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MACHINE TOOLS CONTROL SYSTEM – THE NEW GENERATION –

Alexandru EPUREANU[1], Gabriel FRUMUŞANU[2*], Ionuţ CONSTANTIN[3], Florin Bogdan MARIN[4]

1) Prof., PhD, Department of Manufacturing, Robotics and Welding Engineering, "Dunărea de Jos" University of Galaţi, Romania
2) Prof., PhD, Department of Manufacturing, Robotics and Welding Engineering, "Dunărea de Jos" University of Galaţi, Romania
3) Assist. Prof., Department of Manufacturing, Robotics and Welding Engineering, "Dunărea de Jos" University of Galaţi, Romania
4) PhD., "Dunărea de Jos" University of Galaţi, Romania

Abstract: *In this conceptual paper, an analysis concerning the premises which carry on the evolution of nowadays machining systems, the challenges to be faced in the years to come and the support for this evolution is presented. As it is already obvious, the main changes will refer to machine-tools control system, the current one evolving towards a new optimal holistic character. A new concept for machine-tools control, a new approach concerning the numerical control and a new methodology of operational control are exposed. A new strategy for dimensional control was developed.*

Key words: *machine tool control system, optimal holistic, holarchic, adaptive/intelligent, predictive, interactive.*

1. INTRODUCTION

Manufacturing enterprises currently have to face growing and sometimes new demands for increased product quality, greater product variability, shorter product life-cycles, reduced costs, and global competition [1, 2]. In the field of machining, manufacturers are turning increasingly more often to automation as an effective way to meet these demands. As consequence, the machine tools control systems are continuously and rapidly evolving. They are enabling higher performances concerning machining process productivity and product quality (precision, surface quality). For example, because chatter is a specific issue of the cutting process, leading either to cutting regime (productivity) limitation, to avoid its occurrence, or to worked surface damages (if it still appears), new, evolved systems were developed for chatter control [3–7]. Other researches were completed by developing systems with a better control of the worked piece dimensional errors [e.g. 8–13]. But the main drawback of nowadays control systems, generally speaking, is the lack of an integrated approach of all requirements that should be satisfied. This kind of approach could be put in practice only by starting from a new philosophy to ground a new generation of control systems.

This paper is presenting the basic features of the optimal holistic control system concept, as it was developed inside ITCM Research Center from "Dunărea de Jos" University of Galaţi, Romania. In the second section, the premises of the control system evolution are enounced, together to the next challenge to be faced and the new paradigm which arises. In the third section, the support for the new generation of control systems development is analyzed. The holonic manufacturing systems conceptual particularities and their conceiving stages are defined in the fourth section. In the fifth section it is presented one among the most significant results already obtained - the new concept for machine tools control. A final section is dedicated to conclusion.

* Corresponding author: "Dunărea de Jos" University, Manufacturing Science & Engineering Department, Domnească str. 111, 800201 – Galaţi, Romania, *http://www.tcm.ugal.ro*
Tel.: 0336/130208; Fax: 0336/130283
E-mail addresses: *gabriel.frumusanu@ugal.ro* (G. Frumuşanu), *ionut.constantin@ugal.ro* (I. Constantin)

2. PREMISES AND DIRECTIONS OF THE CONTROL SYSTEMS EVOLUTION

Major changes emerged on the market have determined changes concerning material, data, knowledge processing and orders, as described bellow.

2.1. Materials processing evolution

At conceptual level, nowadays, manufacturing systems can be classified in three categories: universal, dedicated and flexible (Fig. 1).

The universal manufacturing systems (UMS) are composed from universal machine tools, without automation and designed for an irregular production. Their economic efficiency level is low, but they are still used today because representing an investment yet not recovered.

By dedicated systems (DMS) we mean the rigid manufacturing systems, made from machines with high productivity but poor adaptability to market demands, characterized by a rigid automation. They are used in present only for simple parts mass production.

The flexible manufacturing system (FMS) consists in a basic numerical controlled machine tool, with flexible automation, together to various modules to be added for completing its hardware architecture. FMS is dedicated to a diversified production and it has a low productivity level (relative to DMS), but a high degree of adaptability. Same time, the existence of a large number of modules combined to the fact that, at a given moment, most among them are not used means a capital waste and a lowered economical efficiency.

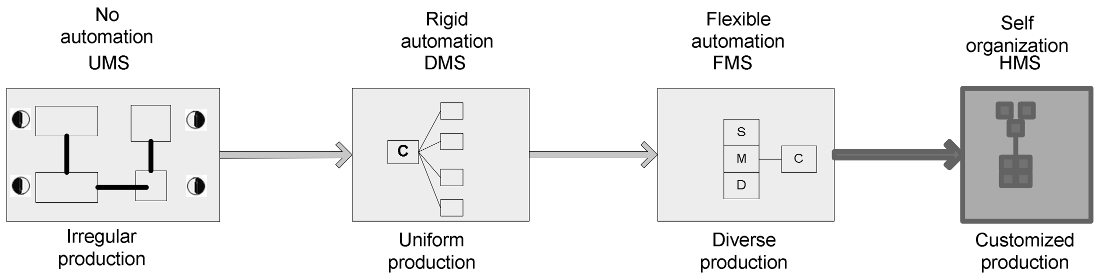

Fig. 1. Materials processing.

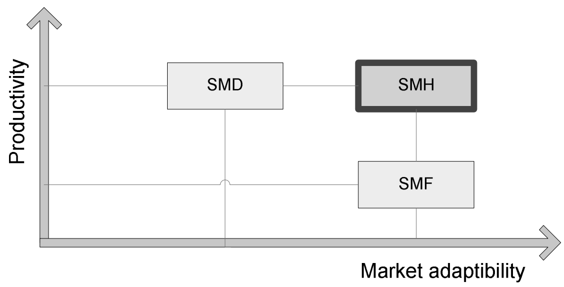

Fig. 2. Manufacturing systems productivity versus market adaptability.

We consider that the future will own to the holonic manufacturing system (HMS), characterized by a self-organizing control system and dedicated to a highly customized but efficient production. HMS positioning relative to DMS and FMS is illustrated in Fig. 2.

2.2. Data processing

An important amount of data needs to be processed during the entire economic cycle, starting from price calculation and continuing with offers building, followed by product design and manufacturing and, finally, by product marketing (see Fig. 3).

All along this economic circuit, CAD / CAM / CAB software are used for data processing. The actual trend is to use a software product which integrates, as much as possible, the whole data flux. The last challenge concerning data processing is the use of a CIB (Computer Integrated Business) software.

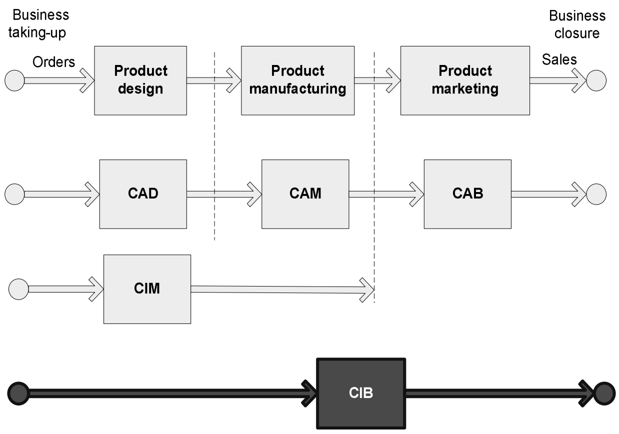

Fig. 3. Data processing.

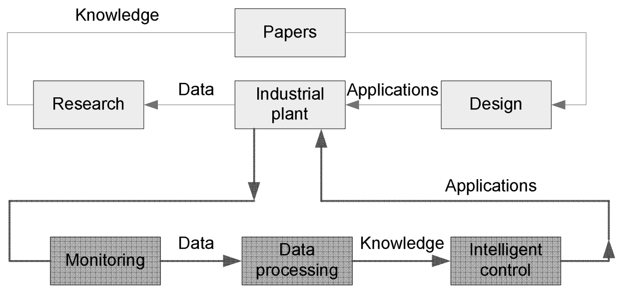

Fig. 4. Knowledge processing.

2.3. Knowledge processing

In the past, the industrial activity knowledge circuit was starting with data acquisition, from experimentally study, followed by research activities, bringing out new knowledge. The new knowledge vehicle to carry it back to the manufacturing level was the scientific papers. The time needed by knowledge to complete this circuit was too long, leading to a low efficiency. The actual trend is to integrate in the circuit from above the machine tool control system (Fig. 4), meaning that the data outputted from machining system monitoring are directly processed to obtain new knowledge, for process intelligent control.

The new approach has two important advantages:

- *Higher speed of the processing loop*, relative to the speed from the traditional case.
- *Knowledge higher accuracy*, because data source is right the manufacturing system where the new knowledge will be further used (instead of an experimental machine), and also because data are outputted from machine current state and a real process (replacing a simulation of the real functioning).

2.4. The next challenge & the next paradigm

The essential evolutions defining the challenge to be faced by the future manufacturing system, provided with the new control system are expected to be:

- *Economy globalization*, meaning an increased competition.
- *Requirements customization*, leading to products customization.
- *Capital boosting*, because of higher expectations concerning investments efficiency.
- *Industrial & commercial structures partition*: small and medium companies groups instead of big facto-

ries, commercial centers instead of supermarkets, selling agents instead of selling units.

The key-ideas of the new paradigm should be:

1. *Reconfigurable* systems, instead of *flexible* ones.
2. *Available* capital, instead of *stagnating* capital (capital waste).
3. *Specific* knowledge, *rapidly synthesized and applied*, instead of *general* knowledge, hardly to be particularized.
4. Informational input should be the expected ***result***, instead of the ***way*** to obtain it.
5. *Self-organization*, instead of *automation*.
6. *Intelligent distributed* control, instead of following a *centralized* control *program*.
7. *Fully monitoring* instead of *permanent surveillance*.

3. THE SUPPORT OF THE CHANGE

The new generation of control systems development and implementation would not be possible without a consistent support from more directions, as we will mention below.

3.1. The scientific support

Science evolution during recent years in combination with computers and soft progress created a powerful set of tools staying at the background of the intelligent and sophisticated control systems, required by the self organized manufacturing systems. We might classify these tools in three main categories:

A. *Modeling techniques*, based on:

- parametric analytical models;
- recursive models;
- harmonic models;
- neuronal models;
- numerical models;
- decisional tree models.

B. *Investigation algorithms*, illustrated for example by:

- Genetic algorithms;
- Ant colony algorithm;
- Particle swarm algorithm;
- Simulated annealing algorithm;
- Active interrogation.

C. *Knowledge processing techniques*, indispensable for extracting the searched output from huge amounts of available information; we may mention the following:

- Rough set technique;
- Case based reasoning;
- K-nearest neighbor;
- Voronoi diagrams;
- Support vector machine;
- Data mining.

3.2. The technological support

The new paradigm should be based on the following support technologies:

A. *Fully controlled driving systems* that are able to provide high quality kinematical outputs, no matter if talking about speed variation law and magnitude, precision concerning the quantity of motion delivered to the machining system kinematical chains or speed of reacting to the control system commands.

B. *Sensors & sensors fusion* – the deep control of all manufacturing system parts requires a large number of sensors giving information about position, displacement, speed, acceleration, force, temperature, pressure. The information delivered by them must be characterized by high precision and also must be very quickly processed. Processing speed can be improved by sensors fusion. Data derived from disparate sources are combined such that the resulting information is more accurate, more complete, or more dependable than it would be possible when these sources were used individually.

C. *Embedded systems* – as in the case of many equipments working in other fields, the new machining system will be provided with an embedded control system, including modules dedicated to perform the different attributions concerning the machining process: stability control, dimensional precision control, economical efficiency control, and ecological impact control.

3.3. The political support

The UE frame programs are already mentioning the strategic targets to be reached during the next years, with application to the manufacturing systems development. We may cite among these documents, the following:

- **NSF -Visionary Manufacturing Challenges for 2020**

Grand Challenge 3: Conversion of Information to Knowledge

"Grand Challenge 3 is to *"instantaneously" transform information from a vast array of diverse sources into useful knowledge and effective decisions*."

- **Manufuture Platform – a Vision for 2020**

"*A new knowledge-based economy is emerging, with profound effects on markets, society and technology. This calls for a new approach to manufacturing, based on high value addition and the incorporation of knowledge content at all levels The paradigm was described in "Manufuture – a Vision for 2020", and is the basis of this SRA.*"

- **FP7 - ICT Work Program 2007-2013**

Challenge 2: Cognitive Systems, Interaction, Robotics

"*In order to meet this challenge, a mix of innovative scientific theory and technology is needed, based on natural and artificial cognition, in conjunction with new systems design and engineering principles and implementations for machines, robots and other devices which are robust and versatile enough to deal with the real world and to behave in a user-friendly and intuitive way with people in everyday situations.*"

4. HOLONIC MANUFACTURING SYSTEMS CONCEPTUAL DEVELOPMENT

The holonic manufacturing systems, regarded as the future manufacturing systems, are characterized by the following main conceptual particularities, distinguishing them from the current manufacturing systems:

A. The system structural elements are:
- autonomous;
- reconfigurable;
- cooperative;
- intelligent.

B. Their system control is:
- holarhic (occasionally cooperation) and not hierarchic (permanent subordination);
- adaptive/intelligent;
- optimal holistic;
- predictive;
- interactive with the human operator.

C. Their strategic target includes:
- mass-customization;
- integrated economic circuit;
- self control based on self cognition.

In conjunction to the world-wide progresses concerning the holonic manufacturing system concept and its practical implementation, the researches from ITCM Research Center from "Dunărea de Jos" University of Galaţi, Romania were performed in two stages, as below presented:

- **Preparation stage**: *Conception of a new embedded systems class – manufacturing embedded class*

- *Operating control*: virtual operating, real operating, target, tool path, planning, consumptions, off-line exploring control of planning-simulating type (within CEEX 24 contract).

- *Precision control*: identification, prediction, compensation, assessment, "In cycle" adaptive, intelligent and predictive control (ID 653 contract).

- *Stability control*: stochastic, chaotic, periodic, on-line predictive – restrictive control (CEEX 22, ID 794 contract).

- *Economical efficiency control*: capital, materials, energy, time, on-line, optimal, holistic and adaptive control (CNCSIS 520 contract).

- **Developing stage**: *Holonic manufacturing systems conceiving*

- *Reconfigurable architecture conceiving*: modules typology, modules structure, degrees of freedom, geometry (CEEX 22 contract).

- *Holonic structure conceiving*: holons typology. generic holons structuring, internal control algorithm (CNCSIS 520 contract).

- *Operating system developing*: informational flux, internal regulations, communication protocols, human – machine interface.

5. THE NEW CONCEPT FOR MACHINE TOOLS CONTROL – THE ATTRIBUTIVE HOLARCHIC CONTROL

5.1. The attributive holarchic control levels

The holistic–integrated approach concerning the control of the couple machine – process supposes to conceive a control architecture that should be able to optimal – adaptive manage all the aspects regarding both the cutting process performance and the machining system economical efficiency & ecological impact.

The conceptual flowchart illustrating control levels and information circuit inside the new kind of control system is presented in Fig. 5.

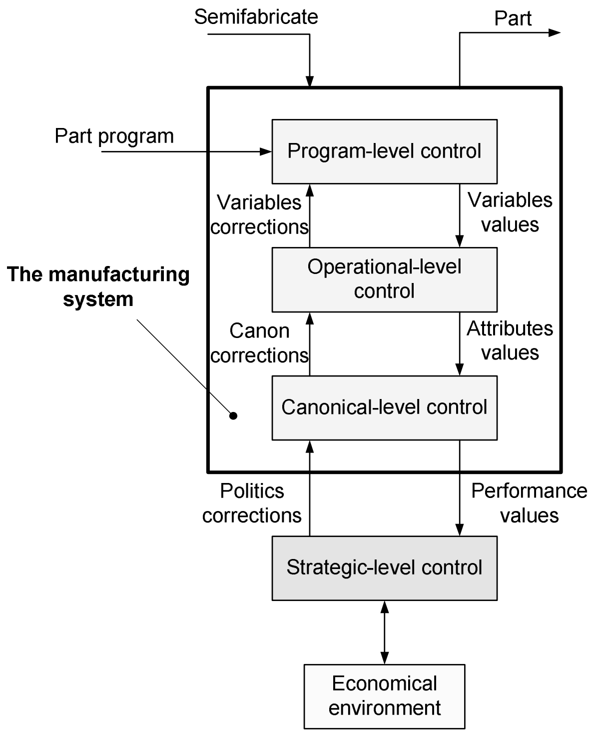

Fig. 5. The holistic-integrated control system.

Program-level control means system management in order to perform semi-finished product transformation into part, through specific technological operations.

The achievement of all requirements imposed to the part, from technological point of view, by only delivering at system input a correct part program, would be ideal. In fact, this never happens, the machined part being not at all identical to the programmed one, because of shape and dimensional deviations, and also because of errors concerning the relative position between different surfaces. Same time, the initially set cutting regime could be inadequate, being either too low (which affects the process productivity), or too intense (leading to system stability loss and further, to cutting tool damaging and poor quality of the machined surface). Thus, the necessity of applying corrections to the initial part program, aiming to control the machining process towards its target, but according to the machining system real situation, is obvious. The setting up of appropriate corrections is the duty of the *operational-level control*, on the base of information received from the machining system – cutting process couple.

Canonic-level control consists in commanding the operational-level control system according to a system of preset rules ("canon"). These rules are referring to aspects concerning the priority directions regarding the machining precision & productivity, the economical efficiency, and the ecological impact.

Strategic-level control is performed by the management system. As input it has the changes which affect the economical environment, together to the current values of the performance indicators. At the output, we find politics adjustments, necessary to realize manufacturing system adaptation to the economical environment realities.

5.2. Program-level control

The machining systems provided with the new generation of control systems will be, most likely, reconfigurable. The hardware reconfiguration key idea is machine tool structuring in mechatronical, universal modules. Each module covers one among the machine tool active degrees of freedom; the junctions between these modules give its passive degrees of freedom.

At this level, the principle of *reactive planning* was developed in order to eliminate the necessity of numerical control reconfigurability, when machine tool hardware architecture has to suffer modifications. According to this principle, the part program is a software product which enables to define, *with high resolution*, the working cycle, based on data regarding the machining task and the machining system features.

Series of system variables values are delivered to a logical control unit, which further adequately allocates them to the machine tool mechatronical modules (see also Fig. 7). This is the program-level control, and if the initial data from software product would not suffer modifications, then the output results will be exactly the programmed ones. This is not happening, because of the above mentioned reasons, and that is why a feed back control loop is required, to enable system adapting to the new conditions. This action consists in *rescheduling the machine tool working cycle*, immediately after at least one among the initial data suffered a modification.

5.3. Operational-level control

The holistic-integrated control system architecture is depicted in Fig. 7, where the main structural elements of both program-level control and operational-level control are highlighted. The program-level control system has at input a parametrical model of the machining system – cutting process couple. This model is built as a software specific product, and it is controlled through a set of parameters, having implicit initial values. The values are then adjusted by the operational-level control system, during worked piece machining, if the current process state requires this action. For this reason, the programmer can use only approximated values for parameters.

The output of machining system – cutting process couple software parametric model is represented by a control variables trajectory – more specific, a list including the operating point position along tool path, referred to each among the working axis. The list is communicated to the logical control unit, which plays the role of sequencing the working cycle, by sending, at well specified moments, the command values for displacements after each among machine tool axis.

The machining process – cutting process physical input is represented by the semi-finished product to be transformed into finite part. The program-level control system is monitored by the operational-level control system (Fig. 6), which builds a database that will include information delivered by machine tool sensors.

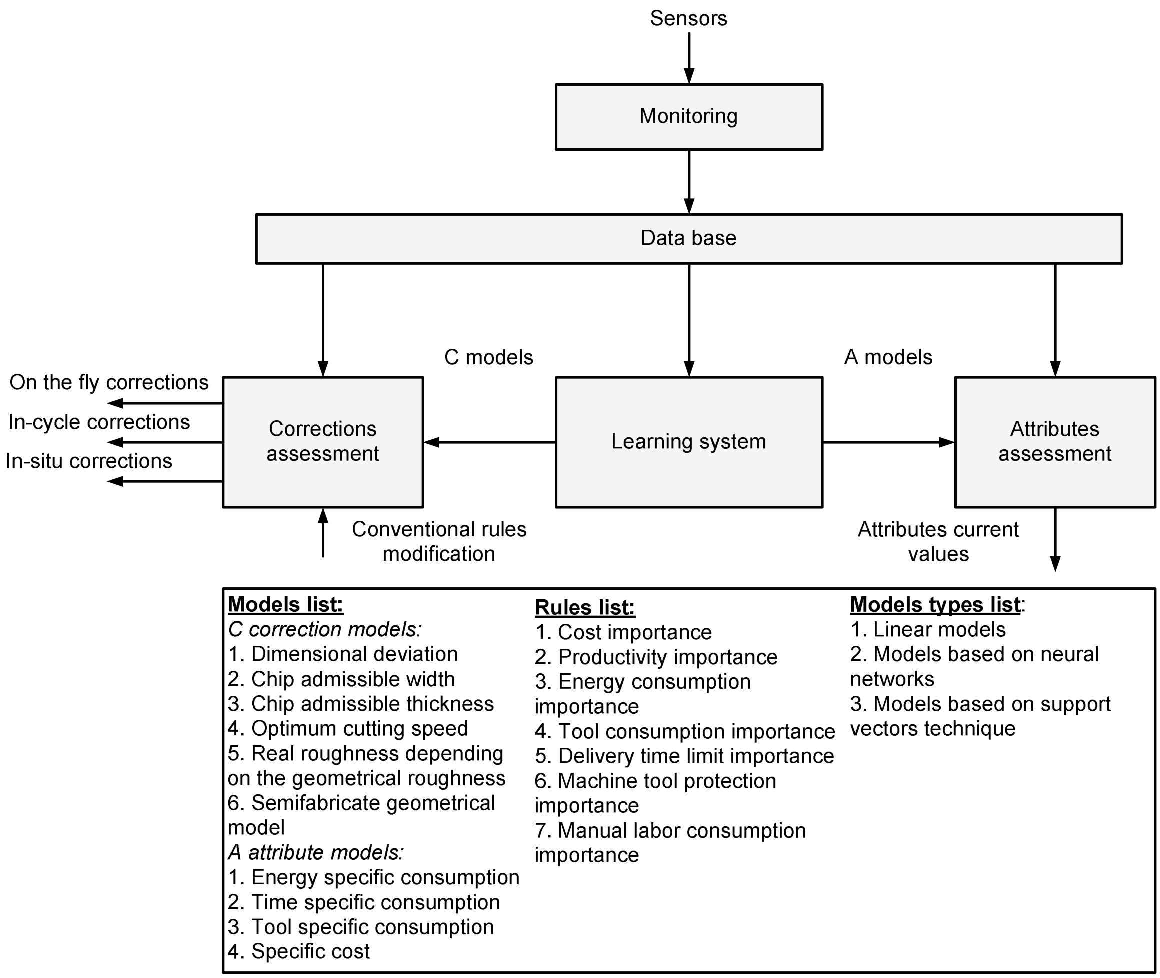

Fig. 6. The operational-level control system.

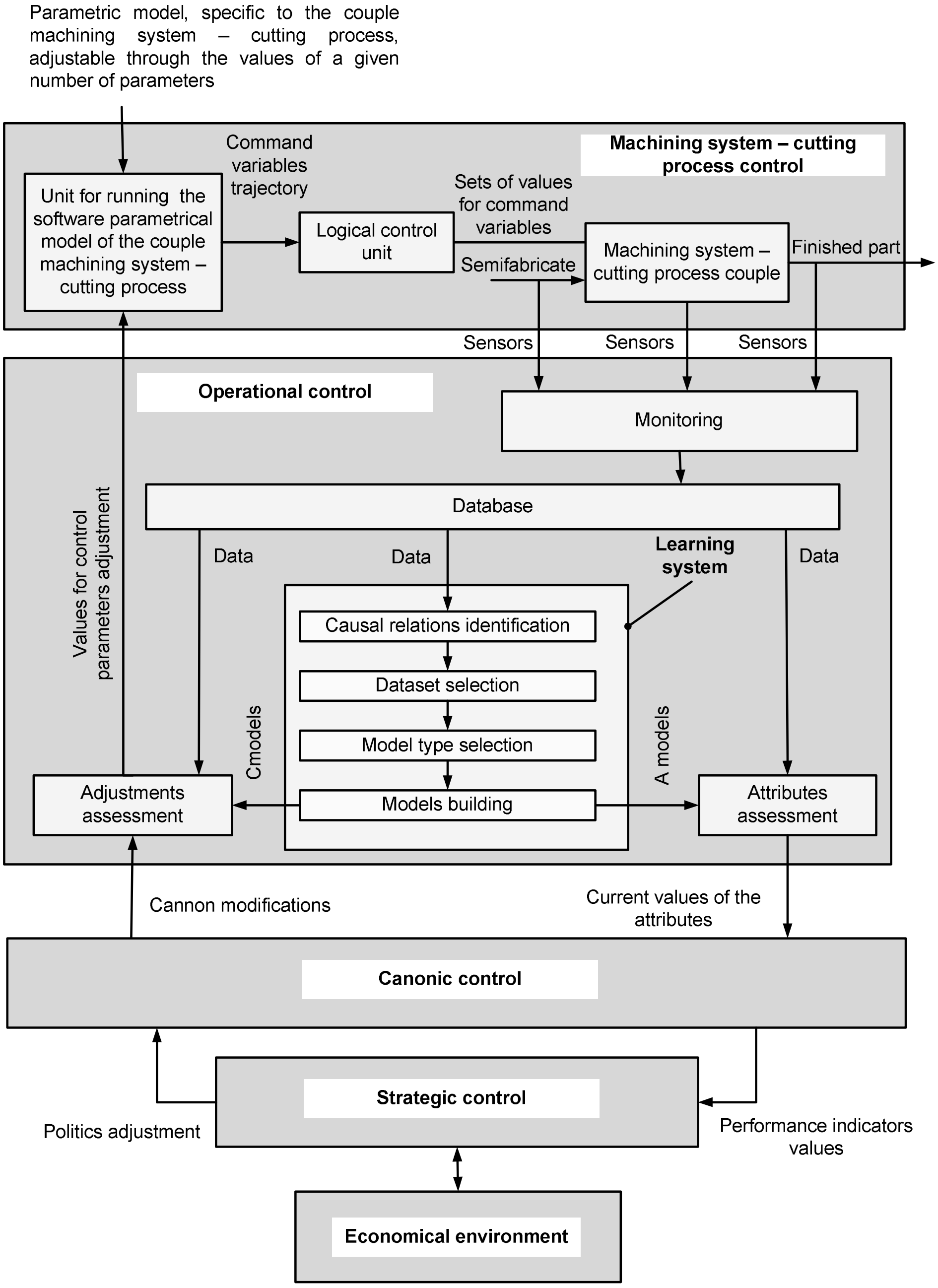

Fig. 7. Architecture of the holistic-integrated control system.

The information is received during the machining process, but also before or after it. The semi-finished product model is identified before machining, while machining result is found at the end, by assessing the machined part.

The operational-level control is grounded on a *learning system*, which plays the role of building two types of models: *control parameters correction models* and *attributes assessment models*.

To generate models, the learning system firstly finds *causal relations*, in order to identify which among the variables from the database will be used to build the model. The *relevant datasets* (meaning the recorded data that will be used in this purpose) follow to be selected after identification. An analysis of available models typology is then performed to establish the *type of model* enabling minimum modeling errors.

Correction models main purpose is to find the following control parameters, used by the unit that runs the software parametric model of the machining system – cutting process couple:

- *Predicted dimensional deviation*, corresponding to a set of points owning to cutting tool path, relative to the worked piece.
- *Chip admissible width*, variable involved in cutting process stability.
- *Chip admissible thickness*, feed rate restrictive parameter, in order to protect the cutting tool edge integrity.
- *Chip admissible area*, restrictive parameter, in order to protect the machining system against overloads produced by cutting force.

- *Optimum cutting speed*, parameter with influence onto process productivity, economical efficiency and ecological impact.
- *Admissible geometrical roughness*, depending on the real roughness, as imposed by the manufactured part execution drawing.

The models used for attributes assessment deliver attributes current values, that follow be used by the canonic-level control system in order to decide about the possible canon modifications. These attributes are:

- Energy specific consumption.
- Time specific consumption.
- Cutting tool specific consumption.
- Specific cost.
- CO_2 emission corresponding to a specified amount of detached material (e.g. 1 dm^3).

Causal relations identification could be realized, for example, by using data-mining methods known as "attributes filters". The techniques RRelief and Correlation Feature Selection should be used to find the causal relations between the followed variables (used for building the model) and the rest of them, included in the database.

Dataset selection must keep in view the idea of using the optimum number of data to enable the mathematical model building, on such a manner as it describes as well as possible the modeled couple behavior.

Model type selection can be realized based on virtual retrospective assessment of all the models available inside the operational-level control system, looking for their modeling performance. In this purpose, each among the available models should be successively tested, by virtually applying it for the operational control of each finished part machining (from the already processed set). Simulation result will be then compared to the measured values of the controlled parameter, in order to assess the modeling performance. After all the available models are analyzed, the one proving the best performance can be chosen, and further used for the operational control of current worked piece machining process. This way, model type selection becomes an exhaustive optimization process.

Model building consists in determining the parameters of the selected model, on such a manner as the modeled system behavior, at the current moment, is made at the best possible level.

5.3. A new strategy for machining process dimensional control

By *dimensional control* we mean that control modality which aims to reduce the dimensional errors appearing after the machining process. There are two ways to achieve this:

i) Modification of the cutting process parameters (meaning, in fact, a diminution of cutting process intensity) and/or improvement of machining system performance concerning precision and accuracy. This is a passive approach, with negative economical impact, because leading to lower productivity and higher costs.

ii) Modification of the control strategy – a normal cutting regime and regular machining system combined to a new control approach that eliminates the errors before their appearance (by predicting them and by applying appropriate corrections at machine tool kinematical chains level). This approach is more efficient from economical point of view, because same results as in the first case may be obtained without big investments in precise machine tools or special cutting tools, but in terms of intense cutting regimes.

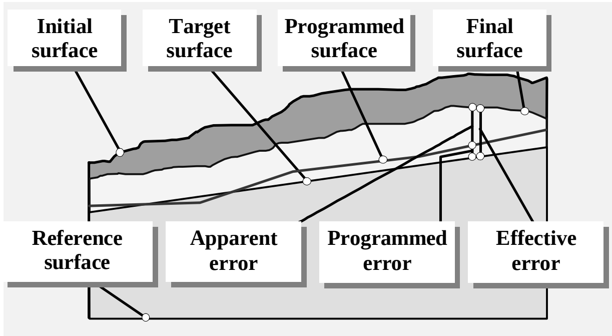

Fig. 8. The system of analyzed surfaces.

The problem of errors compensation instead of dimensional errors diminution involves obtaining a final surface as close as possible to *target surface* (meaning the surface imposed by part execution drawing). The system of surfaces to be considered for dimensional errors compensation is depicted in Fig. 8. The machining allowance must be detached in order to obtain the target surface, as machining process result. If the machine tool would be set to realize the target surface directly, then a different surface will be generated, because of inherent dimensional errors. According to the new strategy, the machine tool should be set to realize another surface, namely the *programmed surface*. Obviously, even if the dimensional control is performed, differences between the target surface and the final surface still remain.

The programmed surface position is determined by the applied correction. The target surface is characterized, in general, by a set of parameters e.g. the nominal dimension, its tolerance zone, the required roughness, but also the target surface position relative to the other surfaces defining the worked part final surface, called *reference surfaces*. In many cases, the reference surfaces are machined before, their absolute position being not the nominal one. The necessity of finding values of the parameters giving the reference surfaces position issues from here.

The dimensional control systems should be grounded on the following strategy:

- Data resulting from machining system monitoring are acquired during the operating cycles;
- Recorded data are organized into a database, that contains information regarding current and previous machined parts;
- A mathematical model is built based on the information from database, in order to predict the dimensional deviations;
- The model is used to find the appropriate corrections to be applied at machine tool kinematical chains level in order to minimize the dimensional deviations.

In mass production case, the mathematical model building is easier to be solved, because of the high amount of available data. Problems could appear only when machining lots made by fewer products.

The main aspects to be considered when applying the dimensional control are the following:

1. The dimensional control must be performed localized. The control system will assess the errors in a great number of points owning to the worked surface. By dimensional error compensation, in each point will be controlled:

- deviations from nominal dimensions;
- shape deviations;
- errors regarding the position relative to the reference surfaces.

Shape errors and, sometimes, relative position errors could not be compensated by using a global correction system, for the entire worked surface.

2. Determination of model parameters. The influence of parameters giving the dimensional precision could modify during machine tool functioning. It appears the necessity of finding the causal relations between dimensional deviation magnitude and the variables included in the database.

The most significant modification of these causal relations occurs when using reconfigurable machine tool, whose structure might change between successive fabrication lots.

3. Finding the number of worked parts to be used for building the mathematical model. The mathematical model can be built based on information gathered by using data

- from all pieces worked before the current one;
- from the last worked piece;
- from the last *m* worked pieces.

Using data from the entire lot of pieces brings the advantage of a large amount of recorded data, which could form a solid database, but also the disadvantage of considering data which could be no more correlated to the current state of the machining system.

At the opposite pole, the data only from the last worked piece are more recent but it might be not enough for detecting the machining system functioning trend.

4. The domain for building the model. Mathematical models which could be used for the entire machined surface might be built, but there is the risk to result too complicated. Their main advantage is being more robust regarding the noise affecting the sensors.

Division of the machined surface into smaller zones for separately modeling the dimensional deviation has the benefit of localizing the problem hence a simpler model will be used. The neighborhood necessary to built the model cannot be restricted too much, because this leads to a small number of available recorded data and the model becomes sensible to an important impact of measuring errors and noise.

6. CONCLUSIONS

In this conceptual paper, the premises which carry on the evolution of nowadays machining systems, the challenges to be faced in the years to come and the scientific, technological and political support for this evolution are analyzed.

Elements concerning the holonic manufacturing systems conceptual development are also presented.

A new concept for machine tools control – the attributive holarhic control – was stated and detailed with referral to control levels, program-level control and operational-level control.

A new strategy for machining process dimensional control was defined and developed.

The new concept for machine tools control, together to a new conceptual approach of numerical control – *the reactive scheduling control* – and to a new methodology for operational control – *the attributive operational control* – will be used in future to realize a proof-of-concept machine tool.

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