Complexity in Intelligent Manufacturing: Heuristic and Empirical Approaches

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Abstract

Manufacturing processes are generally driven by single input, single output decoupled control loops. Position or angle measurements are related to motor references by analytic relationships, mainly PID´s. Other magnitudes can be individually used like circuit breakers or alarm thresholds: electric current, temperature, force or torque, vibration (chattering), etc.

Present work deals with tightly coupled multi-sensor multi-actuator systems that will probably constitute the next generation of manufacturing processes. New systems capable to make in real time adequate decisions are needed to treat with data coming from numerous and heterogeneous sensors by using spreaded sources of human knowledge ussually expressed in different languages.

Complexity and uncertainty characterise this type of industrial environments in which Perception - Action loops must be established. New formal tools such as Fuzzy Logic and Pattern Recognition techniques constitute some approaches for process diagnosis and control. Heuristic modelling and empirical learning mechanisms can greatly extend the present landscape of the manufacturing world.

Keywords:

Intelligent Architectures, Fuzzy Logic, Manufacturing, Classifiers, Artificial Perception, Fuzzy Modelling

1 - Introduction

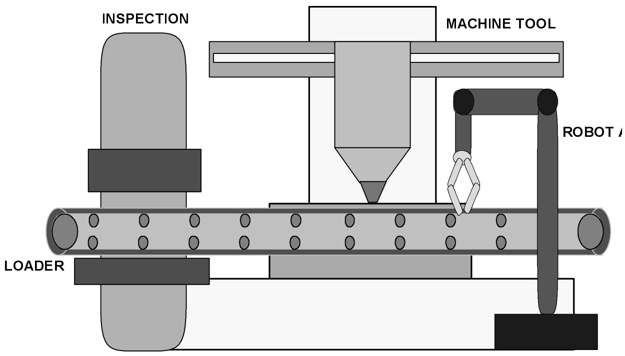
The increasing processing power and the decreasing price and size of recent electronic devices have spread digital automation in manufacturing processes. Machine tools have four, five or more degrees of freedom in the movement of independent mechanical axis. Position and velocity control loops have angular and linear position encoders and/or tachometers as inputs, and voltage references to motors as outputs. A manufacturing planning to originate a piece in a particular machine implies the successive activation of defined control loops or elementary modules of machine behaviour in the C.N.C. programming language. Load first tool, go to initial position, set cutting speed, describe cutting trajectory, change to a new tool, etc. would be a typical program of machine operations.

Decoupled linear control loops can be efficiently implemented in real time by analytic relationships such as Proportional-Integral- Derivative algorithms driven by the measured error in position or velocity. Fast interpolation techniques, look-up tables or distributed processing architectures have expanded greatly the capabilities of former C.N.C.´s to new machines and improved processes. Simultaneously, more and more sources of relevant information have become available. Initial fuses for overcurrent in electric feeding circuits and limit switches in mobile parts, has been complemented with operator protection devices, temperature, force, torque or vibration threshold alarms, incorrect feeding detection and many other devices to increase productivity and safety in manufacturing processes.

To allocate this fertile and heterogeneous information flow in the theory and practice of control architectures in manufacturing, the new field of Intelligent Control is growing in Science and Technology. Tool holders handled by multiple joint robotic arms are a clear example in which dynamic decoupling can not be achieved in the Cartesian decomposition of conventional machines. On the other side, many other measurements could be convenient to perform real time control decisions, increasing or decreasing speed due to temperature or force changes, replacing a born tool or stopping the process in case of breakage or machine failure.

Intelligent Architectures deals with efficient information processing in systems and environments characterised by complexity and uncertainty. Three lines can be considered in this direction: The logic based approach [Nilsson,69], the analytic approach [Meystel, 86], [Saridis,88] and the behavioural approach [Brooks,86], [Mataric,92]. Expert systems could be a relevant group in the first approach in which decision making is supported by linguistic rules close to human knowledge expressed in natural language [Barrios,92], [Betancourt,91]. Multi- resolutional nested Hierarchical Architectures represent a clear paradigm of the second approach. The proposal of Intelligent Machine Systems by [Albus, 92] in the American NIST is a detailed application to the field of manufacturing.

The main interest of previous propositions was to solve complexity in information processing. Uncertainty, inherent to real environments, require decision making with incomplete data or unexpected events. Fuzzy Logic techniques extend logic inference mechanisms to make



NIST Paradigm for Manufacturing Work Station

correct decision with partial information by using linguistic variables and expression, close to human language descriptions and reasoning. Typically a Fuzzy Logic System has two levels, one with detailed description in numerical variables and an upper level with symbolic language in which inference mechanisms are linguistic rules.

Other point of view is presented by behavioural, reactive, flat architectures. This idea was a response to the excessive conceptualisation of symbolic reasoning [Brooks, 86], presenting embedded support for physical and logical Perception - Action loops which are tightly coupled by simple decision making algorithms o agents of behaviour. These agents compete for the whole control of the system resources under a unique arbiter. System responses are not planned but fired by sensing stimulus coming from the environment.

Present work summarises two complementary chores in order to simultaneously reach a solution to complexity and uncertainty problems in manufacturing. Fuzzy Logic Reasoning and Example based Diagnosis have been developed during years in our Centre. A new and common proposal merge from this work already done: a hierarchy of inference loops in which the complex machine experience is selected and tuned by human knowledge.

2 - <u>Modelling and Control: Fuzzy Logic Techniques</u>

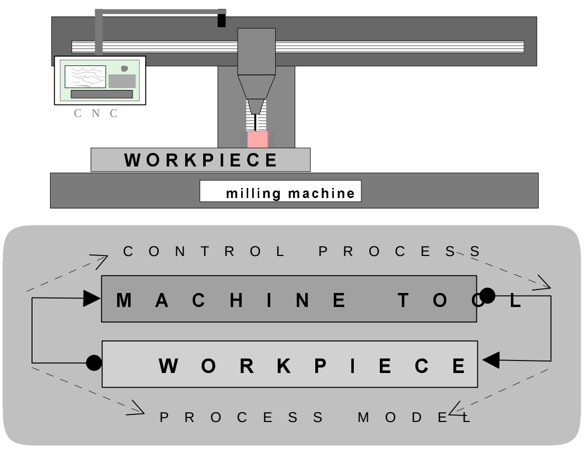
Model based reasoning is currently a very active area in the A.I. field., which attempts to generate new paradigms for the modelling of physical systems as a previous stage for monitoring or control tasks. An explicit model of a physical system consists on a set of input output relationships capable to provide predictions concerning the behaviour of the system with adequate accuracy. Analytic models have been useful for decades in single input single output linear equations. However, over thirty variables could be considered in de analysis of efficiency in a metal cutting process such us: Type, power and size of the machine, cutting tool features (type, diameter, material, length), material of the workpiece (hardness, machinability, homogeneity), cutting specifications (feed per tooth and feed velocity, cutting speed), rigidity of the machine, cutter and workpiece, tool wear, tool wear rate and cutting tool life, chatter and other machine vibration, surface finishing, thermal effects, etc.

The machine tool operator knows the characteristics of the machine, the workpiece material and the machining process from which he defines the set of cutting parameters: feed rate, cutting speed and depth of cut, that must be in the process program written in the C.N.C.. This task is highly dependent on the human knowledge, stated in tables and data bases as a complement to his own experience. This way, the operator can find the most suitable values for the specific workpiece material, cutter type and machining task to be accomplish (slotting, profiling, pocketing, sculpturing, facing, turning, drilling, etc.). These values are always very conservatives attending the type of cut (roughing, finishing, cornering, ramping). Operators commonly further reduce the programmed speeds by 50-60% due to environmental noise, problems in cleaning chips, maintenance and safety. This means that necessary precaution considerations clearly impede optimum level of efficiency, then increasing production costs.

Relationships among variables in a cutting process are multiple, highly non linear, with great disturbances and variations in the cutting conditions (workpiece material properties, tool and machine characteristic and evolution, lubrication, cutting conditions, possible failures and external events, etc.). In addition, information coming from existing sensors could be noisy, heterogeneous and often too large to perform an easy interpretation. Therefore, classical control estrategies offer limited contributions to machinning processes. I.e., fix gain controllers like P.I. (proportional integral) and L.M.R.C. (linear model reference controller) presents performance problems if machinning conditions, like depth of cut or workpiece material characteristics, change over the process. M.R.A.C. (model reference adaptive controller) can be affected by unmodelled dynamics due to cutter runout. The bias problem can be eliminated by filtering with a reduction in the controller performance.

Fuzzy logic techniques deal with uncertainty and imprecision, critical points in systems with formally ill-defined complexity like metal cutting processes where inference links among variables are not easy stated. Fuzzy model is expressed as a set of rules in the form "if... then..." relating "fuzzy" or "linguistic" variables, close to human linguistic reasoning. A control strategy can be considered the inverse model, in which working enviroment outputs are machine sensors and control actions constitute working piece inputs.

A hierarchical control system based on Fuzzy Logic for a milling machine is being developed at the I.A.I. It has a classical fuzzy controller in its lower level with cutting force as input and cutting speed and feed rate as system outputs[Agüero,93], [Haber,94]. A fuzzy model of the milling process constitutes the higher level of the



hierarchy, taking into account present values of cutting speed, depth of cut, tool diameter, and workpiece hardness[Haber,94].

Experimental work has been performed at a vertical, medium size five axis machining centre in milling operation, working with different types of aluminium and steel alloys. A dynamometer must provide to the C.N.C. the real time components Fx,Fy,Fz of the tool- piece force, as a complement to the conventional control sensing: position and speed.

Several techniques of fuzzy modelling can be found in references [Sugeno,85], [Xu,87], Morita,90]. We have used the MISO (Multiple Input, Single Output) approach of [Sugeno- Yasukawa,93]. A Model is built from a set of experimental values by mean of some rules or "If..(condition). Then ..(action)." sentences. The fuzzy reasoning method is based on the "max product" and the "centre of gravity" as defuzzyfication method.

The identification of the relational structure has to solve two questions. First, among all the variables involved in the process to be modeled, what is the set of input variables that affect the output. Second, to find the input/ effect relationships that imply the number of rules to be defined and the fuzzy partition of the input space. In the parameters identification stage, the parameters of the membership functions of the rule antecedents are etched. In the Sugeno approach it can be done separately after the structure identification.

The method consists in constructing sucessive models, starting with only one input variable (one model per input variable) and increasing the number of variables sucessively. The selection of variables is performed for the Regularity Criterium minimizing the error between the model output for each group and the crossed output. Different models of the process have been developed, considering each material individually and looking for consistence by mixing two o more test groups in a new model.

Conclusions to our work in Fuzzy modelling could be:

- Fuzzy modelling is a powerful technique by which it is possible to model highly dynamic ill-defined processes in manufacturing.
- Absolute and relative model errors increase when two or more different types of material are considered together. This suggests the idea of working with a library of models.
- Applying the technique of Sugeno-Yasukawa it is easy to reach increasing levels of accuracy, just modifying the number of rules according to the level of abstraction of the model.
- We have developed five different models considering a reduced set of input-output variables of the cutting process. The obtained values of absolute and relative errors [Agüero,92] show the power of this approach.
- The small number of rules and good accuracy of our model demonstrate the adequacy of this technique to real time work, giving the appropriate values of cutting force to the reference of the lower level fuzzy controller in the proposed hierarchical system.

In summary, we think this technique is very powerful to obtain the fuzzy model of a process. it deals with uncertainty and incomplete knowledge and allows us to improve the model until reaching the level that satisfies our expectations.

3 - Example based Learning Systems

Multi-sensor systems offer a wide universe of possibilities for interpretation of real world scenes. Many methods have been proposed with this aim. Classifiers are statistical recognition methods based on examples with high flexibility and generalisation capability in many application domain. New generations of cheaper and powerful sensing devices and electronic processors arrived recently to the technology market.

Some examples are: Integrated accelerometers, Acoustic Emission sensors, Infrared cameras and arrays for non-contacting temperature measurement, semiconductor strain gauges, special high sensitivity narrow cone microphones, position and speed e.m. probes, optical interferometers, etc. The fast evolution in decreasing prices and increasing processing capabilities of digital devices and systems is even more dramatic yet. Signal processors and distributed system offer splendid cost/ effective opportunities for real time machine monitoring and control.

Scientific projects and research publications offer new possibilities to extract significant information from the manufacturing process using adequate transducers, signal processing techniques and processing equipment. The typical research module consists on a certain type of sensor (like a set of accelerometers), a digital data acquisition board connected to a digital computer (an A/D board and a P.C. or Workstation) and a processing tool (Fourier Analysis). This signal information chain focuses its work at extracting or recognize a particular feature concerning a manufacturing problem (i.e. detection of chattering or breakage of a gear in the machine).

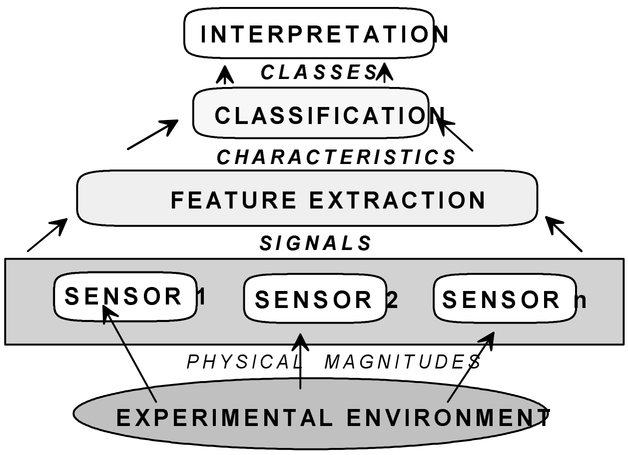
Laboratory experiences have showed quite interesting results related to significant problems for the manufacturing industry like collision detection, tool wear and tool breakage, chattering, preventive maintenance and many others. Compared to the performed research effort, a comparatively small number of these sophisticated sensing-action mechanisms have been commercialised and a still smaller number of them continue effectively working after a few months in the industrial environment. An eloquent exception should be considered for the most simple "fuse type" based on a threshold decision for maximum admisible force, vibration or motor current.

The possibility to get several million data per second are not the complete solution to make fast and good decisions at each moment of the production process. A new strategy of information processing is required, it must be able to match the operator skills and engineering knowledge with the complementary world of information related to the machine experience. Both must cooperate to reach the conditions of quality, safety, productivity, etc. weightly defined as industrial objective for the manufacturing process.

Pattern Recognition techniques have been developed in order to link huge amounts of sensor data to a few states or classes labeled by the human observer. Definition of the machine states to be recognized as an origin of commands or actions to be accomplished: stand by, free moving or tool cutting state, type of tool and material, processing conditions (cutting speed, depth, etc.), failures or interference with other machines, emergency situations, etc.

A typical Pattern Recognition block diagram usually condenses the information received from the environment through several stages or levels constituted by standard processing techniques: Feature Extraction, Classification and Syntactic Analysis of chains or sequences of states. Many algorithms are available for each level. But, a particular Pattern Recognition architecture, defined as set of processing tools implies the rejection of the rest of the alternatives in a conventional system.

Unmanned manufacturing requires flexibility of design. I.e. the recognition of a tool breakage in order to stop the machine requires immediate response at risk of unnecessary interruptions of the process by false alarms.



On the contrary, the wear process is comparatively slow an the decision to change a worn tool can be verified several times before deciding its replacement.

These signals need to be characterized by quick computing features, as maximim, threshold or other morphological descriptors to avoid a excessive delay at the feature extraction level. Similar requirements of computing velocity must be considered for the recognition stage. Thus, a Neural Net classifier should be appropriated to perform the task in despite of its large training period while a Bayesian method could be too slow for this particular problem.

Although different classifying strategies can be found in multi-sensor integration references no systematic comparison among experimental results is frequently done. Beyond the "classifying power" or recognition success, other evaluation criteria must be taken into account in order to select and use the most adequate information processing strategy from a practical point of view.

Consequently, a flexible recognition system must support and consider available alternatives at each level of the recognition process. It must be able to integrate new computing algorithms to the set of already existing sensors, features, classifiers or symbolic inference methods. A criterion of efficiency or "evaluation space" allows the definition of a metrics. Using it for a measurement of matching between processing tools and the desired objective, alternative processing modules are selected for a certain application or system goal.

An efficient Pattern Recognition Hierarchy condense perceived information from the environment to simplify and make efficient decisions at higher levels in a bottom-up structure. Nevertheless, criteria for evalution of different elements of the perception process emerge from the global system goal, being instanciated to lower levels by a top-down hierarchy of evaluation mechanisms.

Our group has been developing a common programming support able to share diverse classifiers [Guinea,91]. Distance based techniques, K of N Neighbours assignment, Neural Networks and Minimum Entropy Tree classification, are able to compete for a precise objective in the same computing shell. A global evaluation strategy is proposed as a "quality space" for results location. Other factors related to the efficiency of a certain recognition method are:

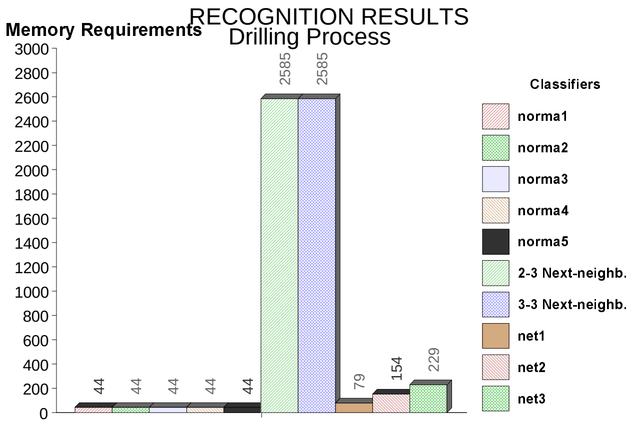
- **Learning Time** relative to the duration of the training process.
- **Execution Time** needed to classify a new example.
- **Memory Requirements** to store the information required by the considered technique.
- **Rejection Ratio** or percentage of non classified test elements.
- **Condensation Ratio** between the size of input and output spaces.

As an example, we will comment some experimental results of empirical learning in a drilling process by a set of competitive classifiers in a C.N.C. machining centre. [Guinea,94]. A set of heterogeneous sensors monitor most relevant physical magnitudes of the process [Guinea,90] using adequate data structures to hold efficiently multi-sensor information flow [Ruiz,92]. Feature generation and selection are critical stages in the process [Ruiz,90] solved by cumulative experience of techniques and limited search to particular goal achievement. Complexity inherent to the perception strategy oriented us to distributed hardware and software processing architectures, defining a dedicated machine to this type of requirements [Ibañez,92], [Bustos,92].

Let us consider briefly different classifier strategies from the point of view of the above defined evaluation criteria. A typical example of memory ill-use for broad population of examples could be the Next Neighbours classifiers which learn by heart and must maintain the complete examples universe alive. Therefore memory requirements could be excessive compared to other methods. This implies a very low condensation of the input information, increasing the required amount of memory.
Neural Networks present acceptable performances except a very high learning time. Net2 with 6 unit hidden layer offers optimum results considering more and less units. This is clearly shown in the learning time graphic.

Distance based functions, specially norma1 and norma2, are perhaps the best choice in the considered application. They offer acceptable errors without rejection samples, low learning and execution time and very good condensation ratio.

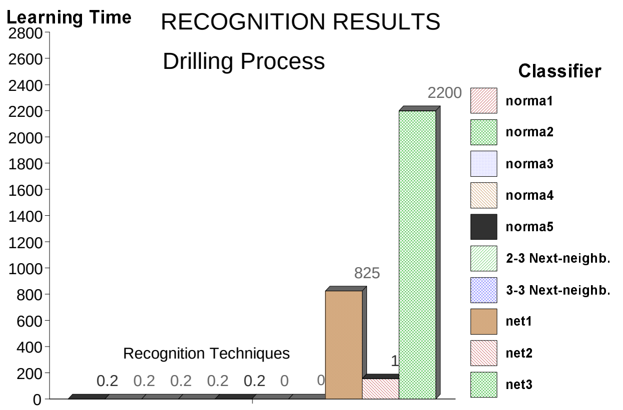
A detailed explanation of the perception strategy,



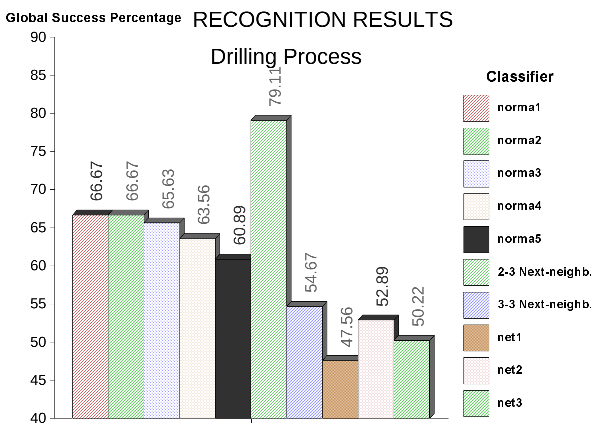
computing algorithms, experimental conditions in diverse manufacturing processes (turning, milling, drilling) and results can be found in references.

Conclusive remarks on our experimental work on empirical learning methods in manufacturing could be the following:

- The problem has been carried out from a defined



sensor set to the evaluation space. Success rate is related to the number and type of sensors, to the generated universe of features, to the used selection criterion and to the employed classifier.
- Information coming from each sensor is considered significant for tool wear estimation, in this example. In



this system every sensor can be disconnected with minor loose in the recognition power of the whole set.

- Increasing the success rate imply a wider search for adequate signal descriptors but it can be done by new sensors to collect new information from the studied environment or by the use of a better classifier.
- Results of example based techniques depends on statistical consistence of the empirical basis of inference. Thus, laboratory or real work examples used as support of future identification for new samples, must be planned on a careful experimental design. This must assure a representative population to generalise each category or class to be recognise in future works.
- The suggested experimental design will be a wide and systematic information retrieval, closer to factory management than an "aseptic" scientific experience in laboratory. Information from the machine C.N.C. (type of tool, cutting conditions, accumulated working time, material supplied, etc.) can be complemented by human observations when necessary.
- Classification techniques could be multiple and co-operative for information interpretation and decision by integration of numerical data and symbolic codes.
- At present, proposed sensor integration system is composed by many different processing modules: signal pre-processing and edition, functional transformations, scalar descriptors, classifying methods and criteria for results evaluation, tuning strategies for diverse tools, etc.
- This represent a complex programming structure for maintenance, for expansion to new applications or for designing connection links with other Processing Systems as Expert Systems or Heuristic Planners.
- Searching for homogeneity, Neural Networks offer a general, simple and flexible function approximation methodology. Hence a general feature extraction procedure based on Neural Networks is being investigated.
- In a first step, learning abilities of Neural Networks to emulate function and scalar computations from standard methods are being studied. A second step will imply autonomous feature searching strategies based on Genetic Algorithms.
- A generalised and systematic methodology to evaluate classifiers may constitute the nucleus of autonomous strategies for Artificial Perception, dealing with efficient smart self- organisation in sensor data analysis architectures.

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