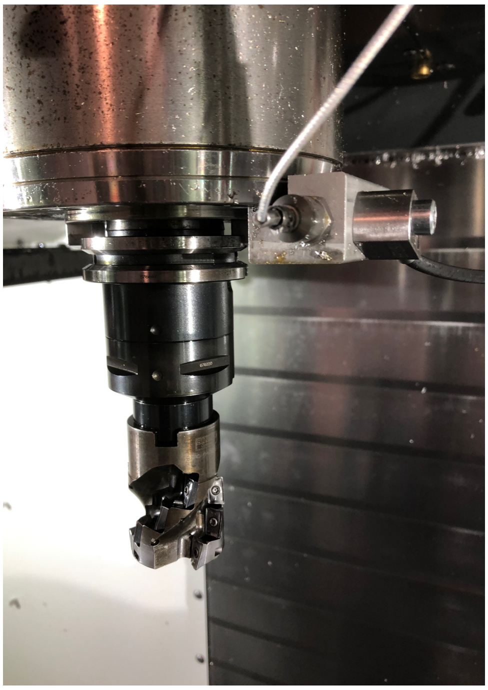


Figure 4.10: Machine spindle with accelerometer and ultrasoinc acoustic emission sensor installed.

The data acquisition system is based on Beckhoff EL*xxxx* and ELM*xxxx*. In particular the base configuration of the system involved an *EK1100* bus coupler, to allow the connection via EtherCAT to the industrial PC and the power supply to the analog input modules via E-bus, two *EL3632* two channels IEPE analog input, and a *EL3751* two channel voltage analog input. The IEPE modules are connected to the triaxial accelerometer and, if needed to an additional monoaxial accelerometer. The voltage analog input module collects the data coming from the acoustic emission sensor and from the power sensor. All the data acquisition hardware is located into a metal electrical cabinet installed on the rear panel of the machine by means of purpose made brackets. The additional electrical cabinet host also the power supply and all the auxiliary hardware needed by the system such as signal conditioning devices. It's worth noting that all the signals cables between the sensors and the data acquisition devices are shielded coaxial cables in order to minimize the risk of electrical interference from the machine components (figure 4.11).

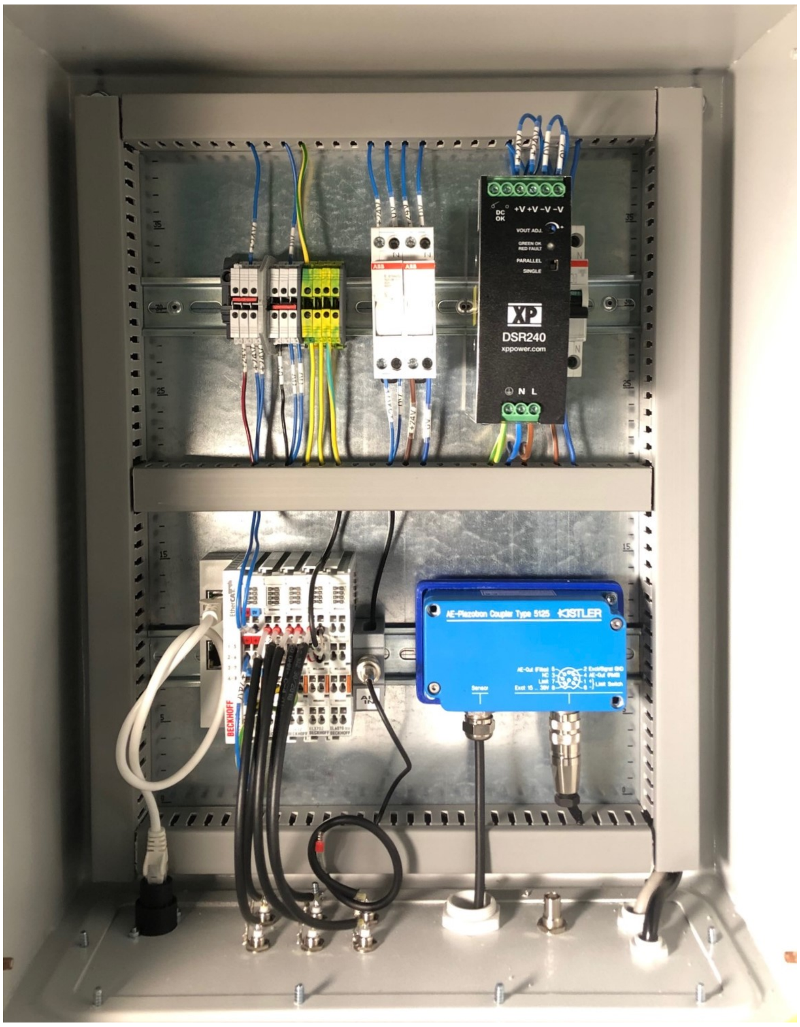


Figure 4.11: View of the electrical cabinet with the data acquisition hardware.

The data acquisition system is completed by an industrial panel-PC which is mounted beside machine tool's HMI. The panelPC hosts the software parts of the monitoring system, from the data acquisition PLC to the data elaboration and HMI software (figure

4.12).

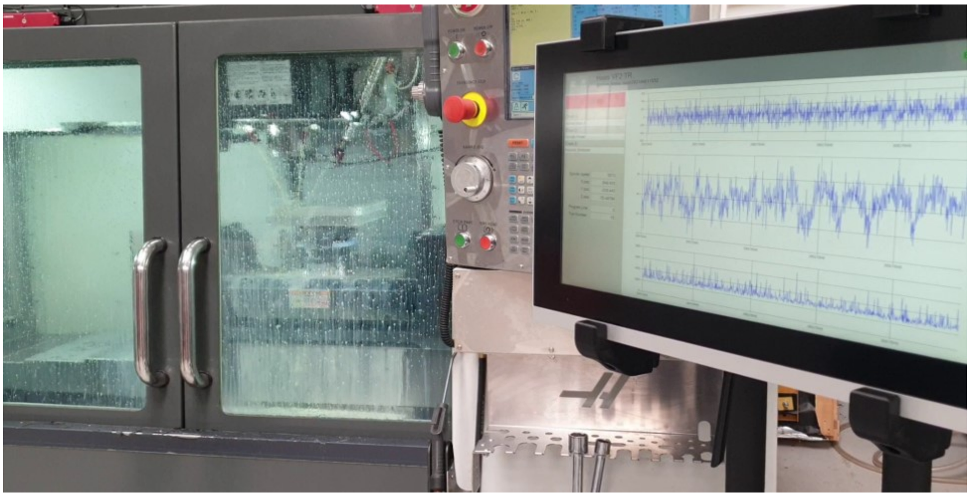


Figure 4.12: Panel PC installed aside machine's native HMI.

4.2.1 Data acquisition software structure

The data acquisition software is divided in two main parts, a low level parts, which runs on the TwinCAT runtime, devoted to the management of the data acquisition hardware, and a higher level part, which runs on a Windows Application. The data exchange between the two software is carried out using via ADS protocol. ADS (Automation Device Specification) is a proprietary protocol provided by Beckhoff which provides also the libraries for the implementation of this protocols in the more utilized programming languages.

The data acquisition PLC software is very similar to the one described in 2.1.5 so only the high level software will be detailed in the following pages.

The most important software part of the monitoring system is integrated into the windows application. This program carries out many tasks for data acquisition, data analysis, visualization and communication.

The *data acquisition* is in charge of two different tasks, the first tasks carries out the communication with the machine tool numerical control through serial protocol. This task, cyclically, every second, sends a request for a data packet to the machine, then the machine replies with a string with the data requested. The data packet contains:

- Position of the X axis;
- Position of the Y axis;
- Position of the Z axis;
- Spindle Speed;
- Number of tool in use;

- A specific variable of the CNC which can be programmed by the user;

The machine don't send a timestamp and there's no way to know exactly the time to which the received data are referred so it's assumed to be the time of reception of the packet by the software. The second data acquisition task is in charge of the communication with the data acquisition PLC using the ADS protocol. At start-up the software tries to establish the connection with the PLC and if succeed it receives from the PLC a string with a code then the software will compare the code with his own in order to ensure to e connected to the right PLC. If the connection doesn't succeed or the code string doesn't match, the program will raise an exception and an error message will be displayed to the operator.After the connection between the software and the PLC, if a machining session is started, the program creates a listener object which will call an interrupt function every time that a new data buffer from the PLC is received (every 100 ms). Once the buffer is received by the application, the binary stream is converted in proper values following the predefined data-structure and the values are stored in a data structure which will be used for the calculation of the statistics, together with the timestamp,if the datalogging has been activated by the operator flagging the proper check-box in the HHI, the buffer is also copied into a binary file which can be analyzed offline with other software. The values coming from the PLC are also stored in a set of arrays needed for the rendering of the real time charts and in a circular buffer for the frequency domain analysis. However, for the charts arrays the data are copied with a down sampling of factor 10 in order to lighten the rendering.

Cyclically, every 500 ms a task is launched just after the reception of the package from the PLC, this tasks extract the statistics from the data structure and reset it in order to calculate the statistics of the next cycle. Along with the statistics calculation, the task perform also an FFT on the circular buffers and record the value of the first forty more powerful harmonics in the range 50 Hz to 2000 Hz. These data are stored in an array of data-structures which will be used afterwards for the creation of the MQTT message.

Every second, once the coming from the CNC of the machine has been received and the statistics has been extracted, the program runs a task which take the data coming from the machine and the array of data-structures containing the data extracted from the high speed signals and pack all the data into a Json structure that contains also the machine identifier, a message ID, a machining session identifier ,and a timestamp. The package is then sent to the cloud storage server via MQTT.

The windows applications has also a graphical user interface which allows the operator to start and stop the machining session and to see in real time the data collected by the monitoring system. The high speed data coming from PLC are plotted on three stacked charts. The operator has the possibility to chose what signal has to be plotted on every chart by selecting it on a drop down menu. The operator can also switch, for each chart, the visualization between time and frequency domain, in case of frequency domain the harmonics related to spindle speed are highlighted with a red dot. The slow speed data coming from the CNC are printed on the sidebar.

4.2.2 Cloud storage software and data visualization dashboard

The developed monitoring system includes also a cloud data storage module and a data visualization and diagnostic dashboard. The cloud storage module is based on a PHP script that firstly connects to the MQTT broker on which the machine send the message and subscribe the topic corresponding to the data sent by the machine. Then every time a new message is received, a routine is triggered, The script starts checking the syntax of the message and if it's consistent it start parsing the Json structure. The machining session identifier is stored in a SQL database with the id of the machine that sent the message and the timestamps of the first and the last message received with the same machining session id. Statistics and measures are stored in a time series database and tagged with a unique id which corresponds to the primary key of the SQL database in order to correlate the measures with the test.

The data visualization dashboard can be accessed by any browser and any device, even mobiles. The homepage of the dashboard present a list of the registered machining sessions obtained by querying the SQL database, then if a session is selected, the overview page is displayed. The overview page contains the charts of all signals collected during the specific session obtained from the time series database for the corresponding session. Then the user can switch to the analysis page. The analysis page is composed by three charts, on the top chart the user can choose one of the measured signals and two threshold that defines low, medium and high ranges for the signals, then on the chart, a bar plot shows the distribution of the signal on 16 levels between the minimum ant he maximum values of the signal. The height of each bar correspond to the cumulated time the signals had a value in this level. The bars have different color depending if the value of the signal is under between or over the threshold. On the bottom part of the page there are two square X-Y charts in which the user can select which variable has to be selected for each axis. Once the two variables has been selected, a scatter plot is plotted, the colour of the point plotted correspond to the value level of the signal selected on the above chart.

For example, selecting on the top part the acceleration signal and setting the thresholds to an acceptable level of vibrations, if in one of the bottom charts are selected x position and y position as variables to be plotted is possible to have a projection on the x-y plan of the toolpath with the indication of eventual high vibration points, then selecting on the second chart x position and z position, is possible to verify if the anomalous vibrations are at a specified z level or along all the machining operation.

4.3 Advanced Monitoring System

This system, developed on the machine tool presented in chapter 3, represent an up to date advanced monitoring system with a comprehensive set of function and with great development opportunities. The system includes both offline and online monitoring functions allowing in-process diagnostic as well as advanced offline data analysis with third part software. In particular the numerical control integrates an on-demand high-speed data logging system, a cloud-based machining statistics logger, an event logger and a set of functions for online monitoring during machining. The monitoring systems uses the

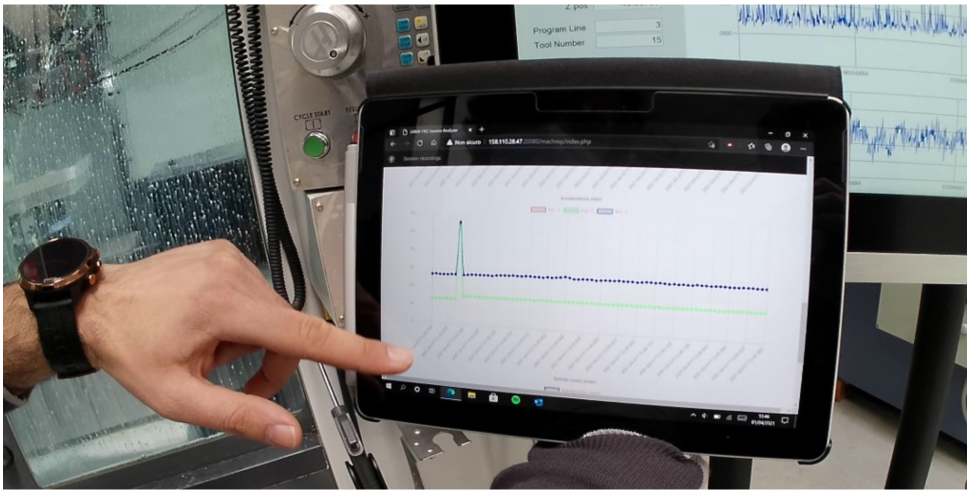


Figure 4.13: Operations on cloud analysis system with portable device

data acquisition hardware and sensors which are already, and permanently installed on the machine, however, it's possible, with a reduced effort, to expand the data acquisition hardware, by connection of new modules to the EtherCAT fieldubs of the machine. Finally the monitoring system can by accessed directly by third party devices connected to the CNC via Ethernet. In this last case, using the TwinCAT measurement suite, is possible to see in real time the high speed collected data and record them directly on the device.

The machine allows the acquisition of numerous data coming from many sources such as interpolator task, PLC, CNC, axes drives and analog inputs. Depending on the source of the data, the signals have different data rates, however the synchronization between signals is intrinsically ensured by the system. The signals which are currently collected by the machine are:

- Axes Positions, velocities and accelerations;
- Axes Currents;
- Axes Following Error;
- Raw position value obtained from motor encoders;
- Spindle Speed;
- Spindle Current;
- Values from IEPE analog inputs;
- Values from Voltage analog inputs;
- Mains voltage and current;
- Number of program block;

- Current file offset (on the part program);
- Speed override set.

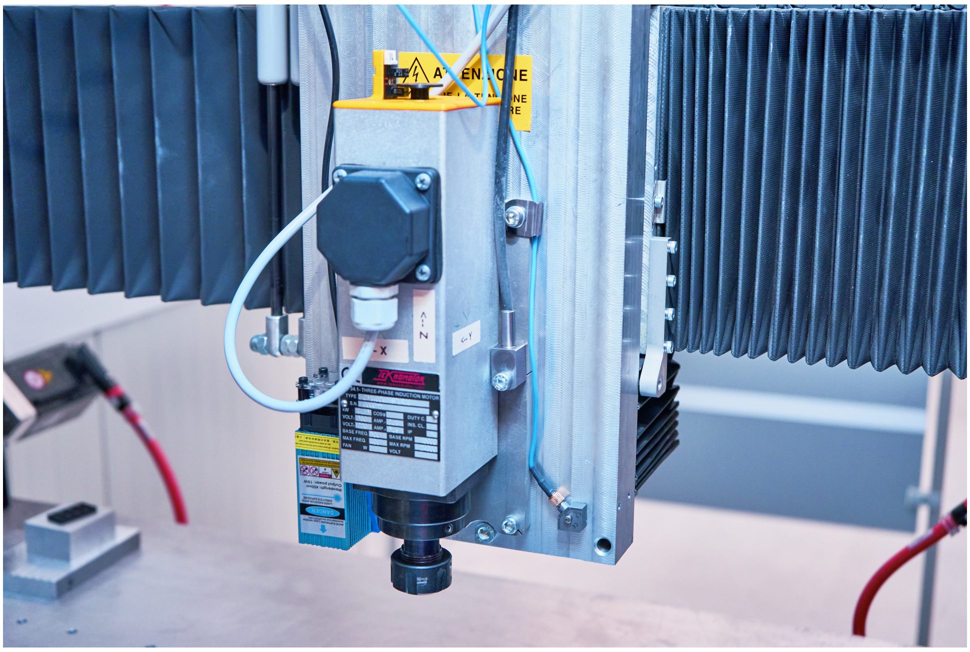


Figure 4.14: Ultrasonic acoustic emission sensor and triaxial accelerometer installed near the spindle.

4.3.1 On-demand data logging system

This system, integrated in the numerical control allows the user to activate and deactivate the data logging function during the execution of a part program using two custom defined M codes. When activated the system record a comprehensive set of variables describing the status of the process, of the machine and its components. In the current configuration the system is able to collect up to 40 signals with sample frequencies up to 20 kHz. The collected data are exported on a self described CSV file which allows high compatibility with third part software and allow the an easy understanding of the recorded variables. The data logging system is completely developed using the PLC libraries and functions provided by Beckhoff in order to be seamless integrable with the numerical control of the machine. The system takes advantage of the *TwinCAT 3 Scope Server*, a server which allows the data recording directly from a TwinCAT system. Once configured the system can be remotely controlled by a PLC using the appropriate function block. When a recording session is ended, another function block executes a windows batch command which starts the conversion of the data collected in a CSV file. The data logging could be activated manually, whit the specific buttons on the HMI panel or in the G-code with the special M functions, M100 to enable the data logger and M101 to disable it. Together with the M100 function, an additional parameter can be passed as an integer number. The value of the parameter defines the channel configuration used by the data logger. If no parameter is passed, the default configuration with all the available channels is used.

To manage the data logger states and the transition between the states, avoiding forbidden state transitions, an appropriate state machine has been implemented in the PLC function block developed for the on-demand data logging function.

4.3.2 MQTT data logging system

The MQTT (Message Queue Telemetry Transport) monitoring system allow the machine to send data to a cloud server in order to continuously monitor the status of the machine and of the process. Also the MQTT monitoring system is integrated into the CNC using a PLC function. The monitoring system uses the native MQTT libraries and function blocks provided by the manufacturer, together with some purpose made programs, function blocks and data types in order to build a comprehensive and fully integrated system. In order to allow the connection to the MQTT broker, the machine can be connected to the network via cabled or wireless connection, depending on the characteristics of the installation.

The monitoring system work with two principles, sending two distinct type of message, both containing a JSON structure in which are encapsulated the data sent by the machine. The first data logger type, named “events logger”, involves the transmission of a message any time an “event” happens on the machine, while the second data logging is more similar to the one implemented in the *plug- in monitoring system* 4.2 but in this case there isn’t Windows applications involved.

Events Logger

As said before the events logger send a message to the cloud storage system every time of an event is detected on the machine. The events are codified depending on the type of event and are classified by severity. Here is a brief list of the events which are currently logged by the machine.

- Machine Power Status, every time the machine is powered up, as soon as the PLC is started it sends a startup message, also for power-off, if the machine is powered off with the correct procedure it will sends a power-off message;

- Machine Mode Change, every time the machine mode is changed, it sends a message with the new selected mode. The currently available modes for the machine are manual, HMI, and Automatic;

- Machine Status Change, when a status transition is detected, the machine sends a message with the new status of the machine. The status on which the machine could be are:

    - **Emergency**, one of the emergency switches has been pushed, the main contactor is opened so all the axes and conditional powered devices are de-energized;

  - **Error**, the CNC has encountered an error, the machine needs a reset. It's the typical status after an emergency reset;
  - **Idle**, the machine, and all its components are powered and there isn't any error. Nevertheless the axes are not yet enabled;
  - **Ready**, the axes are activated, the machine can move;
  - **Running**, the machine is executing a part program;
  - **Stop**, the execution of the part program has been paused.

The message contains, besides the type of event, some useful information such as the error code or other information which can be used for diagnostic or can be interesting for future analysis such as the name of the part program executed in run mode or the conditions of the machines when the emergency button has been pushed. In addition the message contains, obviously, the identifier of the machine tool and a time stamp.

Statistics Logger

The numerical control includes also a statistics logger which is activated whenever the machine is executing a program. The working principle of the data logger is based on a series of specialized data structures in which the data coming from the I/Os and from the machine are stored, then, at a fixed time a function evaluates the statistics from the signals and creates a JSON structure which is packed in an MQTT message together with the machine identifier, and a time stamp. The message is then published on a specific topic.

The base statistics evaluated for each signal are:

- Minimum and Maximum Values;
- Average;
- Standard Deviation;
- Skewness;
- Kurtosis;

An harmonic analysis could also be activated on the signals in order to identify the dominant harmonics of the signals which in some cases can be useful for process diagnostics.

4.4 Conclusions

A brief introduction on research topics and developments in machine tools monitoring system has been given. Then the types of signals which can be used for machine monitoring has been discussed with some examples of the types of sensors employed in machine monitoring and their field of application. The monitoring systems based on internal signals has been discussed with some examples from the scientific literature.

The second part of the chapter is dedicated to the presentation and discussion of three example of machine tool monitoring system which has been developed. Although they can seem repetitive, the three systems has different characteristics, in fact each system has a different underlying principle and has been developed to fulfil specific needs.

The first proposed monitoring system has been developed with a numerical control manufacturer and is currently integrated in their products. The main objective of this system were to implement in the numeric controls a set of advanced algorithms, possibly usable also in real-time, which can help both the machine operator and the machine manufacturer during the machining operations and for diagnostics in case of machine issues.

The second proposed monitoring system has been developed as an upgrade for existing machine tools which doesn't provides natively monitoring functions and connectivity. As the system has to be installed on production machines, it had to be less invasive possible and the installation of the required additional sensors cannot influence the machine performance so, sensor with the lowest possible impact on the machine. The installation of this system is completely reversible as, when the additional cabinet and the sensors are unmounted from the machine, it returns to its original state. Such as a system can also be employed for temporary monitoring campaigns on productions machines.

The third presented system constitutes a comprehensive examples of different kinds of monitoring systems which can be implemented on a modern machine tool. The system is currently under continuous developments and soon it will include real-time advanced monitoring algorithms which can be used for the implementation of an adaptive numerical control. From the scientific point of view this is the most flexible of the three proposed systems as, due to the possibility to act at a very low level on the automation, it allows to develop and test advanced signal filtering and control techniques.

Chapter 5

Milling Process Digital Twin

The increasing digitalization of production processes opens up a wide range of possibilities to increase effectiveness and productivity, especially in machining operations. The concept of Digital Twin was firstly introduced by Grieves in 2002 [37] as a concept for product lifecycle management without naming it. The name Digital Twin was then given to the model by John Vickers of NASA [45]. The data created during machining processes, and collected by the advanced monitoring systems could be used to realize a digital counterparts of the process from which precise and punctual process informations could be obtained. Then the results of the simulations conducted by the digital twin can return to the shop floor as knowledge base, or as a quality parameter. Digital twin can be exploited, in machining processes to support operators in decision making and to improve process efficiency through, for example, monitoring and prediction of working parameters. In research, there are many examples of applications of digital twin in manufacturing. For example Botkina et al. [11] proposes a methodologies for the construction of a digital twin of a cutting tool. The digital twin is based on the ISO 13399 cutting tool data representation and exchange, in order to make it compatible with many software servicing cutting tools. In order to allow data exchange between different machines with different protocols, purpose made information system architecture has been developed. Digital twin could also be applied for the preliminary study of machine reconditioning, in order to design and validate a machine reconditioning without the need to have the availability of the physical machine, reducing drastically the downtime [7]. Some scientific papers proposes comprehensive literature reviews on the themes of the digital twin and their application in manufacturing. Negri et al. [70], proposes a comprehensive review on the application of digital twin in manufacturing industries. It's also worth noting the review proposed by Monostori et al. [68] in which the principal aspects of research and Digital twin are depicted and analyzed.

This chapter is devoted to the description of a preliminary example of implementation of milling process digital twin in order to obtain, from the data collected by the milling machine, a set of indicators which allow to detects machining issues related to workpiece material characteristics or to tool wear. The proposed system uses the cutting forces measured during the machining together with the data coming from a milling process simulation to verify the material which is machined and the wear status of the cutting tool.

Moreover an example of indirect cutting parameters estimation by comparison between simulated and measured data is presented as a preliminary result.

5.1 Force measurement in machining operations

Measurement of forces resulting from the interaction between cutting tool and workpiece during machining operation is a crucial topic in the realm of process monitoring and optimization.

Knowledge of process forces during machining, enables extended possibilities of application. For instance the values of the forces could be utilized to assess the condition of machine components or for tool's condition monitoring [3]. Moreover these information are useful for the prediction of workpiece quality since it's possible to estimate the tool deflection caused and compensate it [20]. Cutting forces have also a great impact on surface roughness, so it's possible to control the final roughness of the workpiece by controlling the forces during machining [18, 56]. Furthermore, cutting forces measurement enables the possibility to implement on-line optimization of the cutting parameter in order to maximize the material removal rate implementing the so-called adaptive numerical controls [51].

Nevertheless, despite the intrinsic benefit brought,the measurement of cutting forces, on production machines, is not so diffused as it could involve some problems and limitations. For example, direct measurement of cutting forces involves the use of a plate dynamometer or of a rotating dynamometer. Apart from the high costs of these instruments, their installation on a machine tool heavily impact the performances of the machine. The installation of a plate dynamometer, for example, causes a substantial reduction of the working area. More in general, the installation of a dynamometer implies an alteration of machine tools dynamic and rigidity, which is not ever acceptable in a production context.

Many research works try to overcome the problems related to direct measurement of cutting forces. Luo et al. [61], for example proposed a force measurement system, based on PVDF sensors, integrated in a milling tool. The proposed system overcome many of the limits related to the traditional dynamometers, however it has still some limitations due, for example to the wireless data transmission which cannot be always reliable in environment with heavy RF disturbances such as an industrial environment.

Given the issues related to direct force measurement on industrial machine tools, many research focused on indirect force estimation using other sensors such as accelerometers or electrical power sensors installed on the drive axes. These last sensors have an absolutely low impact on the machine however the signals obtained are usually highly affected by electrical noise. Moreover, the signals collected from feed drives have usually a low bandwidth due to the effect of the machine structure which act as a low pass filter. To overcome these limits many researcher are developing innovative filtering methodologies which enable precise estimation of cutting speed from feed drive currents.

An example of indirect cutting force estimation was proposed in 1992 by Y. Altintas [3]. In order to obtain a precise estimation of the pulsating cutting force, a dynamic model of the feed axis were built and used to evaluate the current-force transfer function. The model was then tested by comparison of the estimated forces with the forces measured by a dynammeter. The limits of these approach were substantially related to the low bandwidth of the current loop of the machine which makes the system unusable for machining operations in which the tooth passing frequency is higher than 120 Hz.

More recent examples of indirect cutting forces estimation are presented by Albertelli et al. [2], Miura et al. [66], Yamada et al. [98], and Aslan et al. [6].

Albertelli proposed an estimation of cutting forces and tool vibration in milling using multiple-sesnor measurements. In particular, the acceleration of spindle housing and the relative displacements between spindle shaft and spindle housing were measured. Then, using a Kalman-based observer, tool-tip vibration and cutting force were estimated and, in validation phase compared with the corresponding quantities measured directly on the machine. Validation cutting tests highlighted a good agreement between estimation and measurements.

Miura proposed a cutting force estimation system based on the measurement of voltage and current on the axis motor power lines using external sensors. This approach overcome the limitations due to the usually low bandwidth of the data provided by the outer control loop of the machine controller. The proposed method used an observer for the estimation of the back-EMF induced by the motor. Then the motor current related to external forces has been estimated starting from the measured current and the transfer function of the motor drive control loop. Afterwards the cutting power has been calculated and from this the cutting force values has been extracted. The system has been validated performing straight slot milling test on a five-axis commercial milling machine, showing promising results.

Yamada presented a cutting force estimator based on the signals available on a fully closed control loop axis, where a linear encoder signal is available in addition to common current and motor encoder signals. The estimator is based on an expanded dynamic model in which the dynamic behaviour of ball-screw system are taken into account. Then an observer is built in order to estimate the cutting force. The system has been validated on a test-bed, performing straight slot milling.

Aslan presented a comprehensive model for the estimation of cutting forces, from feed drive current, on a five axis milling machine. Each axis of the machine has been identified in order to obtain models for inertia, friction, transmission ratio and response function. Then for each axis a dynamic compensation of drive current has been set up, based on the identification results. So the whole machine kinematics has been built assembling the transformed models of each axis. Finally the system has been validated on Quaser UX600 machining center during turbine blades milling operations. The estimated signal has been compared with the cutting forces measured by a rotating dynamometer.

5.1.1 Direct Cutting Force Measurement

To directly measure cutting forces during milling experiments, a plate dynamometer has been installed on the machining test bed. The dynamometer, developed and built at LAMA FVG (Laboratory for Advanged Mechatronics of the University of Udine) embeds four triaxial high-sensitivity piezoelectric load cells Kistler 9016B4 in a geometric configuration similar to the Kistler MiniDyn95266C2. The structure of the dynamometer is

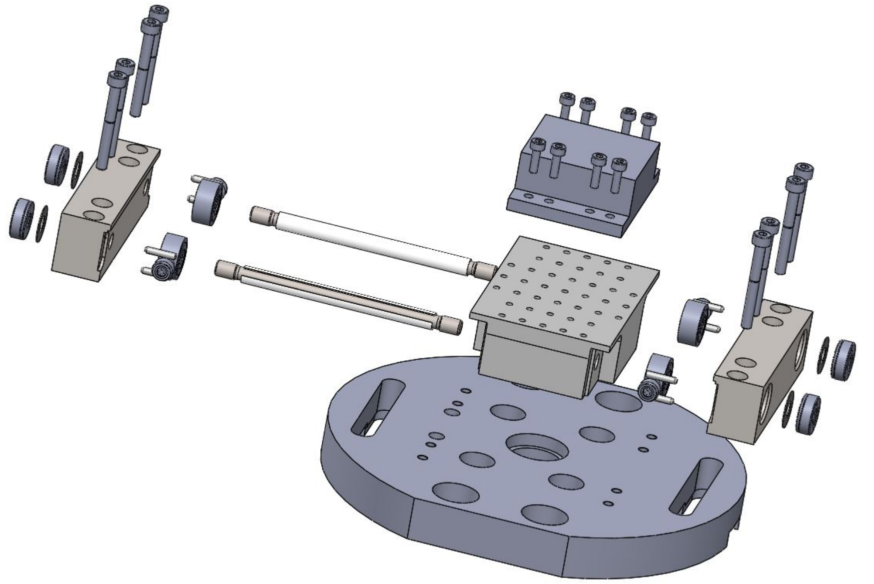


Figure 5.1: Dynamometer exploded view.

built by a central platform, made by additive manufacturing, of AISI 316L stainless steel, and two side elements made of Ck45 steel. The load cell are installed between the side elements and the platform and are held in place by two tensioning rods which allow also to preload the cells. Side elements are fixed on a platform which allows the installation of the dynamometer on the machine tool.

From the dynamometer are collected 12 force signals, 3 force components for each cell installed on the device. In order to reconstruct the main components of the cutting forces along the principal direction from the collected signals, a calibration phase is needed. The calibration allows also to increase the performances of the dynamometer in therms of measurement bandwidth. Using the calibration procedures proposed in [91] and [90] is possible to dramatically increase the frequency bandwidth of the device up to 5 kHz.

Then, after the installation of the dynamometer on the machine table and after its alignment with machine axes, the dynamometer was calibrated. The calibration was carried out applying an impulsive force, with an instrumented hammer, on the workpiece installed on top on the dynamometer plate. The procedure was done following the procedure explained in [90]. The data collected during the calibration were then analized and processed in Matlab in order to obtain the filter. The filter was then tested on the input force obtained during the calibration pulse tests with good performances.

The application of the filter to the data obtained in actual milling test revealed an unexpected poor performance, in fact some harmonic oscillations with a frequency of about 1 kHz were still present in the filtered signal. An extended analysis has been conducted in order to identify the cause of this decay in filter performances. Various tests has been carried out, including dynamometer calibration with different machine coordinates and analysis of the transmissibility function of the machine structure, analyzed by executing

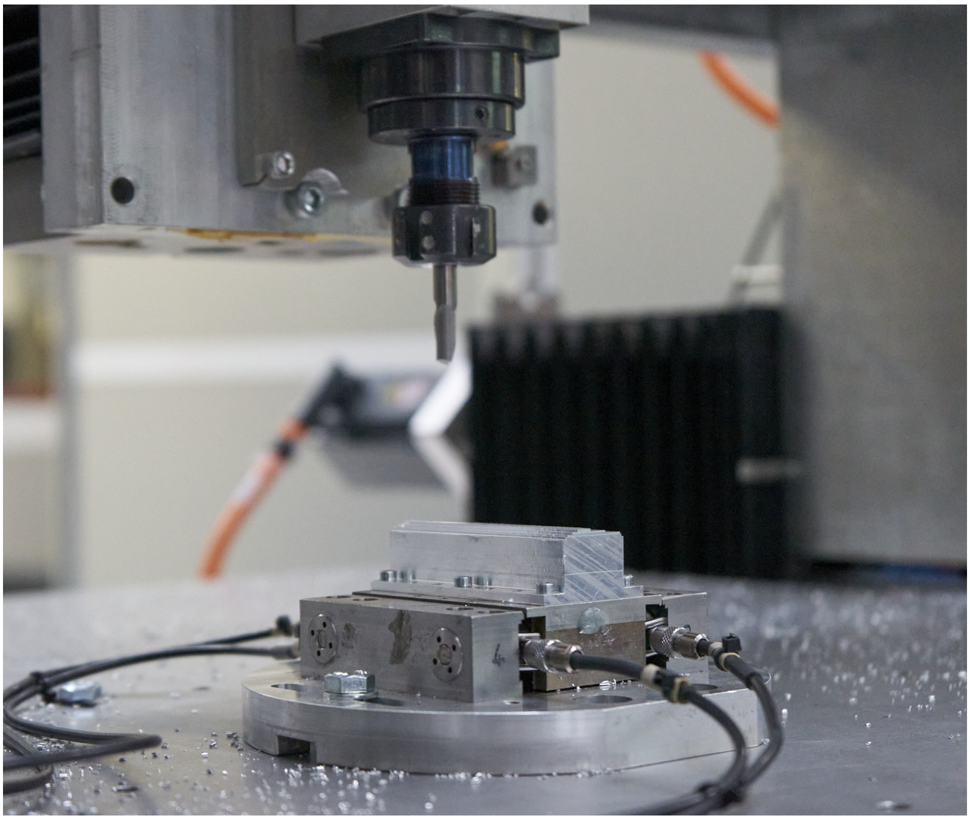


Figure 5.2: Dynamometer installed on the machine.

a set of pulse tests with the force applied on the spindle collet and measuring the output signal on the dynamomemeter. Other tests has been realized by pulse testing the spindle while moving the axes in order to verify the response of the axis drive to an impulse force. The analyisis of the data collected during tests revealed that:

- Transmissibility functions of the dynamometer measured applying the forces on the workpiece are the most important functions for the evaluation of the filters. However these functions are heavily affected by the machine configuration, so different positions of the axes implies different filters, even for relatively small displacements.

- Transimissibility function of the dynamometer measured through machine structure, obtained by application of the forces on the spindle collet, could gave a significant contribute in filter building, due to the flexibility and lightweight of machine structure. Nevertheless, for the time being, its contribute to the force reconstruction seems to be not so relevant and in some cases seems to even affect negatively filter performances,

- There are some inertial effect due to the spindle rotation which causes a variation in forces of about a N. These effects, in first approximation, could be neglected.

- Both axes torque and dynamometer signals have strong harmonic contributes at frequencies around 1 kHz. These contributes are likely due to the outer position control loop of the CNC. These vibration, generated by the axes drives as a consequence of the position error, propagate through the machine structure and reach the table on which the dynamometer is installed interfering with measurements. The filter evaluated from the transmissibility functions measured in stand-still conditions cannot filter these contributes effectively. A way to compensate these disturbances would be the installation of a set of accelerometer near the dynamometer in order to measure and compensate these oscillations.
- Machine work-table have low rigidity, this negatively affect the measurements, especially in direction of spindle axis.

Thus, for these first preliminary tests a simpler filter based on singular value decomposition has been used for the force estimation. This filter didn't allow high signal bandwidth, but, considering the bandwidth of the signals collected from the machine automation system, its more than enough.

5.2 Milling process simulation

In order to obtain the theoretical cutting forces values to be compared with the measured ones, a milling simulator was set up. In literature there are many examples of milling process simulators mainly based on finite elements or finite volumes numerical analysis but also analytical and empirical models has been exploited for process simulation.

Analytical models are based on the analysis of the lip line-field. One of the first examples of this kind of models was the shear plane model proposed by Merchant in 1944 [65] which used a single shear-plane. Then, in 1951 Lee and Shaffer presented an analytical model which was used, together with the mathematical formulation for the construction of slip-lines proposed by Hill, until 1990s. These models have been used as a base for the development of several other analytical models. Among these, are remarkable the centred-fan slip-line mode for machining with restricted contact tools proposed by Usui and Hoshi[92] and Johnson [46], the admissible and inadmissible slip-line models for machining developed by Kudo[53]; Dewurst's lip line solutions for non-unique machining with curled chip formation [22] and the following extended curled chip formation model proposed by Shi and Ramalingam [85]. A universal slip model that incorporates all the six previously presented models has been developed by Fang et al. [1]. This model enables the estimation of cutting forces, chip curl radius, chip thickness along with other interesting parameters.

Finite Elements and Numerical Models. In the finite elements simulations realm there are two main mathematical formulations: *Lagrangian* and *Eulerian.* The main difference between the two method is in the definition of the mes. While Lagrangian mesh deforms in time whit the material, Eulerian mesis fixed in space (the so-called control

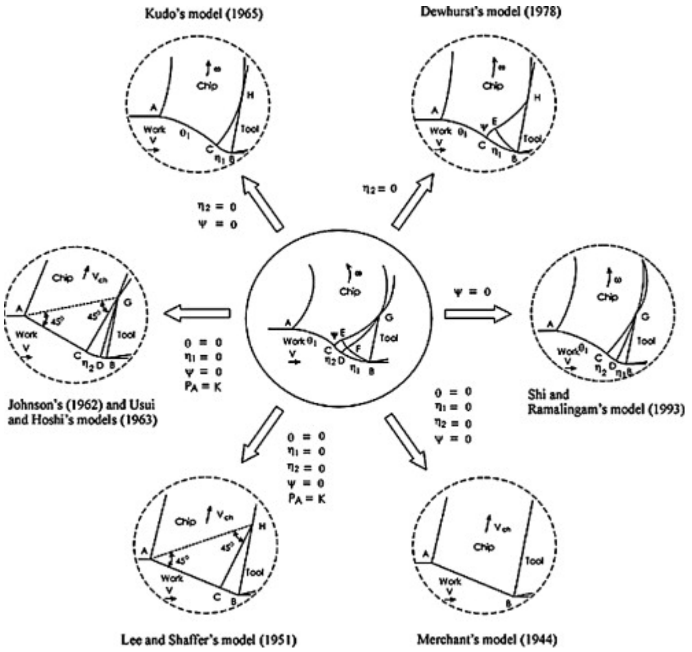


Figure 5.3: Universal slip-line model and its transformation to six previous models. [5]

volume). For machining simulations is more adopted the Lagrangian formulation, due to the mesh which deforms together with the material. However there is a simulation method called ALE (Arbitrary Lagrangain -Eulerian Tecnique) which combines the features of Eulerian and Lagrangian formulations adopting an explicit solution technique for fast convergence. There are other numerical methods based on conservation of momentum energy and mass. Amon these last techniques ther are also the meshless techniques in which the material and states variable are approximated by their values at a set of discrete points or particles. Theses techniques avoids all the common problems related to the mesh such as distortion, separation criteria and contact conditions.

Empirical models Empirical approaches are the simplest among the modelling approaches and are still widely used in absence of other meaningful models. As empirical models relies on experimental data, they often are only valid for the ranges included in the experiments. Empirical models are based on designing experiments with varying processes inputs, and measuring process outputs such as cutting forces, surface roughness, tool wear and all that can be considered valuable for process description. Then inputs and outputs are correlated. In order to obtain a robust model, heavy experimentations are needed.

In this case, since the simulation has to be integrated in the control loop, a lightweight model has been chosen. The process simulation presented in this pages will be based on the geometrical evaluation of the cutting forces based on the shearing and ploughing model. In order to evaluate the cutting forces in the three principal directions, the model need the following inputs:

- Cutting tool geometry. The model of the cutting tool consists in a set of segments

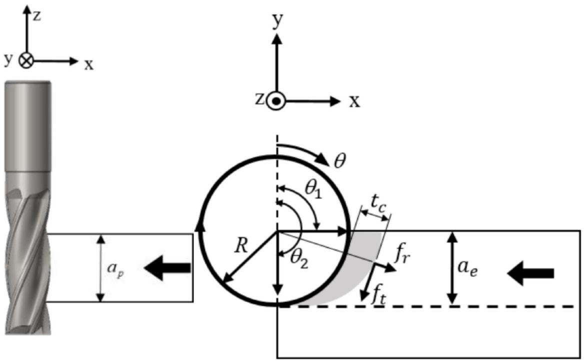


Figure 5.4: Schematic representation of milling process.

which describes the cutting edges of the tool.

- Workpiece material model. The material is described by means of four parameters which describes the specific shearing forces in tangential and normal direction K_{cs} and K_{ns} (N/mm^2), and the ploughing forces in tangential and normal directions K_{cp} and K_{np} (N mm^{-1}).
- Radial depth of cut, described with two distances from the cutting tool centre according to figure 5.4. Depending on the sign and magnitude of the two distances different milling configurations could be described.
  - a_{L1} and $a_{L2} < 0$ partial face milling, upmilling;
  - a_{L1} and $a_{L2} > 0$ partial face milling, downmilling;
  - $a_{L1} > 0$ and $a_{L2} < 0$ face milling.

  The model works only if $a_{L1} > a_{L2}$;
- Feed per tooth F_z (mm/(tooth · rev));
- Axial depth of cut a_p in mm;
- Cutting speed in RPM;
- Time-step in s.

Basing on the input data, the simulation provide,as as output, the instantaneous forces (along the three main axes) calculated on one cutting tool rotation.

Cutting tool geometry discretization

In order to speed up the simulation process, the tool is discretized as a rotating group of segments which represents the cutting edges of the tool

The segments are classified in two categories in order to distinguish the cutting edges located on the face of the mill, which develop in radial direction, from the side cutting edges which can be helical or straight and develop along the axial direction of the mill. The modelling of the cutting tool starts with the definition of some geometric parameter such as cutting tool diameter and helix angle. Then the maximum admissible feed per tooth $F_{z,max}$ and axial depth of cut $a_{P,max}$ are set in conformance with the tool's limits. So, depending on the geometry of the tool, the actual modelling phase is carried out. As an example, the process for the discretization of a single flute endmill will be presented, however the modelling process can easily be extended to endmills with more flutes. The first parameters to set are the length of the front cutting edge and the length of the base element used for the discretization of the cutting edge. The length of the front cutting edge is measured from the external face of the mill, towards the center. The cutting edge is then divided in segments and for each element, the coordinates of start and end points, in cartesian and cylindrical coordinate systems, are evaluated and stored in appropriates data structures. For each segment the total length and the length in axial direction are evaluated.

So the side cutter is modelled. In this case the discretization is done by steps in axial direction, so the definition of the axial length of the segments D_z has to be defined. The Z axis of the mill is then divided in step of length D_z. For each Z step, the coordinates of starting $P_{0,i}$ and ending $P_{1,i}$ points of the portion of cutting edge are calculated and stored in the related structure. For each segment are also evaluated the coordinates of the midpoint $P_{m,i}$ and the axial versor $\vec{v_A}$. Then the normal versor $\vec{v_N}$ is evaluated.

$$P_{0,i,xy} = [x_0\ y_0\ z_0] \qquad P_{1,i,xy} = [x_1\ y_1\ z_1] \tag{5.1}$$

$$P_{0,i,r\theta} = [r_0\ \theta_0\ z_0] \qquad P_{1,i,r\theta} = [r_1\ \theta_1\ z_1] \tag{5.2}$$

The $i-th$ segment is represented as:

$$S_{i,xy} = [P_{0,i,xy}\ P_{1,i,xy}\ T_s] \tag{5.3}$$

in cartesian coordinates system or

$$S_{i,r\theta} = [P_{0,i,r\theta}\ P_{1,i,r\theta}\ T_s] \tag{5.4}$$

in cylindrical coordinates system. T_s is the type of segment classification $T_s = 0$ identifies a front cutter segment while $T_s = 1$ identifies a side cutter segment.

The axial versor of the segment is calculated as:

$$\vec{v_A} = \frac{P_{1,i,xy} - P_{0,i,xy}}{(P_{1,i,xy} - P_{0,i,xy})^2} \tag{5.5}$$

Since the algorithm evaluates the normal versor on a plane normal to the segment, passing by the midpoint of the segment and intersecting the axis of the cutting tool, the algorithm executes only if the axial versor of the segment has a non-zero $v_{z,A,i}$ component. To estimate the normal versor, first, the distance between the plane perpendicular to the segment, described by the axial versor, and the midpoint of the segment P_m is evaluated.

$$D_{S,PM} = P_{m,i} \times \vec{v_A} \tag{5.6}$$

Then the Z coordinate of the intersection point between the plane perpendicular to the segment and the axis of the mill $Z_{ax,i}$ is evaluated.

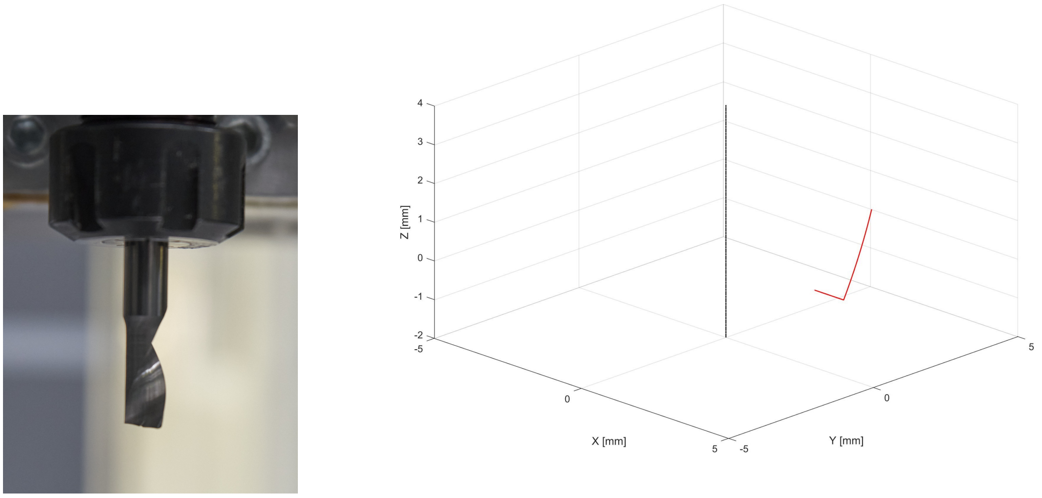
$$z_{ax,i} = \frac{v_{x,A,i} \cdot z_{ax} + v_{y,A,i} \cdot y_{ax} + D_{S,PM}}{v_{z,A,i}} \tag{5.7}$$

The intersection point between the plane perpendicular to the segment and intersecting the segment in its midpoint, and the rotation axis of the cutting tool is

$$P_{ax,i,xy} = [x_{ax} \; y_{ax} \; z_{ax,i}] \tag{5.8}$$

So the normal versor can be evaluated.

$$\vec{v_N} = \frac{P_{ax,i,xy} - P_{m,i,xy}}{(P_{ax,i,xy} - P_{0,i,xy})^2} \tag{5.9}$$



(a) Actual cutting tool.

(b) Simulated cutting tool

Figure 5.5: Actual vs Simulated cutting tool.

5.2.1 Milling simulation

The aim of the developed milling simulator is to obtain for one rotation of the spindle, the waveforms of the cutting forces along the three axes. The tree estimated forces could then be compared with the measured ones. The simulator is developed in a Matlab function which requires as input data, the structure containing the characteristics of the cutting tool, the structure containing the characteristic cutting force coefficients of the machined material, the spindle speed rpm, feed per tooth f_z, radial depth of cut (a_{L1} and a_{L1} figure 5.4), axial depth of cut a_p, and time step dt.

The core of the simulation is a function which rotates the modelled cutting tool of an angle corresponding to the selected time step $d\theta$.

$$\omega = \frac{2 \cdot \pi \cdot n}{60} \tag{5.10}$$

$$d\theta = \omega \cdot dt \tag{5.11}$$

Then the algorithm check if any of the segments composing the cutting edges is "inside" the workpiece. The coordinates of the middle point of each segments are taken as a reference to decide whether the segment is active or not. The condition of segment activation is that the middle point of the segment is inside the workpiece.

If a segment is inside the workipece volume, defined by a_p, a_{L1}, and a_{L2}, the uncut chip thickness and forces modulus are evaluated, depending on the type of segment.

For a segment of the side cutter, firstly the updated tangential versor v_T is evaluated.

$$\vec{v_T} = \vec{v_N} \times \vec{v_A} \tag{5.12}$$

So the height of the uncut chip related to the segment is evaluated.

$$H_i = \frac{f_z \cdot \cos\theta_i \cdot dZ_i}{L_{S,i}} \tag{5.13}$$

Where $L_{S,i}$ is the length of the segment. Then the magnitude of the cutting forces related to the segments are evaluated as,

$$F_{cs,i} = k_{cs,mat} \cdot H_i \cdot L_{S,i} \tag{5.14}$$

$$F_{ns,i} = k_{ns,mat} \cdot H_i \cdot L_{S,i} \tag{5.15}$$

for the shearing part, and

$$F_{cp,i} = k_{cp,mat} \cdot L_{S,i} \tag{5.16}$$

$$F_{np,i} = k_{np,mat} \cdot L_{S,i} \tag{5.17}$$

for the ploughing contribute. Then the four contributes are combined in order to obtain the forces along the reference axes.

$$\vec{F_i} = (F_{cs,i} + F_{cp,i}) \times \vec{v_T} + (F_{ns,i} + F_{np,i}) \times \vec{v_N} \tag{5.18}$$

For a segment of the frontal cutter, only the ploughing component is present. Since the segment develops in radial direction, its normal versor $\vec{v_N}$ is

$$\vec{v_N} = [0\ 0\ 1] \tag{5.19}$$

The tangential versor is evaluated as:

$$\vec{v_T} = \vec{v_N} \times \vec{v_A} \tag{5.20}$$

Since the ploughing forces depends only by the contact length, the magnitude of the forces is

$$F_{cp,i} = k_{cp,mat} \cdot L_{S,i} \tag{5.21}$$
$$F_{np,i} = k_{np,mat} \cdot L_{S,i} \tag{5.22}$$

So the force contribute of the front cutter segment is

$$\vec{F_i} = F_{cp,i} \times \vec{v_T} + F_{np,i} \times \vec{v_N} \tag{5.23}$$

The forces related to each segments are then summed up in order to obtain the overall forces, the angular position of the cutting tool is moved to $\theta_{act} + d\theta$ and the process is repeated until $\theta = 2\pi$ is reached.

5.3 Milling experiments

In order to validate the milling forces model and to estimate the four ploughing and shearing coefficients a set of data obtained from milling experiments is needed. The experiments involved partial face milling and has been planned and realized following a design of experiments with two parameters, feed per tooth F_z and axial depth of cut a_p varied on two levels, and one parameter, cutting speed V_c varied on three levels. In total $2 \times 2 \times 3 = 12$ cutting tests has been executed, in table 5.1 the parameters and related levels are represented.

Parameter		Low Level	Mid Level	High level
F_z	$\left[\frac{\text{mm}}{\text{tooth rev}}\right]$	0,10		0,25
a_p	$[\text{mm}]$	0,75		1,50
V_c	$\left[\frac{\text{m}}{\text{min}}\right]$	300,00	400,00	500,00

Table 5.1: Parameter and levels of the first set of cutting tests.

All the test described above has been executed with $L_1 = 0$ mm and $L_2 = -4$ mm measured in the reference system depicted in figure 5.4, which implies a radial immersion $a_p = 50\%$.

To explore also the influence of radial immersion on the cutting force and to analyze the response of the models also in this case, another set of cutting tests has been designed and executed. These second tests has been executed varying two parameter, depth of cut a_p and radial immersion $a_{l/D}$, on two levels. In total $2X2 = 4$ cutting tests has been executed.However, due to the choice of the other cutting parameters and to the fact that these test has been execute on the same material, whit the same tool and in the same conditions, other two tests from the previous set can be taken into account and compared, adding another level of $a_[L/D]$. In table 5.2, the parameters and the levels value are summarized.

Parameter	Low Level	Mid Level	High level
a_p $\left[\text{ mm }\right]$	0,75		1,50
$a_{L/D}$ $\left[\text{ \% }\right]$	25,00	50,00	75,00

Table 5.2: Parameter and levels of the second set of cutting tests.

The parameters which wasn't varied during the tests were $F_z = 0.1\ \frac{\text{mm}}{\text{tooth rev}}$ and $V_c = 300\ \frac{\text{m}}{\text{min}}$. All the tests were conducted in down milling.

Workpiece

The cutting tests were carried out on a workpiece designed on purpose to be installable on the dynamometer. Considering the limited spindle power, about 730 W and the structural limits of the machine, aluminum 7075 (*Ergal*) has been chosen as workpiece material. The workpiece has a cuboid shape of about 80 mm of length, 22 mm of width and 25 mm of height. The workpiece is provided with two perforated plates on the bottom part, along the longer sides, to fix it to the dynamometer's platform.

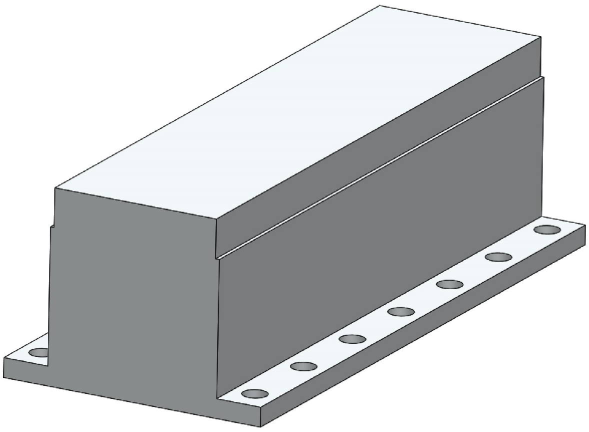


Figure 5.6: Workpiece.

Cutting tool

All the milling tests were carried out using a Sandvik Coromant single flute solid carbide endmill for large chip removal, specialized for non-ferrous materials, *2P230-0800-NA H10F*. The endmill has a cutting diameter $D_c = 8$ 8 mm and a flute helix angle of 30°; the maximum depth of cut is 16 mm and the functional length is 63 mm. The radial rake angle of the mill is 13,5° while axial rake angle is 2°.

Figure 5.7: Cutting tool.

Milling Strategies

The test has been conducted in order to ensure the lowest interaction possible between different testing. Prior to start with the actual tests, the workpiece was face-milled and contoured in order to ensure a perfect alignment between the workpiece and the machine axes, and to ensure consistent cutting dimensions during tests. The tests has been executed on the longest side of the workpiece in order to have a significant portion of signal acquired in steady conditions, without the disturbances caused by the approach or by the exit from the workpiece. The test condition has been divided in groups of four conditions, each group included two testing conditions with the higher level of a_p and two with the lower level of a_p. As can be seen in figure 5.8, the two milling tests with the highest depth of cut has been executed on the external par of the workpiece while the tests with the lowest depth of cut has been realized on the internal part of the piece. This tests arrangement ensures that all the tests undergo the same conditions. After the completion of a test set, the workpiece was prepared for the next set of testing conditions by face-milling.

5.3.1 Data Analysis

Signals coming from the machine ans from the dynamometer has been collected during the cutting tests. Due to technical reasons the dynamometer, for the time being, cannot be integrated into the machine data acquisition system so a second data acquisition system has to be utilized. In this case the dynamometer's load cells has been connected, through their charge amplifiers and electrical interfaces, to a National Instrument cDAQ-9128 data acquisition system on which were installed four NI9215 analog voltage acquisition modules. In order to synchronize the two acquisition systems, an analog voltage signal is generated by the machine PLC and acquired by the two data acquisition system. Dynamometer signals were sampled with a frequency of 50 kHz while the data collected by the machine

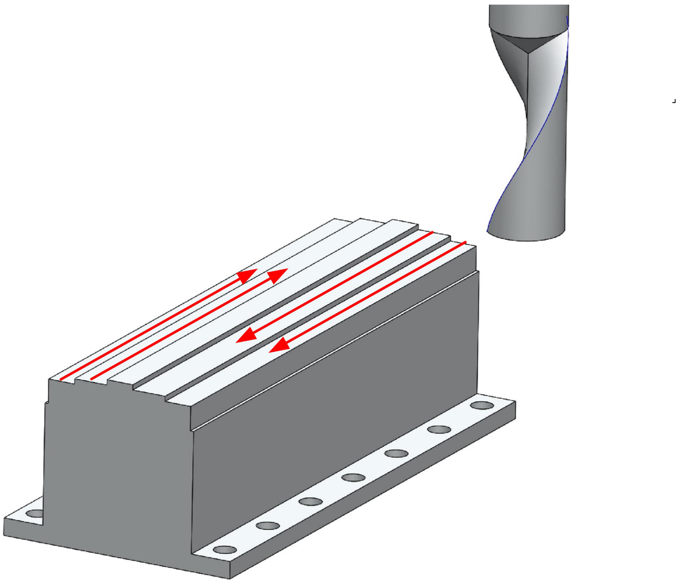


Figure 5.8: Milling tests arrangement.

are sampled at different frequencies ranging from 1 kHz to 16 kHz, depending on the source of the signal. The data more useful for the experiments, such as axes torque and following error, and signals coming from the sensors installed on the machine are sampled at 16 kHz. The data analysis started with the conversion of the data from the CSV file saved by the machine to a Matlab data structure for the following elaborations. The two dataset has been synchronized, using the reference signal, and merged in order to obtain an unique data file for each cutting session. To associate each file to the correct tests, a registry has been created using an Excel spreadsheet. The spreadsheet is organized in different sheets in which are stored respectively, the cutting tests identified by a numerical ID, with the related cutting conditions, the association between cutting tests and files with the indication of the portion of the file in which the specific test is stored, and the channel configuration. The actual data analysis is carried out in Matlab using a set of purpose developed algorithms and functions. The main scrip take as a input an array in whose elements are the identifiers of the tests to be analyzed, the path to the registry file and a pointer to the elaboration function to be utilized for the data analysis, since different functions can be activated depending on the objective of the analysis. Then, for each element of the tests array, the cutting conditions and file positions are imported from the spreadsheet and stored in an appropriate structure which is given as input to the elaboration function.

Cutting force coefficients estimation

The elaboration function starts with the extraction of the test data contained in the structure received as argument of the function, then the file containing the calibration coefficients for the estimation of the forces from the twelve measured components, is loaded. the actual data file is then loaded and the relevant signal are extracted from the data structure. The analysis proposed in the following pages will involve mainly the data collected from the dynamometer so, the first operation carried out on the data is the evaluation of the cutting force components along the main directions using the static calibration coefficients. Then a portion of data in which the operation is in steady state is extracted from the test signals. For the correct functioning of the algorithm an accurate value of the spindle speed is needed, so the spindle speed is evaluated, starting from the nominal speed obtained from the test registry.

The evaluation of the spindle speed is carried out analyzing in frequency domain one of the available cutting force signal. In order to estimate the spindle speed, the algorithm search the frequency component with the highest value nearby the nominal revolution frequency. When the base frequency is identified, the algorithm will search the higher harmonics as multiples of the base frequencies until a defined limit frequency. Once all the harmonics are identified the mean frequency is evaluated. This is assumed to be the real spindle speed. This algorithm allows to take into account and compensate also slight frequency slides and imprecision due to noise.

The sign of the feed speed is then evaluated in order to define the direction of the force and if needed to reverse the direction of the forces in order to make consistent and directly comparable all the tests regardless of the feed direction.

Average Cycle Evaluation The estimation of cutting forces coefficients requires the knowledge of the average forces. To ensure the correct identification of the turn, given that during the test, small variations on spindle speed or sampling frequency may occur, an algorithm which compensate for these effects has been set up. The function takes as inputs the signal to be averaged, the number of samples per spindle revolution and an overlapping percentage required for the elaboration. From the initial part of the input signal a part of length corresponding to a spindle revolution is extracted, then another portion of signal is extracted from the array. Also the new part of signal has a nominal length equal to a spindle revolution, but on the top and on the end are attached to additional portion of signal of length equal to the overlapping factor. Then the old portion of signal is compared with the new signal piece translated of increasing quantities until the maximum correlation coefficient between the two signal is reached. Then the average between the two cycles is evaluated and the average cycle is taken as reference. Another piece of signal starting from the end of the previously selected piece (excluding overlapping) is taken and compared with the reference cycle; when the two signals are collimated, they are averaged and the reference is updated. This process is repeated until all the original signal array has been evaluated and collimated piecewise. The function returns, as output, the average cycle, the standard deviation on the cycle, the number of revolutions included in the averaging, an array with the cycles used for the averaging and an array with the index of the cycles in the original array. The rest of the force signals are averaged using another function which rakes as inputs the signal to be averaged and the array with the indexes of the cycles The function simply extracts from the signal array, all the portions with length corresponding to a spindle rotation starting from the indexes contained in the array. Signal portions are stored in a matrix from which the average cycle and the standard deviation are extracted.

The function then returns the average cycle, the standard deviation on the cycle, and the matrix containing the single cycles used for the averaging. In figure 5.9, the average forces are shown in comparison with the data used for the evaluation.

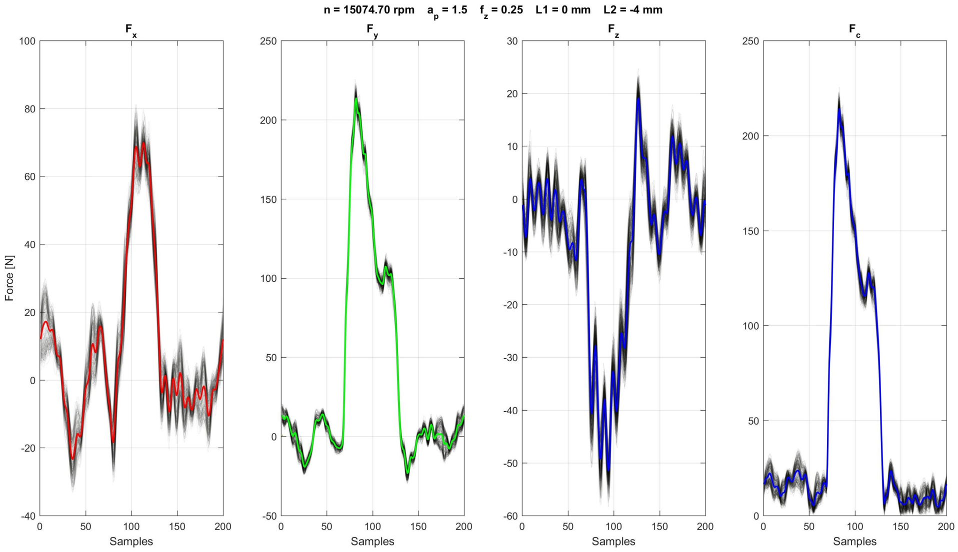


Figure 5.9: Comparison between average and measured forces.

Force contributes simulation To estimate the shearing and ploughing coefficients, the simulated force contributes for each force are needed, then for each test, twelve force contributes has to be simulated. The force contributes are obtained by running the simulator four times with the same cutting parameters of the milling test but using four "special materials". The four materials used for this purpose has the coefficients arranged in order to have only one of the four coefficient equals to one while the others are set to zero, this allow to evaluate the unitary contributes of the coefficient. In figure 5.10, the average measured forces are shown on top of the shearing and ploughing contributes in tangential and normal direction.

Cutting force coefficients estimation The actual estimation of cutting force coefficients is done by regression between the average measured forces and the simulated single force contributes. The data for the regression are obtained executing the function described above on a set of milling tests, the resulting average forces and single force contributes are stored in an appropriated data structure which is then used by the regression function. The regression function extract the data from the structures and prepares the elements for the assembly of the regression matrix. The average forces are assembled together in a three column array, once per direction. Also the single components forces are packet in column arrays, one for each contributes and direction, in the same order of the averaged cutting forces. The function allows different configurations of contributes and force directions to used for the regression, then according to the configuration the

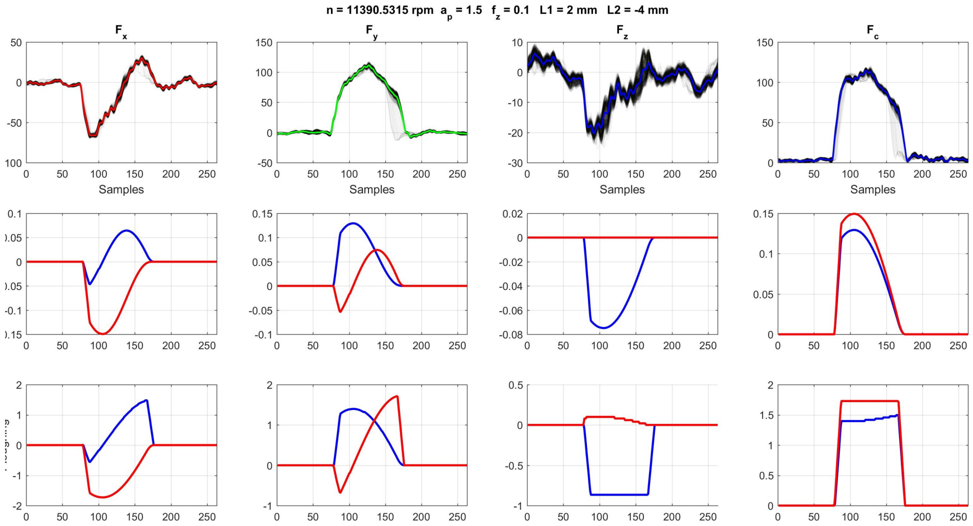


Figure 5.10: Average measured forces and single force contributes.

responses vector Y is assembled putting in column the average forces vectors related to the selected directions. To build the predictor matrix X the column array related to each selected force contribute is assembled like the Y array, then the obtained column arrays are arranged in order to be the columns of the X matrix. The cutting force coefficients pertaining the selected configurations are then estimated by regression. In order to evaluate the estimation performances, the forces are evaluated using the estimated coefficients, then the maximum error and the RMSE are evaluated.

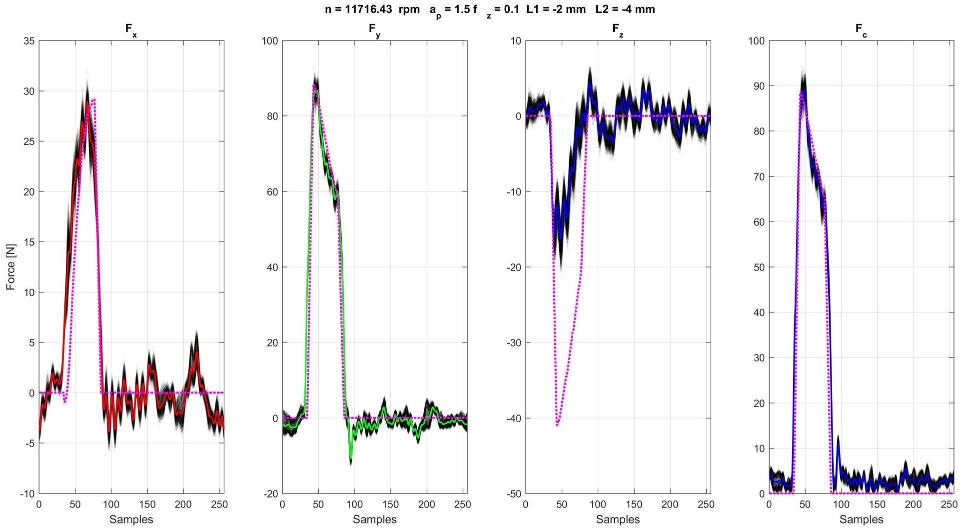


Figure 5.11: Average measured forces and estimated cutting forces.

Many regression has been conducted with different configurations of forces directions and single contributes involved using also different sets of cutting tests. The tests showed that the estimate of the shearing coefficient in tangential direction K_{cs} is pretty stable under different configurations with variations of about ±5% around the mean value. Also the ploughing coefficient in normal direction K_{np} seems to be well estimated under different configurations. Th other two coefficients are more dependent on the configuration used for the regression, however their influence on the force estimation is limited. Regarding the force direction used in the regression, results of the tests showed that the Z direction of the cutting force tends to be overestimated by the model, this can be due to the formulation of the model and to the fact that measured Z forces are heavily influenced by dynamics effects caused by the oscillation of machine working table during machining. The best results in term of maximum error and RMSE has been obtained using all the twenty milling tests, the average forces in X and Y direction and with the estimation of all the four coefficients. In figure 5.12, all the forces obtained by the simulation executed with the parameters of the milling tests are summarized, these can be compared to the corresponding average forces measured during the milling tests and summarized in figure 5.13.

5.4 Milling simulator in process monitoring

Once the model has been tuned by the estimation of the cutting force coefficients, it can be used for diagnosis of the process status or for the estimation of cutting parameters which normally cannot be measured directly during the machining operations such as actual depth of cut and radial immersion.

5.4.1 Cutting force coefficients as workpiece material conformance index

Due to the observed stability of the estimated value of some of the cutting force coefficients and due to the strong relation between workpiece material and cutting force coefficient, it can be used as an in-process indicator of workpiece material conformance. The proposed algorithms allow to estimate reliable values of cutting force coefficients (in particular K_{cs}) within a reduced number of spindle revolutions allowing the evaluation of the parameters almost in real-time during the machining. Then the observation of the amount and speed of variation of the coefficient can be used for diagnostic during the machining process. For example a suddenly variation of the coefficient during the machining could indicate a localized problem of the workpiece such as an inclusion or a cavity. A continuous increasing of the K_{cs}, also during machining of different pieces with the same tool, could indicate a tool-wear process. Variations of the coefficients along the same workpiece could be related to inhomogeneity of the workpiece material. A constantly different cutting force coefficient could indicate wrong workpiece material.

5.4.2 Cutting parameters estimation

The comparison between simulation and measurement could be used for the on-line estimation of cutting parameters which can vary during the machining and cannot be measured directly, such as the axial and radial depth of cut a_p and a_{lD} (defined by L_1 and L_2). The

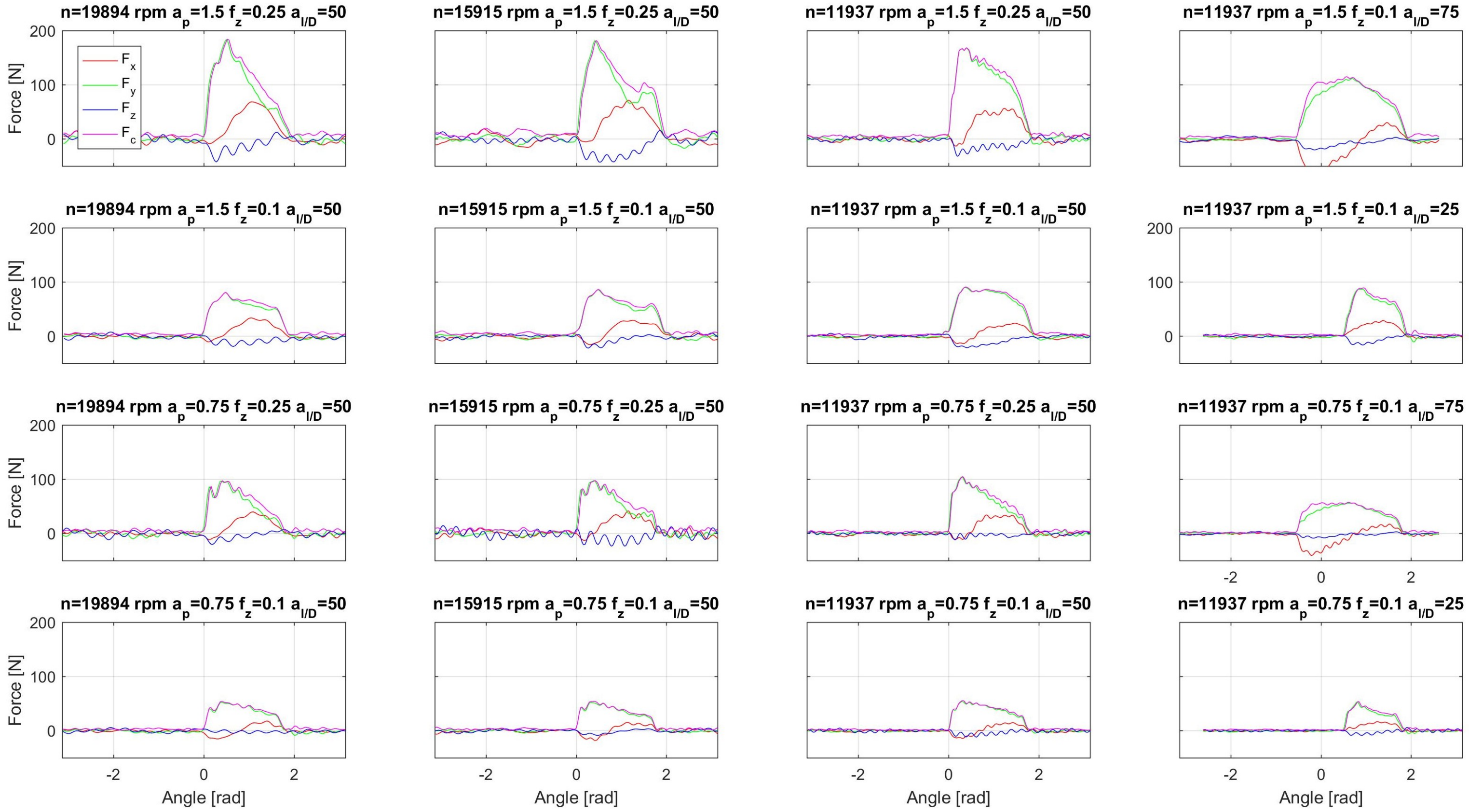


Figure 5.12: Average measured forces summary.

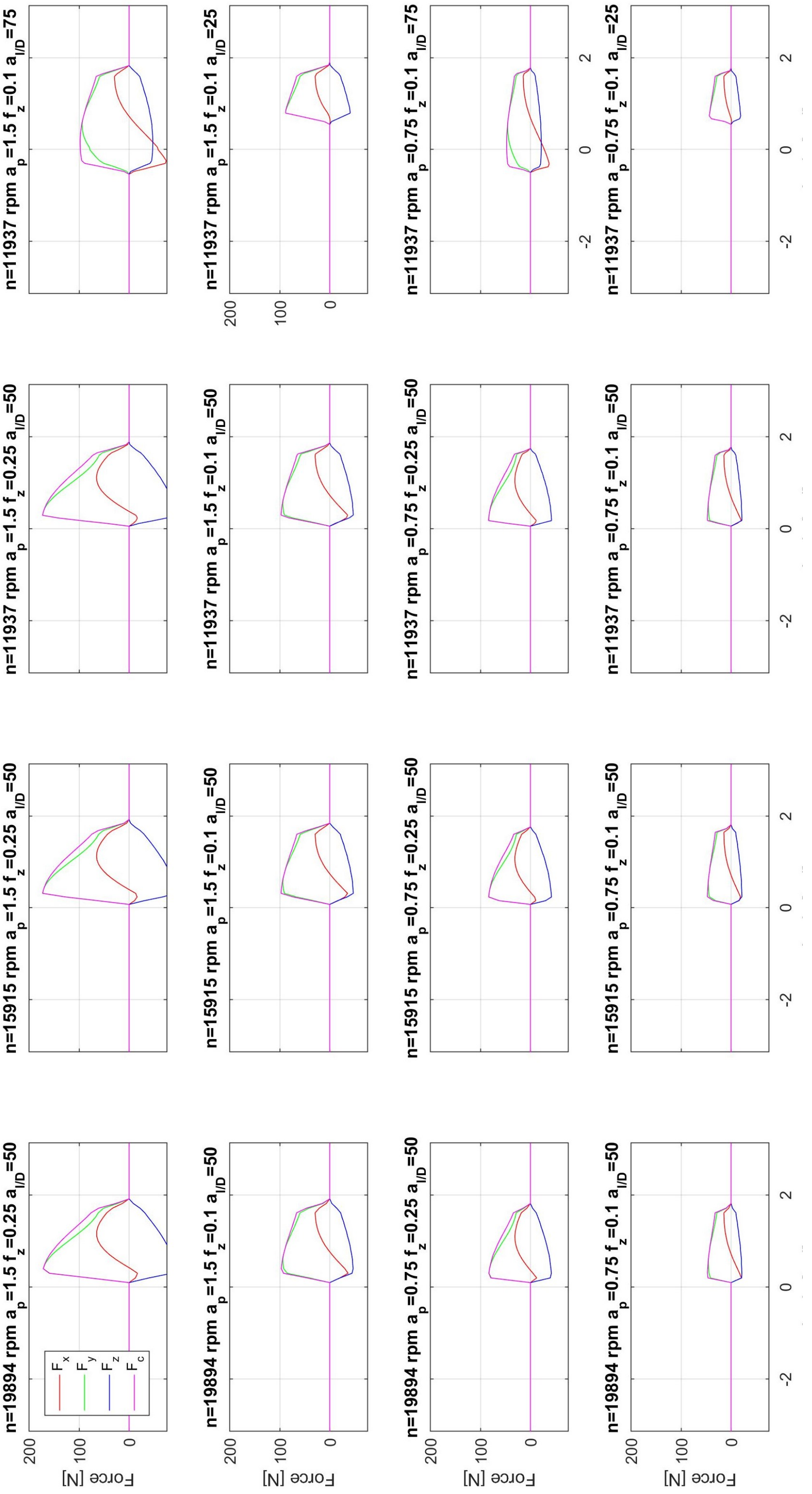


Figure 5.13: Simulated Forces summary.

variation of these parameters is usually due to imperfections in the raw pieces, especially if it has been realized by casting or by forging. Knowledge of these parameters could be useful to actuate advanced control techniques such as adaptive control. In the following pages, a preliminary study on the possibility to estimate the unknown cutting parameters by direct comparison between the measured and the simulated cutting forces is presented.

The process start with the estimation of the average cutting force, this is done using the same algorithm illustrated at page 120 which produces the average forces on one spindle revolution. Then a reference angle is evaluated an the average force profiles are translated in order to center them in the observation window. So, from the average cutting force (evaluated as composition of cutting force in X and Y direction) the active length is evaluated. This is done by identifying the raising and the falling edges of the force signals which represent respectively the ingress and the egress of the mill in the workpiece. Then a series of simulations are launched following a DOE were the unknown cutting parameters are varied in a range according to the limits of the mill. The combinations of L_1 and L_2 are chosen in order to test only combinations which produces contact angles compatible with the estimated one, then the results of the simulations are collimated with the measured signals (if possible) and for each signal $RMSE$ and squared correlation coefficient R^2 are calculated. A combination of parameters is considered optimal if minimizes the $RMSE$ or maximizes the R^2. The algorithm has been applied to the twenty cutting tests carried out in order to evaluate the performance of each parameters in the identification of the correct cutting conditions. In figure 5.14, the performances o estimation are represented for the three parameters and for each test. The blue asterisks represent the nominal parameters, the red markers represents the parameter obtained using the $RMSE$ as estimator while the black markers represents the parameters selected using the R^2. The shape of the marker represent the signal used for the calculation of the parameter, circles for the X component of the cutting force, squares for the Y component, and diamond for the cutting force.

The results of this preliminary tests are promising and shows great possibilities of indirect estimation of cutting parameters through the integration of measurements and simulations.

5.5 Conclusions

An introduction on the concept of digital twin and its application in manufacturing industries opened this chapter, then the importance of force measurements or estimation in milling has been discussed. The issues related to direct cutting force measurements and the solutions proposed to solve this issue has been presented and discussed. Then the focus has been moved to milling process simulation with an introduction to the various methods utilized for milling simulations. Then the implemented methods for cutting tool and milling process simulation has been presented. The design of experiments planned and executed for the tuning and validation of the model has been presented and discussed. The data analysis process has been discussed extensively analyzing the function implemented for different tasks. Finally two examples of possible applications of the proposed data analysis and simulations has been presented and discussed. Although these application

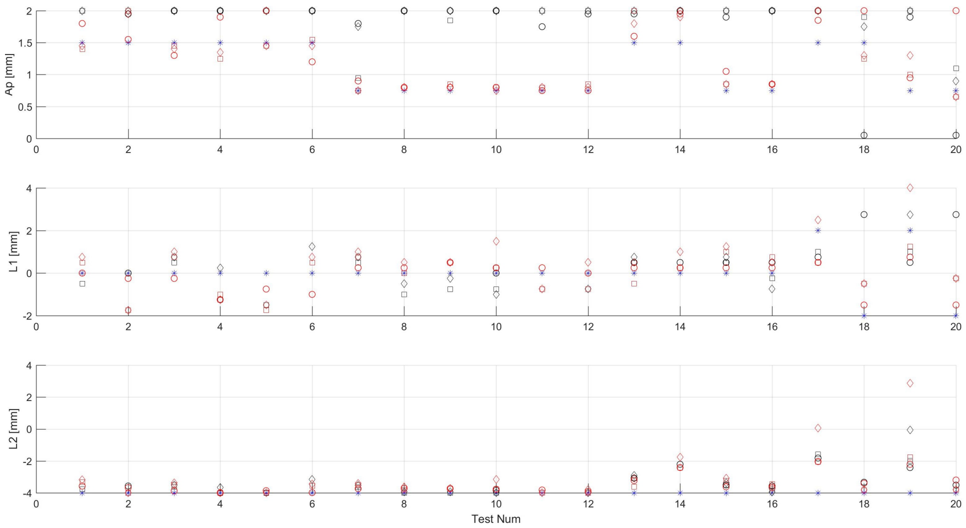


Figure 5.14: Nominal points and estimation for each test.

are still in a preliminary phase, they revealed a good potential for future development.

Conclusions

The increasing demand for efficient and effective machining systems pushes both researchers and machine manufacturers to find and develop innovative and advanced solutions for monitoring and control. This research work was focused on development and application of innovative monitoring and control systems for automated machining centre and in particular for milling machines.

The first chapter was devoted to introduce the concept of CNC machine tools, firstly with an overview on the story of CNC machine tools, then with the description of the main parts composing a numerically controlled machine tool in its mechanical structure and automation system. The structure of the numerical control has been presented and analyzed to identify the different hardware and software parts, their characteristics and their role in the system. Three different architectures of numerical control has been presented discussing main pros and cons of each solution. As well the concept of adaptive control has been introduced and discussed with the description of the classification of adaptive controls for NC machines. In the final part of the chapter the definition of industry 4.0 has been given in order to fix the original concept behind the phenomenon. Then a general description of industry 4.0 concepts and objective has been given. So the focus has been moved to the four industrial revolutions and the related "disruptive technologies" in order to depict the deep relation between invention of new technologies and industries advances.

The main objectives of this chapter were to provide a basic understanding on the path which led to the development of the CNC machine tools as known today and to set ta common nomenclature of the parts composing a CNC machine tool and its automation system as well as to identify and describe the different elements, hardware and software, which composes the numerical control.

The second chapter is devoted to the presentation and discussion of some industrial case studies developed in the realm of advanced monitoring for different applications. The aim of this chapter was to provide a comprehensive overview on the possibilities of digitalization in different industrial applications whit particular attention to the available hardware and software means. The following conclusion can de drawn:

- The development of advanced monitoring systems requires a systemic approach in order to take into account all the aspects of the application and to evaluate the best solution for the application.

- The integration of an advanced monitoring system on a plant, a machine, or a tool, can enable a range of new functions and opportunities.
- In the industrial realm the importance given to the digitalization of plants, machine and products is increasing as this could allow the increase of efficiency and effectiveness of the production.

The third chapter was dedicated to the discussion of the process for the development of a machining process testbed, from the design to the start-up. The process of retrofit planning has been presented with particular focus on the choices in terms of automation system elements and architecture. The requisites which drove the project and the choices has been presented an discussed. Then the actual system has been presented with detailed description of the system architecture both from the hardware and software point of view. As a part of the retrofit project, also the machine commissioning and start-up phases has been presented and describe extensively in order to provide a sort of guide. The final part of the chapter was devoted to the presentation of the identification and modelling phases which involved the machine structure and some components such as axes drives. The main results of these activities are listed below.

- The process for designing a retrofit of an old machine tool in order to update the automation system enabling the digitalization of the machine has been outlined and explained with a real case study.
- The automation architecture design is crucial in machine retrofit planning as in new machine design. Prior to starting the design phase is important to analyze and define the requisites of the system in order to choose the characteristics that better cope whit the requisites.
- The process for machine tool commissioning and start-up has been discussed and described extensively in order to provide a complete overview on the activities carried out in order to make the machine able to work.
- In order to develop advanced monitoring and control algorithms a deep knowledge of machine tool characteristics is needed. An extensive campaign of testing could be useful to study the behaviour of the machine and to translate this behaviour in a set of models which can be used in the following phases.
- When facing the analysis of data collected from machine components such as feed axes or spindle motors, a prior phase of modelling is needed in order to be able to distinguish the contributes relate to the intrinsic behaviour of the components from the contributes related to the processes.

In the fourth chapter the concept of milling machine condition monitoring system was presented. The first part of the chapter includes an introduction on machine tool monitoring system in which some literature contributes were presented in order to give an overview on the context of machine tool monitoring from both the historical and functional point of view. The concepts of sensor-based and sensor-less monitoring system was presented and discussed at the end of the introduction of the chapter. The second part of the fourth chapter was dedicated to the presentation of three examples of machine monitoring systems developed in order to fulfil different requisites in terms of application and functionalities.

- The first proposed system represent an example of a monitoring system developed in order to be integrated into a commercial numerical control in order to add new advanced functionalities. The main results related to this monitoring system are:

  - The realization of an "intelligent" algorithm for the identification of the current status of the machine and the application of the more appropriate analysis algorithm.
  - The implementation of an algorithm for an accurate estimation of the spindle speed in machines which are not equipped with encoder on the spindle.
  - The realization of an algorithm for the evaluation of health status of the axes based on time domain and frequency domain analysis.
  - The implementation of an algorithm for the identification of undesired vibrations during machining operations.

  The developed system and the implemented algorithms has been tested during an experimental campaign conducted at the production facility of a machine tools manufacturer showing good performances.

- The second proposed system was designed in order to be installable on existing machines which are not natively equipped with sensors or monitoring systems. The main results achieved with the development of the system was:

  - The implementation of a modular and flexible monitoring system at a reasonable price which can be implemented on existing machine tools in order to enable advanced functions.
  - The implementation of a set of advanced algorithm for process diagnostic and for harmonic analysis of the signal collected during machining.
  - The realization of an advanced monitoring interface which can help the machine operator to visualize in real-time the machining process indicators and to act promptly in case of issues.
  - The implementation of a cloud platform for data collection and offline data analysis in order to enable the analysis of the data collected during the machining operations and to identify eventual machining issues.

- The third monitoring system was a comprehensive monitoring system which included many functions such as on-demand local data logging, cloud based events logging, and cloud based machining data logging for process monitoring. The system was completely integrated with the machine numerical control and automation system and was able to read high speed data directly from the machine drives. The system constitutes a base for the development of advanced process control systems and for the implementation of advanced control strategies.

The fifth chapter was dedicated to the development of a milling process digital twin. In the first part of the chapter a description of the concept of digital twin and its characteristics was presented together with some application examples from literature. Then the importance of force measurement in machining monitoring has been introduced an discussed. So the direct measurement of cutting forces by means of a platform dynamometer has been discussed with particular focus to the issues related to the interaction between measurement system and machines structure vibrations. The last parts of the chapter is dedicated to the implementation of a milling simulation. The main results are listed below:

- A simple modelling method for cutting tools discretization has been implemented in Matlab. The cutting edge has been modelled as a group of segments in order to reduce the computational load with a low penalization of accuracy.
- A simple milling process has been implemented. The simulation is based on the geometric evaluation of the intersection between the segments which describes the cutting edges and the volume which represent the workpiece.
- A milling test DOE has been developed and executed in order to collect a series of tests conducted with different milling conditions to be used for model validation.
- A set of algorithms for the analysis of the data collected during machining has been developed.
- A method for the estimation of cutting force coefficient estimation has been developed and tested under different conditions.
- Two preliminary studies on the applications of the simulation in conjunction with measurement has been proposed.

Finally, summarizing, this work presented a method for the development of advanced monitoring system and for their implementation in industry in different context and with different objectives. A framework for planning and realizing a machine tool retrofit was also proposed to guide who has to add digital function to an existing machine tool. An example of machining process digital twin, developed in order to made it executable in reltime, has been presented together with two possible applications.

Future developments of this work, will include the development of more advanced and innovative algorithms for condition monitoring of machining processes also extending the adoption of digital twins and artificial intelligence. In the near future, also sensor-less monitoring will be studied and implemented on the machining test bed, analyizing and implementing innovative algorithms for signal filtering which will allow the reconstruction of cutting force signals with a pretty high bandwidth starting from the feed axes torque signals. The main aim for the future developments of this work will be the development of a comprehensive and integrated intelligent machining system which has to be able to self-adapt to the working conditions in order to optimize the process and to prevent eventual issues, increasing the overall efficiency and effectiveness of the system.

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