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A generic system architecture for simulation based intelligent multi-stage multi-process machining system to achieve zero-defect manufacturing

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Abstract: Zero-defect manufacturing paradigm is an important focus area to develop factories of the future. The technologies and methodologies developed so far to achieve near zero-defect manufacturing vary a great deal and are specific to the certain case studies or industrial applications. This paper proposes a generic framework architecture at the machining system level to achieve zero-defect manufacturing through integrated intelligent multi-stage process chain digital model tuned by the real-time extracted data characteristics in order to simulate and optimize the manufactured part quality. The key feature of this system architecture is its general applicability regardless of the nature of machining process. In this way, the proposed architecture provides a robust framework of software tools, hardware systems and quality feedback loops for application in any multi-stage machining system under dynamically changing environmental conditions to reduce part defect propagation across the process chain. It is envisaged that the implementation of this framework will lead to effective advancement towards zero-defect manufacturing.

1. Introduction

Due to stringent quality requirements, the tolerance for defects is almost zero in the aerospace and automotive parts manufacturing. To achieve zero defect level, the focus must be to create processes and systems that result in defect-free products. The overall quality direction of the enterprise is therefore determined by the capability of the manufacturing processes to produce defect-free products. Hence, the emphasis should be on improving the manufacturing processes and their control to minimize the occurrence of defect [1].

In the modern manufacturing industries, quality assurance has attained the same level of importance as improving efficiency and flexibility. The high values parts manufacturers are under ever-mounting pressure to guarantee zero defects in their parts. At the same time, the manufacturers are also under increasing pressure to reduce the cost in order to stay competitive in the global market. The scrap and rework are identified as two dominant sources of increased cost in manufacturing industry [2]. The only way to tackle all these challenges is to produce defect-free parts in first attempt i.e. doing it right the first time. The companies can increase the profits dramatically by eliminating the cost of failure and increasing revenues through increased customer satisfaction. However, in order to produce defect-free parts the first time, the process capability must be very high and all sources of variation must be eliminated by monitoring, real-time optimization and control of the manufacturing processes. Furthermore, the manufacturing system must be capable of predicting the manufactured part quality beforehand and be able to adjust in real-time to produce products within the specified tolerance continuously. This means monitoring, optimization and control systems should be well integrated.

2. Zero-defect manufacturing as a holistic approach

Safe and well controlled processes are the precondition of zero-defect manufacturing (ZDM). A process is considered as safe when the probability that a single measured value lies outside the nominal tolerance is approaching zero. To run a manufacturing process at the limits of performance and precision, all factors influencing the quality in the whole process chain should be monitored, optimized and controlled as far as possible. Therefore ZDM calls for a quality-oriented control of manufacturing processes as a holistic approach implemented at the level of manufacturing system. This is because the quality control at only one or the final stage of a multi-stage manufacturing process is insufficient to compensate for the too large tolerance deviations and defects caused by the preceding stages [2]. The quality controlled must therefore be implemented at all stages including the preceding and peripheral processes. In this way, first the individual processes are improved and then the robust models are developed wherein accurate correlationship between the inputs and output of the manufacturing process are well established. The different stages of the part manufacturing on the production line or sequence are then conceived as multi-stages of the process and the models and control methodologies are enforced at each stage.

3. IFaCOM

The "Factories of the Future" is one of the three public-private partnerships initiated by the European Commission (EC). The basic objective of this initiative is to help EU manufacturing enterprises, in particular SMEs, to meet the challenges of global competitiveness by improving the technological base of EU manufacturing across a broad range of sectors [3]. The EC project *Intelligent Fault Correction and self-Optimizing Manufacturing Systems* (IFaCOM) supports factories of the future vision by focusing on ZDM at the shop-floor level.

3.1 Vision of IFaCOM

The vision of IFaCOM is to achieve near zero defect level of manufacturing independent of the nature of manufacturing process, with emphasis on production of high value parts, large variety custom design manufacturing and high performance products. This vision is believed to be achieved through [4-5]:

- Improved performance process control to reduce defect output and reduce the costs of defect avoidance
- Enhanced quality control to obtain more predictable product quality
- Enhanced manufacturing process capability independent of manufactured parts

3.2 Objectives of IFaCOM

The objectives of IFaCOM are to reach a level of excellence for a systematic body of knowledge on near zero defect manufacturing output through improved process control, and long range stability by use of intelligent manufacturing quality control systems.
An intelligent fault diagnosis and prognosis system will be developed supported by intelligent sensors and signal analysis at all levels. This includes the development of a set of methods for real time self-correcting mechanisms that give immediate effect, methods for medium and long range optimization to increase the overall performance and stability. The application of the IFaCOM methods will make considerable impact on manufacturing processes, allowing manufacturing companies to obtain new levels of excellence. Different aspects of developments in IFaCOM project have already been reported [5-6].
Information and communications technology (ICT) is the key to develop ZDM systems. This is because the interaction between different physical modules of the manufacturing system depends on the consistent flow and processing of information data in real-time to make predictions and decisions with respect to the manufacturing process state. In such manufacturing system, various artificial intelligence (AI) methodologies are considered for developing predictive and adaptive models. In IFaCOM, the fuzzy-nets approach is considered for part quality prediction and process parameters adjustment. Fuzzy-nets based system has proved to be capable of robust predictive and intelligent manufacturing systems applied for machining processes [7]. Other approaches based on regression, neural networks, etc. can also be considered.

4. Framework of system architecture

The major challenge in IFaCOM was to develop a generic IFaCOM system architecture applicable for all kinds of machining processes including but not limited to those typically used in aerospace and machine tool manufacturing sectors, the two representative sectors of demonstration for IFaCOM project. This paper gives the details of the generic framework architecture developed in IFaCOM project implementable independent of the nature of the machining process.

The system architecture portrays the flow of information and data starting from initial process planning stage to the revised plan completing a full cycle in a closed loop. Each building block or box in the software architecture diagram (shown in Figure 1) is the functional module comprising either a software tool and/or hardware to accomplish the designated task. The detailed functional description of all the building blocks of IFaCOM system architecture is presented in section 4.2.

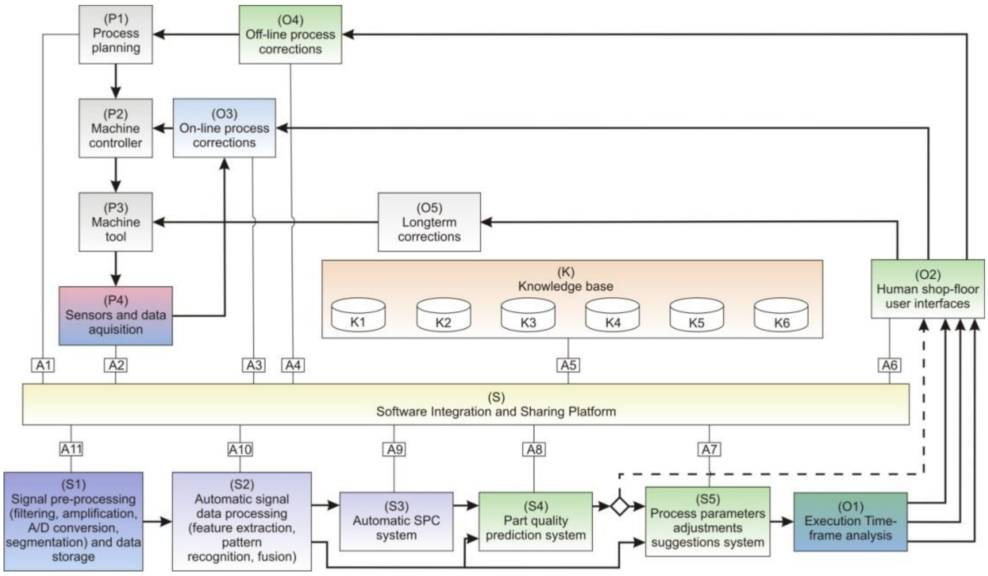

Figure 1. IFaCOM system architecture

4.1. IFaCOM terminology

Some important definitions that will be used in the description of the IFaCOM system architecture are:

Hidden process variable (HPV): process variable that is not included in the process control system nor in the machine tool closed-loop control system and represent the cumulative effect of process disturbances that are individually either uncontrollable or very difficult to control .

Critical hidden process variable (CHPV): hidden process variable deemed to have significant impact on vital quality characteristics.

Part program parameters (PPPs): Specific process parameter included in the part program.

Vital process parameter (VPP): process parameter that affects identified vital quality characteristics of the product.

Vital quality characteristics (VQCs): part quality characteristic that shall be kept within specifications in order to assure zero-defect manufacturing.

Manufacturing system parameters (MSPs): Manufacturing system parameters define the nominal status of elements of the manufacturing system. All systematic causes of the part non-conformities related to the imperfection of the manufacturing system (such as errors due to the kinematic errors and elasticity of the manufacturing system etc.), that can be modeled, will be excluded from the system through initial calibration procedures and corresponding error correction control loops.

4.2. Building blocks of system architecture

The IFaCOM system architecture comprises the following building blocks (modules):

Process planning (P1): This software module depends on end-user’s preference and can be any commercial computer aided process planning (CAPP) package. It can be variant or generative type. This module establishes the general sequence of processing steps that begin with the acquisition of materials and end with the creation of a finished product. This module also provides revision and version control of manufacturing process plans, PPPs, production routing, product descriptions, operation sequencing, tooling assets, and set-up and run-time instructions. The output of this module is the CNC/NC part program going into the machine controller.

Machine controller (P2)*:* This system module comes embedded with the machine tool and hence depends on the machine tool manufacturer. Its function is to convert PPPs and online corrections (in VPPs) into the format executable by the machine tool. This is nothing but conversion of part program into the machine language. In this way, it implements the localized plan of sequencing machine tool motions depending on the type and capability of machine tool. The output of this module is the controlled set of instruction or part program executable by machine tool.

Machine tool (P3): This executes the actual processing operations instructed through the machine controller module (P2). The machine tool also has certain compatible software installed on it which provides an interface for writing a part program directly using a graphical user interface. Long term corrections in the form of maintenance activity or replacing a malfunctioning component of the machine tool are also performed directly on the machine tool off-line.

Sensor and data acquisition (P4): This module comprises sensor system to acquire real-time data of CHPVs to provide the in-situ status of the process continuously. The raw data is shared with certain other modules as depicted in the diagram.

Knowledge base (K): This module serves as the overall knowledge base and stores information about manufacturing rules, desired values of VQCs, process plans, pre-processes and post process sensor signals, manufacturing process parameters and sensor data. This data is shared via an integrated platform provided across the process chain.

Software integration and sharing platform (S): This module controls the flow of information, on-time sharing basis, in/out of Knowledge base (K) module and between various other modules across the process chain in the system as depicted in diagram.

Signal pre-processing and data storage (S1): This module performs signal pre-processing (signal filtering and conditioning) on sensor data/signal and eliminates the noise from the raw signal.

Automatic signal data processing (S2): This module extracts critical features of interest (e.g. frequency and amplitude) from the pre-processed signal. The choice of features depends on the VQCs for a given manufacturing process and the data acquired.

Automatic SPC system (S3): This module monitors the stability of the process and determines if there is a certain pattern of variation in critical features of CHPVs extracted from the sensor signal w.r.t. the reference (standard) values of the respective data. If such a deviation is found, fault diagnosis is performed and subsequently a root cause of the deviation is identified to suggest a preventive or corrective action. This module has broad application and can be tailored to the requirements of the end-user by including a number of statistical analysis and data mining tools. Fault diagnosis and root-cause recognition sub-systems are important parts of SPC to identify a faulty variation. The variation or deviation noted is then associated to a certain root cause (s) from a pool of predetermined potential fault-causes which the system is already trained for.

Part quality prediction system (S4): This module predicts the values of VQCs as a function of current and reference values of CHPVs features, PPPs, VPPs and correlationship between current CHPVs values and VQCs. The process model is based on the AI techniques such as fuzzy-nets, artificial neural networks and certain statistical modelling techniques such as regression. The model is trained for a broad range of parameters and conditions to render it robust and accurate. A sample S4 module based on fuzzy-nets predictive methodology is shown in figure 2.

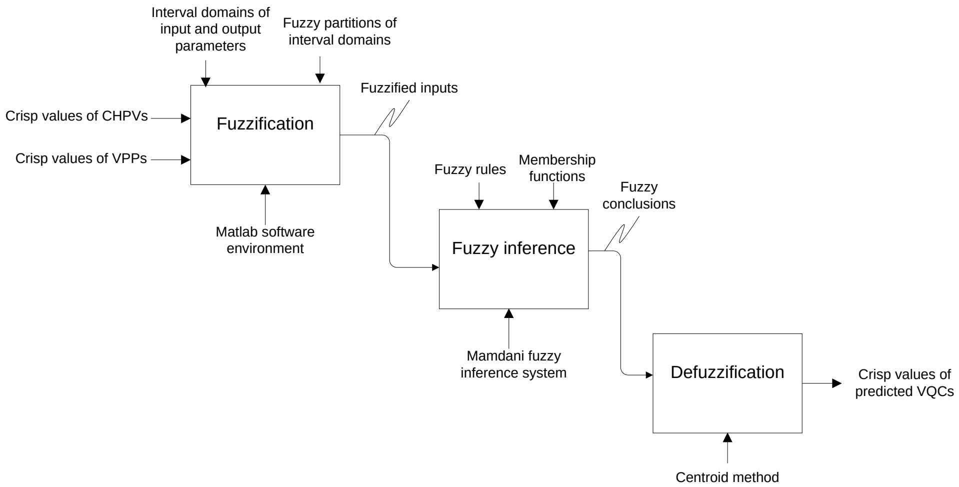

Figure 2. IDEF0 diagram of part quality prediction system

Process parameters adjustment suggestions system (S5): This module computes the adjustments in VPPs, suggests the calibration routines and maintenance activities as a function of predicted values of VQCs, reference values of VQCs, initial PPPs, correlationship between current CHPVs values and VQCs and manufacturing rules supported by learning ability needed to bring the values of actual VQCs close to the desired (reference) values.. A sample S5 module based on the fuzzy-nets adaptive methodology is shown in figure 3.

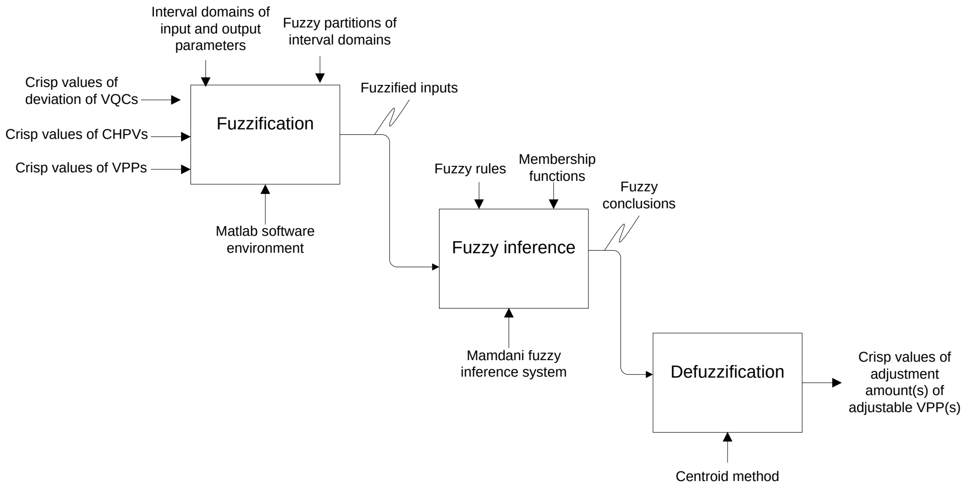

Figure 3. IDEF0 diagram of process parameters adjustment suggestions system

Execution timeframe analysis (O1): After suggestions are made by the module S5, it is important to determine the time frame required to execute the adjustments. This time frame is determined by O1. This module determines the PPPs adjustment suggestions, in terms of mid-term/long term or real-time, based on the time-frame appropriate for their implementation after analysing the suggestions made by module (S5).

Shop-floor user interfaces (O2): This module provides an interface for the shop-floor operator:

- To take the appropriate decisions along the three time scales of interest (time frames i.e. real time/long term/mid-term)
- For immediate failure intervention and system maintenance
- To decide if suggested adjustments in adjustable parameters and set-up/calibration procedures are desired or if the initial part quality is acceptable.

On-line corrections (O3): This module interprets the real-time adjustments, in the VPPs (online adjustments apply only to VPPs), into the corrections commands for implementation in the real-time through the machine controller. This implementation is performed without switching-off the machine on regular basis.

Off-line corrections (O4): Based on the suggestions for off-line adjustment of PPPs, this module feeds corrections in the PPPs to the process planning module (P1). This requires the processing equipment or machine tool to be switched off for implementation of the offline adjustments e.g. a failure is being approached, change of components.

Long-term corrections (O5): This module deals with the implementation of corrections which are associated with machine calibration and/or retraining of computational models and are usually implemented after significantly longer periods of time.

Communication language: Where required to programme, all the modules in the system architecture are commonly programmed in C++ language. By using a common programming language it will avoid possible unsmooth communication problems between system modules and will make the whole system efficient.

Active MQ (A1….An): The communication platform to be used for internal communications inside the system will be ActiveMQ, and it will also be used for connecting the IFaCOM system with the end-user systems.

4.2 Working and implementation

In order to describe the working of the IFaCOM system architecture, an example case of wire EDM process is considered. Wire EDM is a highly complex material removal process. It is typically performed for cutting complex profiles through the thickness of the workpiece. Due to several process disturbances and complications, it can leave a number of surface defects on the machined parts. In this example, we consider two important quality characteristics as the subject of interest or vital ones i.e. surface roughness and 'lines and marks' on the machined surface. The diagram in figure 4 shows the VPPs, CHPVs and VQCs for the Wire EDM case at hand.

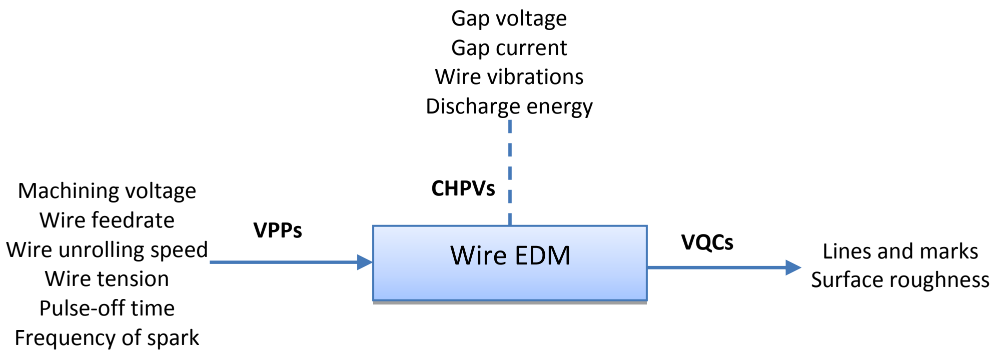

Figure 4. Wire EDM process parameters

As short circuiting, open circuiting and arching commonly occur in wire EDM process, however excessive short circuiting, open circuiting and arching lead to the creation of 'lines and marks' on the surface deteriorating the quality and aesthetic of the machined parts often resulting in part rejection due to stringent quality requirements imposed by the aerospace and automobile industries. Similarly, the surface roughness is also a key quality consideration and it must be below a critical threshold determined by the quality standards. The prime objective in the example considered here is to eliminate the occurrence of lines and marks and at the same time to ensure the minimization of the surface roughness. Not all VPPs are adjustable online and some of them need to be fixed (to their standard values) before the start of the machining process (offline adjustment). Likewise, only limited number of VPPs, determined by regression analysis, influences a certain VQC significantly and hence only those VPPs are considered for the adjustment. Two sensors are installed to implement IFaCOM software architecture i.e. current sensor to measure the gap current and vibration sensor to measure the wire vibrations. The wire EDM process is started for a certain part program. The signals from both sensors are input to the module S1 where the noise from the signal is eliminated and a sorted signal is provided to S2. The critical features from both signals typically include RMS averages, amplitude, frequency, ignition delay time, discharge energy, etc. These features are believed to be the indicators of VQCs which are surface roughness and 'lines and marks'. Lines and marks are considered the more critical of the two VQCs and must be avoided. To achieve this, a stable regime of the process is identified empirically in terms of critical features of interest, CHPVs and MSPs. First it is ascertained if the process is within the stable regime i.e. minimal probability of lines and marks. This is done by performing trend analysis and other statistical process control tools on the extracted features from the sensors signals.

The working logic of the IFaCOM software architecture is depicted in flow chart in Figure 5.

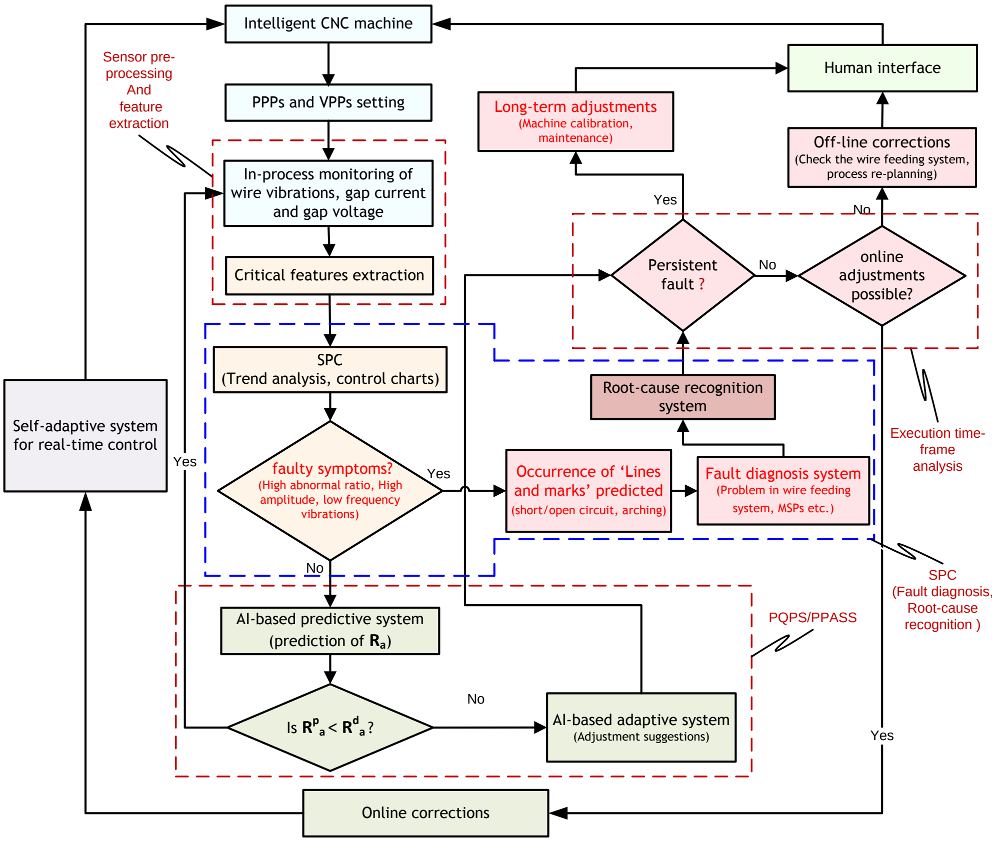

Figure 5. The working logic of the IFaCOM system architecture for Wire EDM process

If a faulty trend is identified in the extracted features, fault-diagnosis is conducted to establish the nature of the fault followed by the root-cause analysis to determine the real cause of fault from a list of potential causes. The corrections in the process/system parameters are implemented on/offline depending on the nature of the diagnosed fault. If the faulty trend persists even after the corrections are implemented, long-term adjustments may be considered such as calibration of the machine tool and detailed maintenance check of the manufacturing system components. The adjustments in three time scales i.e. online, offline and long-term are determined by the execution time-frame analysis.

If no faulty trend is identified in the extracted features of sensors signals, the objective is to produce surface roughness as minimum as possible (below an acceptable threshold value) under the given set of the machining conditions. Based on the extracted features, the value of surface roughness is predicted. If the predicted value is greater than the desired or reference value, the adjustments in the process parameters are implemented online. If the undesired deviation in surface roughness persists even after online corrections are implemented, long-term adjustments may be considered such as calibration of the machine tool and detailed maintenance check of the manufacturing system components. As the minute adjustments are expected to be made regularly during the process, the surface roughness produced should improve continuously (move below the reference value) until it reaches a steady state value whereby no further improvement is possible based on the current process capability. In other words, after several iterations of process parameters adjustments, the system is believed to have overcome disturbances and deviations and have adjusted itself to the stable regime until the next assignable cause of variation occurs.

5. Conclusions

The EC project IFaCOM focuses on zero-defect manufacturing through improved processes and their control. A generic IFaCOM system architecture was proposed and discussed in this study. The general framework of the system architecture consists of the software and hardware tools and can be customized for any machining process. The IFaCOM system comprises two intelligent subsystems i.e. fault diagnosis system and ‘prediction and adaptive system’. The system predicts the manufactured part quality in process by diagnostic analysis on the vital features of interest extracted from the sensors signals acquired in real-time from the machining process. If the predicted part quality deviates from the desired value unfavourably, the corrections in the vital processes and system parameters are implemented. The suggestions to make adjustments/corrections are generated by AI methodologies appropriate for the specific nature of the data handled, nature of the machining process and the VQC. In order to achieve ZDM, the proposed system architecture is capable to make adjustments in three time domains i.e. online, offline and long-term.

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