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FROM AUTOMATED TO AN AUTONOMOUS MACHINE TOOL. APPLICATION TO THE MILLING MACHINE CASE

Gabriel Frumuşanu[1], Alexandru Epureanu[2]

[1,2]"Dunărea de Jos" University of Galaţi, Department of Manufacturing Engineering
Domnească Street 111, 800201 – Galaţi, Romania

Corresponding author: Gabriel Frumuşanu, gabriel.frumusanu@ugal.ro

Abstract: Nowadays, CNC machine tools can automatically perform the physical process according to a program. Although this activity can be assisted by CAM systems, the final decision concerning the values of the programmed variables belongs to the programmer, according to its knowledge and experience. At the same time, other decisions regarding, e.g., the adjustment of the cutting regime, the reaction to perturbations occurrence, the detection of possible malfunctioning of the manufacturing system, and the monitoring of the potential dimensional deviations are the tasks of the machine operator. This paper presents the concept of an autonomous machine tool, seen as a step ahead in machine tools. Such a machine tool, beyond the physical process automation, works without previous programming and makes all the previously mentioned decisions. The concept is illustrated by an application in the case of the milling machine and validated by using a dedicated concept demonstrator.

Key words: Autonomous machine tool, Manufacturing process control, Holistic monitoring, Supervised learning, Automated decision process.

1. INTRODUCTION

Current Industry 4.0-related research initiatives are primarily focusing on the investigation of the integration of smart systems in industry because this is considered one of the main opportunities to enhance the performance and/or decrease the costs of both larger corporations and small and medium-sized enterprises [1].
These initiatives lead to an urgent need to advance current manufacturing systems to a high level of intelligence and autonomy. It is predicted that current CNC machine tools are not intelligent and autonomous enough to support the smart manufacturing systems envisioned by the aforementioned initiatives [2].
Closely related to Industry 4.0, the concept of Cyber-Physical System (CPS) describes the comprehensive integration of physical entities and operations with digital processing and virtual representations. Compared to conventional hardware and software combining systems, the innovative aspect of CPS is that reciprocal feedback loops between the cyber and physical spheres enable condition-based (semi)-autonomous monitoring and control of processes [3]. The basis for this systematic approach is extensive equipping of embedded systems with sensors and actuators as well as the provision of digital infrastructure, algorithms, and data processing capacities [4].
The future of manufacturing systems is to become more autonomous. Autonomy in manufacturing describes a defined and limited environment within a global organization, which acts independently in terms of decision making and execution to reach an error-resistant steering of the manufacturing cell without direct intervention by a human worker [5].
Autonomous systems are intelligent machines that execute high-level tasks without detailed programming and without human control [6].
An autonomous machine tool should be able to plan and conduct a machining operation based on a digital workpiece model and information on the current machine state. Potential deviations should be identified and controlled automatically during the process. Moreover, an autonomous machine tool should be able to learn from prior machining operations and self-optimize its behavior continuously [7].
As the main component of any manufacturing system, machine tools have evolved from manually operated machines into the current computer numerically controlled (CNC) machine tools. The manufacturing of a given part on the CNC machine tool is made on the basis of a program. Such a program is written in a specific language and consists of instructions regarding all required movements of the machine. The program preparation starts

from a sheet belonging to the operations plan, and this is the task of a person having specific training (the programmer). In the case of modern CNC machines, the programming is assisted by CAM, but even if they dispose of prefabricated modules for diverse manufacturing cycles, the final decision regarding the values of programmed parameters (e.g., the cutting regime) is made by the programmer, according to his knowledge (available information) and experience.
The literature in the domain is full of works (e.g., [8], [9]) dedicated to finding the optimal values for the cutting regime parameters through different methods. They can also mention research aiming to automatically determine the tool path and to generate the afferent program sections in G-code. For sampling, the paper [10] presents a MATLAB application that does this thing for a 3-axis milling machine, starting from the CAD model of the part, while [11] deals with CAD-based automated G-code generation for drilling operations.
In what concerns the control of the machining process ongoing, they are known solutions to adjust the cutting regime depending on the machining allowance geometry – e.g., [12] presents a solution for controlling in real-time the feed speed on a CNC, 5-axis milling machine, without affecting the physical integrity of the machine, by applying the so-called "mobile window" technique.
The avoidance of the negative consequences generated by the occurrence of machine malfunctions is an important problem during CNC machines. Numerous solutions dedicated to both machine operation monitoring and online diagnosing of potential technical problems are available. Thus, [13] suggests a server-type system with open communication platform with unified architecture (OPC-UA) together with an application to predict and monitor the machine capability, based on a Linux CNC platform and integrated in the CNC controller.
Another essential aspect of surface generation by cutting is the evaluation, possibly followed by the compensation of the dimensional errors, which may be caused by a multitude of factors. For example, [7] deals with compensating the errors caused by tool elastic deformation. The compensation is obtained by adequately modifying the tool path or the feed speed, according to the information obtained by the monitoring of a force signal, coming from strain-gauges placed on the spindle support guides, followed by finite-element modeling of the deformations that occur.
The imprecision of the reference information, based on which the machine is controlled during its operation, can generate errors in fulfilling the required technical conditions (such as the limitation of forces, shocks, trepidations, or vibrations). These kinds of errors can be avoided by refining the information coming from the previous execution of similar operations. Thus, [14] proposes to connect the CNC machine tool, through a system of MTConnect type, to a database storing the information obtained by monitoring, on the base of a machine informatics model. The model has the shape of an XML file that describes the logical structure of the machine as critical components and their defining variables.
Starting from the above-presented context, one can notice that, in the present, the main challenge in the machine tools field is to step forward from automation to autonomy. This paper defines the concept of an autonomous machine tool and illustrates it in the case of the milling machine. Section 2 presents some conceptual aspects by comparison between "automated" and "autonomous" attributes, concerning the machine tool. Section 3 describes the architecture of the autonomous machine tool, while Section 4 deals with its operation. Section 5 presents the autonomous milling machine as an illustrative example for the proposed concept. Section 6 is for the conclusion.

2. AUTOMATED VS. AUTONOMOUS MACHINE TOOLS - CONCEPTUAL ASPECTS

The accomplishment of a manufacturing task requires the deployment of two intercorrelated processes: a physical process, involving directly the manufactured object, and taking place through the actual operation of a given machining system, and an intellectual process, meaning knowledge processing.
The physical process has two components:
- Material processing, aiming at the change of the manufactured object shape, according to the task specifications, and
- Process monitoring, aiming the obtaining some information concerning the values of the variables describing the task accomplishment, in data form.

In its turn, the intellectual process also has two components:
- Data processing, aiming at the extraction of knowledge from the collected information, and
- Decision making, aiming at the programming of the physical process based on the extracted knowledge.

Starting from here, a certain machine tool receives the "*Automated*" attribute if it can independently perform the physical process, while the "*Autonomous*" attribute is reached if it has the capacity to independently perform both the physical and intellectual processes. In other words, in principle, the automated machine reduces the need of human contribution for its operation & setting, but, however, it depends on an operator who makes the initial setting and the subsequent adjustment & monitoring. Unlike this, the autonomous machine can work independently, making self-adjustments & self-monitoring, and optimizing the manufacturing process without

any human intervention. However, in our vision, the autonomous machine tool needs a human operator to perform the assigned task - machine coupling, and to validate certain decisions of the machine control system.
Moreover, from Figure 1, one can notice that the autonomous machine tool, operated by a single person, can replace two automated machines and the work of four different operators, in order to accomplish a given manufacturing task.

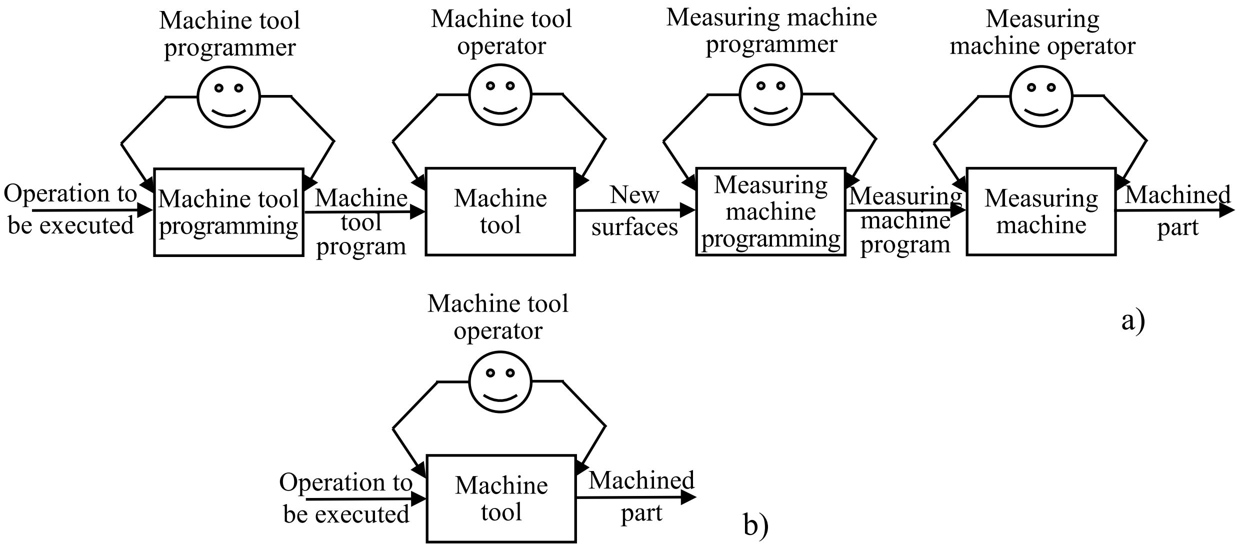

Fig.1. The execution of a manufacturing operation:
a – On automated machine tools, b – On autonomous machine tools

3. ARCHITECTURE OF THE AUTONOMOUS MACHINE TOOL

From an architectural point of view, according to the here presented approach, the autonomous machine tool should be composed of five *ensembles*, namely: Interface, Decision, Execution, Evaluation & Modeling, and Support (Figure 2).

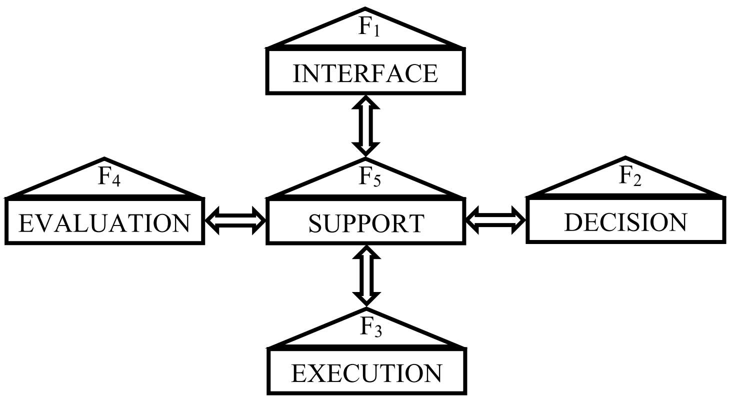

Fig. 2. The conceptual architecture of the autonomous machine tool.

Each ensemble consists of more *systems*, while each system – of more *modules* (Table 1). The functional role of each ensemble, system, or module is described by its function, defined as a relation among some matrix variables. The value of such a variable is described through a data matrix, by data means the values of matrix components. The data on each row corresponds to the values of a given state variable, in the succession of states through which the machine passes during the execution of a certain operation, while the data from a given column represents the values of all state variables in the case of one among the successive states.
The function of a structural element (ensemble/system/module) expresses the causal link between the values of the matrix-variables through which the function is defined, and it is: *i)* expressed as interdependence among matrices or among rows/columns of a certain matrix or among individual data, and *ii)* formalized as an algorithm for data processing.
The INTERFACE ensemble enables the connection between the machine and its environment. At the input, there is the operations plan, while the output consists of the report regarding the accomplishment of the

manufacturing task. Three systems are comprised, namely: *Operation - machine coupling*, *Decision - machine coupling*, and *Observer - machine coupling*, each of them including the operator as one of the components.

- The *Operation - machine coupling* system is composed of the *Part coupling* module, concerning the part positioning on the machine, and the commutation between the machine and part coordinate systems, and the *Task coupling* module, used to load the operations plan (the information describing the task to be accomplished) in a specific form.
- The *Decision - machine coupling* system also includes two modules: *Decision testing* and *Decision validation*. The first one enables the running of a test-cutting process to study the feasibility of the performance-decision (introduced below). More specifically, they test the current availability of the tool intended to be used and the absence of possible collisions when the tool enters the working space. The other module has the role to validate the decision, if the result of the previous sequence is positive, or, if not, to ask for another decision and to start a new testing-validation procedure.
- The *Observer - machine coupling* system is formed by the *Machine observing* module, which means a graphical interface, presenting the values of the variables describing the operation progress, and the *Machine intervention* module, which indicates the requirement for restoring the machine's functional capacity, when necessary.

Table 1. Constructive elements of autonomous machine tool and their roles & functions

Ensembles		**Systems**		**Modules**	
Role	Function	Role	Function	Role	Function
INTERFACE	F_1	Operation - machine coupling	$F_{1.1}$	Part coupling	$F_{1.1-a}$
				Task coupling	$F_{1.1-b}$
		Decision - machine coupling	$F_{1.2}$	Decision testing	$F_{1.2-a}$
				Decision validation	$F_{1.2-b}$
		Observer - machine coupling	$F_{1.3}$	Machine observing	$F_{1.3-a}$
				Machine intervention	$F_{1.3-b}$
DECISION	F_2	Processing decision	$F_{2.1}$	Options identification	$F_{2.1-a}$
				Option selection	$F_{2.1-b}$
		Operating decision	$F_{2.2}$	Machine functioning	$F_{2.2-a}$
				Process ongoing	$F_{2.2-b}$
EXECUTION	F_3	Material processing	$F_{3.1}$	CNC	$F_{3.1-a}$
				Tool vs. part motion	$F_{3.1-b}$
				Process sample extraction	$F_{3.1-c}$
				Trajectory sample extraction	$F_{3.1-d}$
		Processing control	$F_{3.2}$	Processing monitoring	$F_{3.2-a}$
				Command updating	$F_{3.2-b}$
		Operating control	$F_{3.3}$	Functioning monitoring	$F_{3.3-a}$
				Capability restoring	$F_{3.3-b}$
EVALUATION & MODELING	F_4	Evaluation	$F_{4.1}$	Processing evaluation	$F_{4.1-a}$
				Operating evaluation	$F_{4.1-b}$
				Trajectory evaluation	$F_{4.1-c}$
				Model evaluation	$F_{4.1-d}$
				Result evaluation	$F_{4.1-e}$
		Modeling	$F_{4.2}$		
SUPPORT	F_5	Communication display	$F_{5.1}$		
		Tools magazine	$F_{5.2}$		
		Cooling system	$F_{5.3}$		
		Driving system	$F_{5.4}$		
		Bed	$F_{5.4}$		

The DECISION ensemble lies on two systems: the *Processing decision* and the *Operating decision*.

- The *Processing decision* system comprises two modules, namely *Options identification* and *Option selection*. The first one addresses the choosing of all the tools that could be used to accomplish the given task, and of the entry path for each. The other module firstly finds, in the case of each available option, the values of the variables

describing the task accomplishment, and then orders the options according to the descending values of the performance indicators.
- The *Operating decision* system includes the modules *Machine operating*, which establishes, based on statistical data, the reference levels of the machine maintenance indicators, and *Process ongoing*. which similarly sets the reference levels of the process ongoing indicators.
The EXECUTION ensemble consists of three systems, namely: *Material processing*, *Processing control*, and *Operating control*.
- The *Material processing* system has four modules. The *CNC* module is a numerical control system similar to the ones used by current automated machine tools, which controls the cutting process according to a tool path and a cutting regime previously established. The *Tool vs. part motion* module consists of numerically controlled axes (translations and rotations) enabling material removal by cutting, all the axes being provided with transducers (to measure the cutting force and the cutting torque, respectively). The *Process sample extraction* module is a data acquisition system that periodically reads the transducers and records time series of the measured issues (forces and torques) corresponding to the last three successive cycles of the main cutting motion. The *Trajectory sample extraction* module is formed by an electronic comparator, which can be placed in the toolholder, and an application for scanning the machined surface. After each performance of the machining operation, this module delivers the information based on which a variation law of the dimensional errors for the current specimen can be found.
- The *Processing control* system is formed by the *Processing monitoring* module, which is a numerical calculus unit that periodically evaluates the position of tool engagement into the machined part, and by the *Command updating* module, which is a controller that updates the values of cutting regime parameters, depending on the current values of process state variables.
- The *Operating control* system comprises the *Functioning monitoring* module, which is a numerical calculus unit that evaluates the values of the maintenance indicators on the base of the current values of process state variables, and the *Capability restoring* module, which is a controller that compares the found values of the maintenance indicators to their reference, levels for diagnosing the possible capability losses and suggesting measures to be taken, in each such case.
The EVALUATION & MODELING ensemble includes the *Evaluation* system and the *Modeling* system.
- The *Evaluation* system has five modules: *Processing evaluation* and *Operating evaluation* (two numerical calculus units that both evaluate values of some process representative variables based on recorded time series of measured forces and torques), *Trajectory evaluation* (numerical calculus unit that models the current values of the dimensional deviation), *Model evaluation* (numerical calculus unit that evaluates the current values of the variables composing the process numerical model), and *Result evaluation* (numerical calculus unit that processes the collected data and delivers the values composing the report regarding the accomplishment of the manufacturing task).
- The *Modeling* system updates the process model when necessary, based on *Model evaluation* results.
The SUPPORT ensemble is formed by five systems: *Communication display*, *Tools magazine*, *Cooling system*, *Driving system*, and *Bed*.
- The *Communication display* system is formed by a monitor and the afferent graphical equipment necessary to receive, store, and display the values of the state variables corresponding to the current task accomplishment.
- The other four systems are similar to the ones existing on the current machine tools.

4. OPERATION OF THE AUTONOMOUS MACHINE TOOL

The functions that describe the role of machine structural elements, no matter if ensembles, systems or modules, are defined by the following matrix-variables: **OPERATION** (operations plan), **T** (task), $\mathbf{J_f}$ (functional job), $\mathbf{J_p}$ (processing job), $\mathbf{D_p}$ (processing decision), $\mathbf{D_o}$ (machine operating decision), $\mathbf{C_p(k)}$ (processing control at sequence k), $\mathbf{C_o(k)}$ (machine operating control at sequence k), **F(k)** (process sample), **Δ(j)** (trajectory sample), $\mathbf{M(T_s)}$ (process model for T_s tool), $\mathbf{R_p}$ (process evaluation), $\mathbf{R_o}$ (operating evaluation), $\mathbf{R_t}$ (trajectory evaluation), $\mathbf{R_m}$ (model evaluation), and **RESULT** (synthetical result of task accomplishment). The structure of matrix variables depends on the specific machine tool type.
During autonomous machine operating, its structural elements execute a functioning cycle according to the functional diagram presented in Figure 3.
The stages of the functioning cycle are:

- **LOADING**, which is executed by the ensemble INTERFACE, and consists of information & material processing to evaluate the matrix T, based on the data from the OPERATION matrix,

- **DECISION**, which is executed by ensemble DECISION and consists of information processing to evaluate the matrices D_p and D_o, based on the data from T, $M(T_s)$, J_p and J_f,
- **MACHINING**, which is carried out by EXECUTION ensemble, and consists of material & information processing to generate physical surfaces and to evaluate the matrices C_p and C_o by using, for this purpose, the matrices D_p and D_f, and also in periodically extracting process samples F(k) and trajectory samples Δ(j),
- **MEASURED DATA PROCESSING**, which is executed by EVALUATION & MODELING ensemble, and consists of information processing to evaluate the matrices R_p, R_o, R_t, R_m, RESULT by using the data from F(k) and Δ(j) matrices, and
- **DOWNLOADING**, which is executed by the INTERFACE ensemble, and consists of delivering the machined part together with the results of the performed manufacturing task.

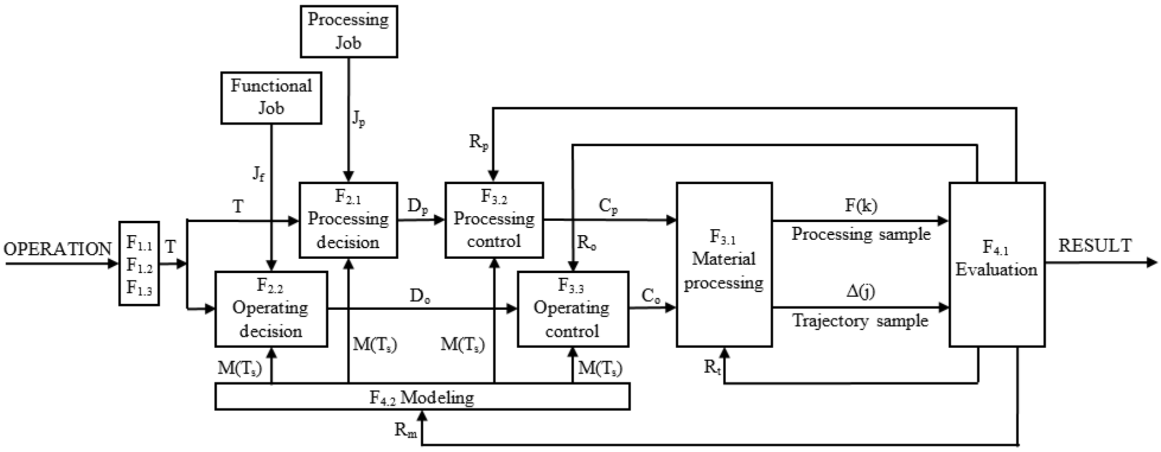

Fig. 3. Functional diagram of the autonomous machine tool

5. ILLUSTRATIVE EXAMPLE – THE AUTONOMOUS MILLING MACHINE

For validating the here-proposed concept of an autonomous machine tool, a concept demonstrator was developed. The validation had the following targets: *i)* To show that the machine tool can fully execute a manufacturing operation after replacing the part-program by the process plan, *ii)* To prove that the optimal regime parameters can be found by online measuring the cutting force and torque, as measure of the machine mechanical solicitation, and *iii)* To simulate the autonomous operating and to evaluate the performance increase thus enabled.

Fig. 4. The hard component of concept demonstrator

The hard component of the demonstrator includes a vertical CNC milling machine (producer Haas, VF-1 type) and a piezoelectric device for measuring forces and moments (producer Kistler, DynaWare 2825 A-03 type), mounted between the machine table and part-fixing device, Figure 4, while the soft component was conceived and implemented through an external computer.

A test specimen (depicted in Figure 5) has been machined to obtain the previously mentioned validation. The used tool was a mill having a diameter of 50 mm, and z = 5 removable teeth of 15 mm height, made from metal carbides. The input for the autonomous operating of the milling machine was the matrix variable OPERATION (Table 2). This comprises the information concerning the task assigned for accomplishment: part material, type of the job and its conditions, profiles (transversal and longitudinal) of the material layer to be removed, roughness of the machined surfaces, maximum dimensional deviations, and performance requirements.
In the addressed case, the transversal profile is defined through the rectangles $AA_1A_2A_3$, $BB_1B_2B_3$, $CC_1C_2C_3$, and $DD_1D_2D_3$ (see Figure 5). The longitudinal profile is composed of two straight segments (AB, CD), and an arc of a circle (BC).

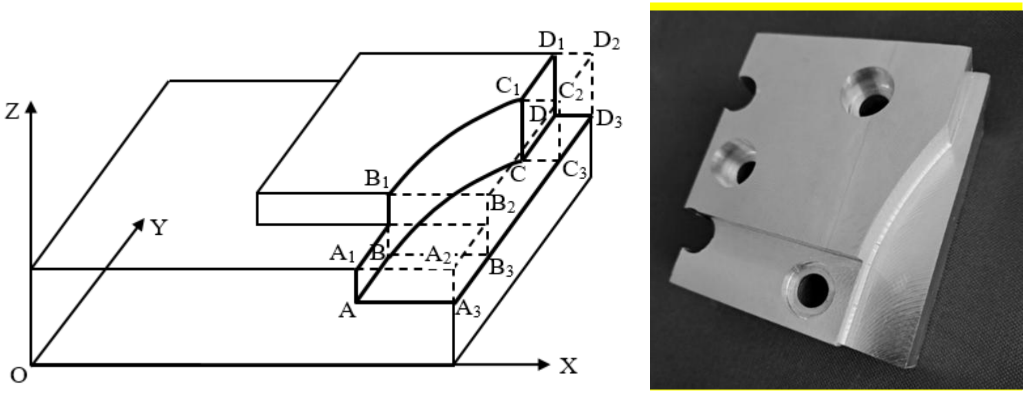

Fig. 5. The test specimen

Table 2. The matrix-variable **OPERATION**

<table>
<tr><td colspan="5">PART: Sample
Operation: Milling</td></tr>
<tr><th>Vector</th><th colspan="3">Component / Value / Zone</th><th>Observations</th></tr>
<tr><td>COMMON DATA</td><td colspan="3">MATERIAL/DAL
REGIME/E1
JOB/F3
A=POINT/70,0,15
B=POINT/70,20,15
C=POINT/80,56.055,15
D=POINT/80,75,15</td><td>Material: Code DAL/Duralumin
Job: Code F3/End milling
Reference zones: A, B, C, D
Operating condition: Code E1/Economical</td></tr>
<tr><td rowspan="3">PROCESSING ALLOWANCE</td><td>A-B Zone</td><td>B-C Zone</td><td>C-D Zone</td><td>Zones for profile definition</td></tr>
<tr><td>POINT/70,0,15
POINT/70,0,20
POINT/85,0,20
POINT/85,0,15</td><td>POINT/70,20,15
POINT/70,20,25
POINT/85,20,25
POINT/85,20,15</td><td>POINT/80,36.055,15
POINT/80,36.055,25
POINT/85,36.055,25
POINT/85,36.055,15</td><td>Transversal profile</td></tr>
<tr><td>LINE/A,B</td><td>CIRCLE/B,C,R70</td><td>LINE/C,D</td><td>Longitudinal profile</td></tr>
<tr><td rowspan="5">REQUIREMENTS</td><td>RZ/3.2</td><td>RZ/6.3</td><td>RZ/3.2</td><td rowspan="5">Part conditionalities</td></tr>
<tr><td>DEV/0.02</td><td>DEV/0.04</td><td>DEV/0.02</td></tr>
<tr><td colspan="3">COST/minimum</td></tr>
<tr><td colspan="3">TIME/2</td></tr>
<tr><td colspan="3">ENERGY/1.2</td></tr>
</table>

The concept validation was then accomplished using the demonstrator, as follows.
- The test specimen was machined after a traditionally written part program, at first. The cutting regime was set according to the recommendations delivered by the CNC equipment, namely the tool rotation speed S = 3000 rot/min and the feed speed F = 1500 mm/min; these values were to be applied to all three zones of the machined part (AB, BC, and CD).

The cutting force components and the cutting torque were measured during the milling process. As it can be seen in Fig. 6, where the cutting torque variation is depicted for sampling, they show major variations during the process, depending on the modifications of the detached layer geometry. Hereby, there is plenty of room for process optimization.

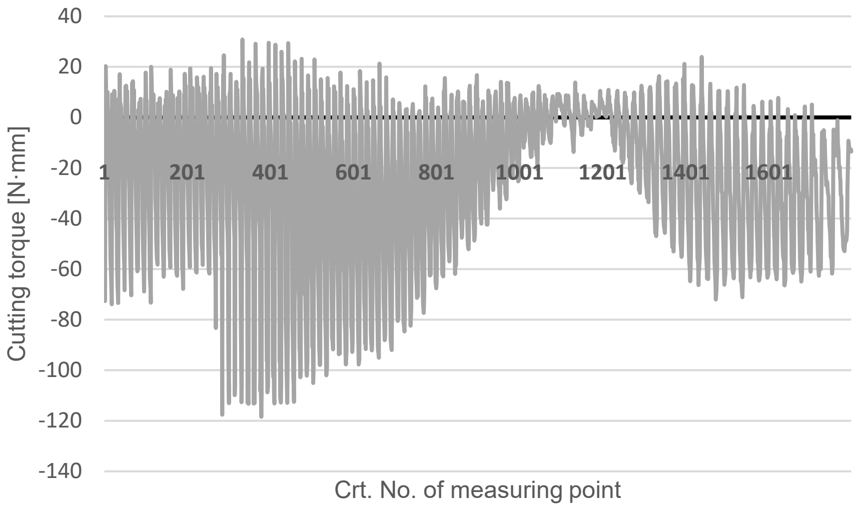

Fig. 6. The cutting torque variation

- To simulate the autonomous functioning of the milling machine, at first, **F(k)** process samples were extracted during the process and stored, such as a sample being presented in Table 3 and Figure 6. The dimensional deviation was also monitored; the results in the case of a trajectory sample **Δ(j)** are presented in Table 4.
- The cutting regime optimization was then performed offline, according to the proposed functional diagram and by using an original algorithm developed for this purpose. Different cutting regimes resulted thus for each segment of the generated profile: S_1 = 2461 rot/min and F_1 = 3371 mm/min (AB), S_2 = 1935 rot/min and F_2 = 2650 mm/min (BC), S_3 = 2500 rot/min and F_3 = 1938 mm/min (CD). The corrections to be applied to the tool path were also found.
- The evaluation of the manufacturing performance and of the machine operating indicators was, finally, offline accomplished. The obtained results are sampled in the case of a process sample from the AB zone, meaning the **RESULT** matrix variable presented in Table 5. As can be noticed, in the case of the addressed process sample, the result of machine tool autonomous operating is a direct cost reduction, Δcost, of 16%, in addition to the diminishing of indirect costs related to programming and measuring.

Table 3. The matrix variable **F(k)** at the *Milling* operation

Vector	Component	Notation	M.U.	Source	Values
TIME SERIES	Sample crt. no.	k	-	$F_{3.1\text{-}b}$ Transducers Specific calculus relations	11
	Measuring point	P(i)	mm		{[75, 8.71, -2.5] … [75, 11.32, -2.5]}
	Distance vs. origin	d(i)	mm		{75.5 … 75.85}
	Force	Fx(i)	N		{-448 … 191}
		Fy(i)	N		{1358 … 2078}
		Fz(i)	N		{-85 … 1}
		$F_{smt}(i)$	N		{832 … 1694}
		dF(i)	kN/s		{380 … 2317}
	Torque	T(i)	N·m		{-128.3 … 56.7}
		$T_{smt}(i)$	N·m		{-118.7 … 55.2}
		dM(i)	N·m		{-15.8 … 18.4}

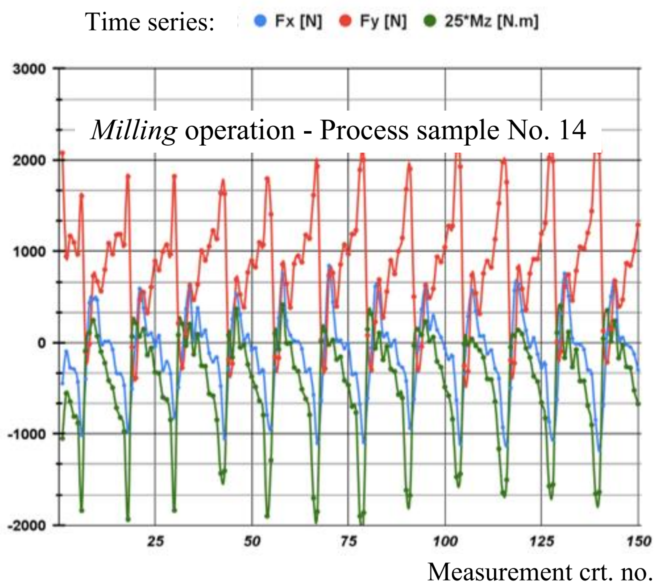

Fig. 6. The cutting force & torque variation during a given process sample

Table 4. The matrix variable **Δ(j)** at the *Milling* operation

Vector	**Component**	**Notation**	**M.U.**	**Source**	**Values**
TIME SERIES	Coordinates of measuring point	X(i)	mm	Measurement	{75 ...}
		Y(i)	mm		{8.71 ...}
		Z(i)	mm		{-2.5 ...}
	Deviation	δ(i)	mm	$F_{3.1\text{-}d}$	{0.02 …}
	Position	L(i)	mm		{75.5 ...}

Table 5. The **RESULT** matrix variable at the *Milling* operation

Vector	**Component**	**Notation**	**M.U.**	**Source**	**Sampling excerpt / A-B Zone**
COMMAND	Tool position	Process seq L	[mm]	$F_{4.1}$	1,5
	Tool	T_s	Code		T_3
	Rotation speed	S	[rot/min]		2461
	Feed speed	F	[mm/min]		3371
PROCESS	Thickness	a	[mm]		0.12
	Width	b	[mm]		5
	Length	c	[mm]		29
	Deepness	d	[mm]		15
	Entering angle	alfa	rad		-1.57
	Exit angle	beta	rad		-0,41
	Front angle	gama	rad		-1.45
	Maximum force	F_{max}	N		1680
	Maximum torque	T_{max}	N·m		75.9
	Rotation pattern	$PATTERN_r$			0.049/1.02/0.343
	Shock	SHOCK	kN/s		1366
	Trepidation	TREPID	N·m		40.5
CONSUMPTION	Tool cons.	C_{tool}	[%/mm]		1.09·e-6
	Machine cons.	$C_{machine}$	[%/mm]		1.04·e-10
	Energy cons.	C_{energy}	[Kwh/mm]		3.03·e-5
	Time cons.	C_{time}	[min/mm]		2.97·e-4
PERFORMANCE	Cost	C	[MU/mm]		0.0116
	Loss	Δcost	[%]		19.6
	Time	T	[min/mm]		18·e-5
	Energy	E	[kWh/mm]		9.4·e-6

6. CONCLUSIONS

In present, four workstations, involving two programmers and two operators, are needed to perform a machining operation. Instead of them, a single autonomous machine tool could be used, which means, obviously, an outstanding increase in efficiency. The autonomous machine can work independently, by self-programming, self-monitoring & optimization of the manufacturing process, and self-modelling, without any human intervention. Hereby, instead of specifying how to accomplish the machining operation, the operator has to only input the expected results.

This paper conceptually presents an autonomous machine tool that works without being previously programmed and makes all the required decisions. According to the proposed concept, the working cycle includes five stages: *Loading*, *Decision making*, *Machining*, *Measured data processing*, and *Downloading*, which are performed by the five ensembles composing the autonomous machine tool architecture, namely: *Interface*, *Decision*, *Execution*, *Evaluation & Modelling*, and *Support*. The autonomous functioning requires modeling the machine tool and continuously updating this model by machine learning. In other words, the autonomous machine tool is supposed to learn from its own experience.

It was proven here that the machine tool modelling can be based on measuring the cutting force & torque, as the machining performance indicators are directly related to the mechanical loading level. Based on this, an algorithm to make the decisions during the ongoing process was developed.

The autonomous operating concept was validated in the milling machine case through a dedicated demonstrator. In this case study, the performance improvement consisted of reducing the direct machining cost by about 20%.

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