

Simulation and optimization in a multi-process environment using STEP-NC

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Abstract— With STEP-NC object oriented programming standard, the next generation of CNC controllers promises to be more open, intelligent and interoperable. This standard totally integrates CNC into the CAD-CAM-CNC numerical chain and is an opportunity to be a common support for various manufacturing processes. New possibilities are offered at the CNC level to make machine tools more autonomous, to perform intelligent part program generation, to increase the productivity and the adaptability in an intelligent multi-process environment. This paper gives a proposal for multi-process manufacturing using STEP-NC as the optimal data model for process planning, process specificities, and inter-processes simulation spaces.

I. INTRODUCTION

Next century promises to be full of great advances in the manufacturing and production environment. Changes in customers' expectations, delocalization of production centres, communication and transportation increasing facilities will lead to deep transformations of modern manufacturing. Companies that will early anticipate these fundamental changes by developing flexibility, transportability and interoperability for their production equipment will benefit from a large advantage to meet the customers' needs. In this context, intelligent systems, advanced control techniques as well as suited data exchange and programming standards will be required to support the increasing complexity of scenarios. Various manufacturing processes are developed to increase productivity and capabilities of machining operations, each one involving specificities linked to the process itself. High Speed Machining (HSM) [1], Rapid Manufacturing (RM) [2], Electro-Discharge Machining (EDM) [3], Incremental Sheet Forming (ISF) [4] are examples of processes that can be used to manufacture a product. The choice of the most appropriate one is often linked with feasibility, quality, cost or production time [5]. Combining these processes can also be a well adapted solution, even for a single part. A lot of research works lead to push back the limits by developing

new technologies, increasing computation and control capabilities and integrating the manufacturing processes into the numerical chain [6]. However, there is still a lack of links in CAD/CAM/CNC numerical chains using different processes and the corresponding machining process data. This paper introduces the interest of a common process data standard for supervision and simulation in a multi-process manufacturing environment. After a brief state-of-the-art on multi-process integration in the current numerical chain, a new approach is proposed for simulation and optimization based on STEP-NC object oriented programming standard.

II. MULTI-PROCESS IN CURRENT MANUFACTURING

A. Current G-code based numerical chain

Product manufacturing usually involves several processes. Most of them are integrated in a conventional numerical chain, also called CAX manufacturing chain. The Computer Aided Design (CAD) system is used to create a digital model of the part. Then, manufacturing experts translate this global geometry into a group of machining features well adapted to a defined machining process, relying on their own experience. Even if a CAD file is only containing a global geometry, the choice of a process to machine an area of the part leads to speak of machining entity. A lot of factors can inflect the selection of the best machining process: feasibility of the part, respect of the tolerances, availability of the process in the factory, knowledge of a qualified subcontractor, price, cost, manufacturing time, etc. but also some more subjective criteria linked to the experience of the experts, which are difficult to capture.

The model information is then exported to Computer Aided Manufacturing (CAM) software. The CAM software enables the user to add manufacturing data linked to the selected process. For HSM, data such as machine tool, cutting strategies, tools, operation sequence are used to generate the tool paths that apply to the features. These object oriented information is stored in a proprietary CAM format. Today there is no standard to exchange manufacturing data between the CAM software of different companies. The CAM suites are often processing one single manufacturing process and compatibility between CAM software suites is hardly possible. A solution is to use a single vendor suite but it is usually not available for various processes (for example HSM, RM and EDM). Moreover there is still a problem if a subcontractor uses another CAM suite. Then the tool paths and machining parameters are processed by a postprocessor selected for a unique machine tool. There are consequently

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as many postprocessors as existing CAM software/CNC/Machine tool configurations. The resulting low level information is translated by the postprocessor into NC code which is most of the time a G-code file based on ISO 6983 standard. For every process considered independently, there is unidirectional information flow from CAD to CNC with no possibility to have an overview of the manufacturing data at the CNC level. In this context, there is a real need to dispose of a generic standard for manufacturing data exchange (Fig. 1).

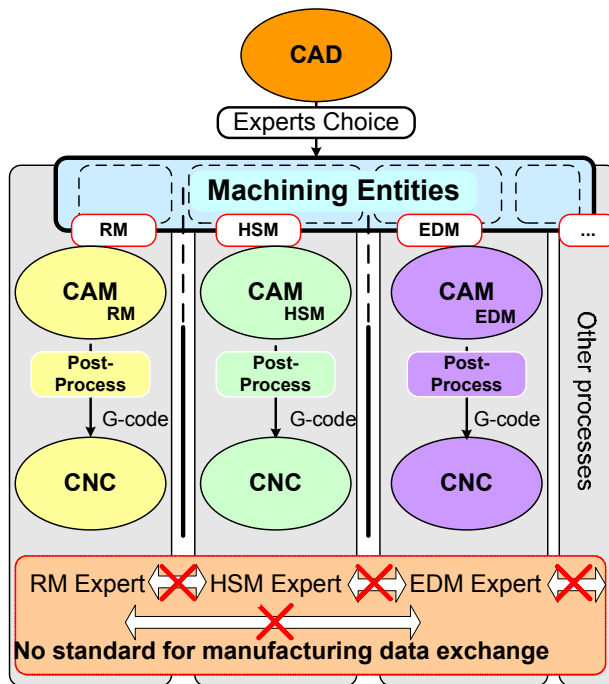


Fig. 1. Current numerical chain in a multi-process environment

To make this numerical chain data flow efficient, multi directional data exchange is necessary. First, a feedback from CNC to CAD/CAM would allow a total integration of the process into the numerical chain. Then, a multidirectional data exchange between all the processes would lead to new possibilities for supervision and interoperability. A range of research works were carried out to design and implement intelligent CAD/CAM systems for CNC programming, especially for milling applications, but often restricted by the use of G-code machine tool programming [7]. However, very few works have been lead to create a link between the processes using a unique numerical chain. There is no concrete solution in the current situation to support data exchange at the CAM/CNC level between processes that are culturally different and isolated inside their own numerical chain.

B. Multi-process machine tool

Combined turning/milling machine are increasingly used in industry and provide large productivity gains and more flexibility. Combined machining programming also becomes

more complex. CAM software suites are integrating vendors' modules to improve the axis control involving complex algorithms for avoiding collisions. However, the numerical chain still sticks to basic unidirectional principles with no feedback of milling-turning interactions out of the vendor CAM software. To go further in the current 'multi-process' approach, some machines tools are offering very different processes, as the "Desktop One" described in [8] which has milling, EDM and ECM (Electro Chemical Machining) functions. This kind of configuration is often limited to micro-machining applications. It demonstrates that combining these processes either on a single machine tool or into a unified numerical chain can be an efficient solution. Indeed, it takes advantage of their complementarities at larger frame, which is one purpose of this paper. A multi-process environment means an environment where several processes can be used to machine a single part or an assembly, not necessarily by using combined machines tools.

C. Discussion

Multi-process manufacturing conveys an important stake for the future but it still relies on old and conventional ways of proceeding and thinking. The use of CAM proprietary standards, postprocessors and the structured low level information of G-code are today the main locks for a totally integrated manufacturing numerical chain. In this context, STEP-NC data model offers new possibilities for achieving a multi process manufacturing environment.

III. STEP-NC: A DATA STANDARD WELL ADAPTED TO MULTI-PROCESS MANUFACTURING

The STEP (STandard for Exchange of Product data model) standard ISO 10303 [9] has been developed to allow information exchange avoiding proprietary format. This standard is widely spread for data exchange in the case of 3D part model, by the Application Protocol AP203 or AP214 for automotive and is available for export on most of the CAD software suites. A new data standard, STEP-NC, is under development to integrate manufacturing information to the feature based CAD model built using data structure of Application Protocol AP224. STEP-NC refers to ISO 14649 Application Reference Model (ARM) [10] and ISO 10303-238 Application Interpreted Model (AIM) [11]. ISO 10303-238 is mapped from ISO 14649 ARM. ISO 14649 contains the structure of process data. It describes workplans and workingsteps made of manufacturing operations, machining strategies, tools, machining parameters, etc. This work is based on ARM ISO 14649 standard but can be reflected to ISO 10303-238. Object oriented STEP-NC programming offers a new opportunity to support high level and standardized data from design to NC controller. It allows bidirectional data flow between CAD/CAM and CNC with no information loss at any stage of the numerical modelling. Several processes are under implementation in STEP-NC Standards and will enable a multidirectional data flow to integrate the manufacturing numerical chain (Fig. 2).

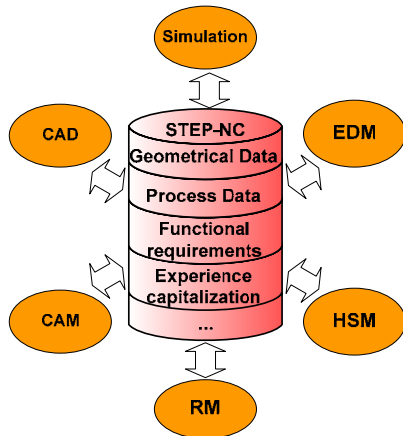


Fig. 2. STEP-NC Multi-process integrated numerical chain

STEP-NC research has been conducted for several processes linked with researchers' main competence fields of manufacturing [12]. The first and most popular one is milling. Several International projects lead to the first publications of ISO Standard 14649 Part 10 (General process data [13]) and 11 (process data for milling [14]) and completed with Part 111 (Tools for milling). These standards give the frame for STEP-NC milling. Turning applications are also included in the Application Reference model of the STEP-NC standard. ISO 14649 Part 12 [15] gathers process data for turning and part 121 tools for turning. For hybrid turning/milling applications, Rosso et al. present in [16] the results of their study for the use of STEP-NC in manufacturing of asymmetric rotational component. Their conclusion is that the ISO 14649 Part 10 is capable of supporting the features required by these complex components and outlines a feasible solution to use the ISO 14649 data model for turn/mill machining. As STEP-NC ISO 14649 standardizes a data model for computerized numerical controllers, it is not restricted to milling and turning applications. ISO 14649 part 13 is under development for EDM data process [17] and research works are done in this field [18]. Some other works are done to build STEP-NC data process for Rapid Manufacturing [19]. By supporting all these different kind of process data, STEP-NC offers new possibilities to integrate, supervise, link and make interoperable all these processes in an integrated manufacturing numerical chain. Each process has its own specificities. The current G-code numerical chain results in insulating their implementation. Information available in G-code files cannot be exploited as it is too low level and only includes a small quantity of the data linked to the machining process. As STEP-NC supports a large field of object oriented data from CAD to CNC, it allows integrating multi-process relations with a common standard for several machining processes. Although STEP-NC standard proposes all the required characteristics to support a multi-process environment, very few research works were done concerning this approach. This paper gives a proposal for the integration of intelligent multi-process supervision using STEP-NC numerical chain.

IV. STEP-NC MULTI-PROCESS NUMERICAL CHAIN

A. A step towards intelligent manufacturing

An intelligent multi-process system can be defined as a comprehensive system supervising autonomously several manufacturing processes with a minimum interaction with a human operator. STEP-NC standard provides a complete data structure that gives a support for information exchange of several numerically integrated processes. When the current numerical chain only relies on expert users' practices, STEP-NC offers new possibilities of integrating a comprehensive data support. It opens the way to a strong communication hub between experts by using a common well adapted language but also provides a data support for computational simulation and optimization of the multi-process workplan.

B. Building a multi-process STEP-NC file

STEP-NC file is an innovating support for manufacturing data and a large part of the work consists of building this optimized and well adapted file for intelligent manufacturing. The data structure of a STEP-NC file can be schematized by several overlapped parts of a puzzle (Fig. 3) describing a complete scenario. Today, to build the STEP-NC file, a hierarchical method is adopted. From the CAD model, an automatic or manual recognition of the manufacturing features is operated based on their compatibility with a chosen process. Manufacturing features are sequenced to create the workplan during process planning. This workplan is composed of a list of workingsteps with the possibility of involving several processes. A STEP-NC CAM software allows the user to select process data for every workingsteps. The STEP-NC file is then completed and can be sent to the NC controller. An interpreter in the CNC reads the object oriented data in the STEP-NC file and generates the tool paths which are well adapted to the production equipment. A machine functional model is available and can be included to the process simulation. The main principle is the same at the CNC level for each process required in workplan. Data feedback is available from CNC to CAM/CAD as any process data or geometry modification is directly reflected in the STEP-NC file, even at the shop floor level. Experience capitalization, in the STEP-NC file if needed or in a database, and can be exploited for building or optimizing STEP-NC file process data.

C. Building an optimized multi-process STEP-NC file

Multi-process approach involves more and more complex scenarios and new issues. STEP-NC provides all the bases to support intelligent multi-process manufacturing. A large part of the intelligence is now to simulate and optimize the STEP-NC data and their interpretation at CNC level. In this large transversal field for actions, it is complex to reach a simulation of all the possibilities offered by the multi-process environment. It is all the more complex to find an optimal solution. The presented approach aims at modelling simulation fields in a multi-process environment.

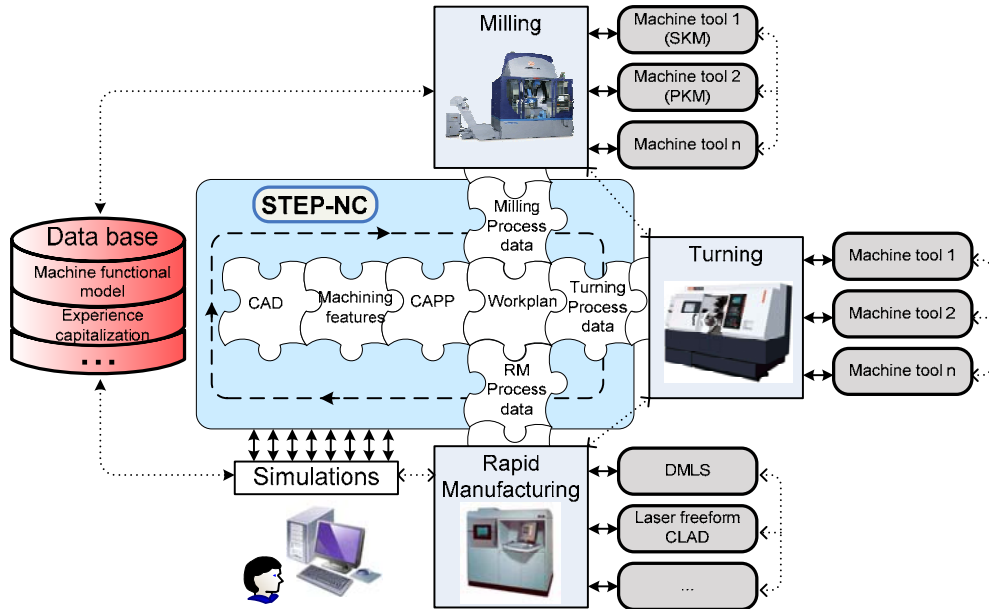


Fig. 3. STEP-NC multi-process numerical chain

V. SIMULATION SPACES IN A MULTI-PROCESS ENVIRONMENT

A. A proposal for modelling the global simulation environment

This proposal is based on dividing three main simulation spaces (Fig.4). A simulation space can be defined as a boundless but structured set where simulations can be performed. It is schematized here with imaginary boundaries representing knowledge limits but can be infinitely extended.

These simulation spaces can be distinguished by their respective objectives. They are complementary, interdependent and closely linked.

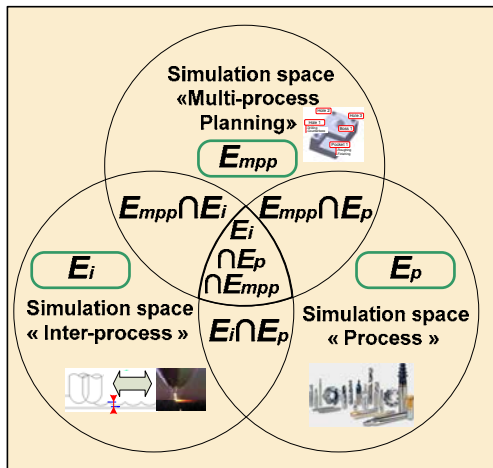


Fig. 4. Simulation in a multi-process environment

The main input of the manufacturing numerical chain is the CAD model of the part. This CAD model contains data for part geometry, tolerances, material, etc. These characteristics must be respected and are a theoretical objective for manufacturing process. However, every process has its own constraints that must be taken into account when deciding the manufacturing workplan of the part.

1) From CAD to AP224 manufacturing features and process plan: the Multi-process planning simulation space (E_{mpp})

Discretizing a CAD model into manufacturing features means more than recognizing usual geometrical entities. A lot of research works have been done on manufacturing feature extraction [20]. It appears that the solution can hardly be separated from the manufacturing process involved. In other words, the choice of manufacturing feature geometry is linked to a process. Thus, a simple part can lead to several feature decompositions depending on the process choice in a multi-process environment, as the process is not fixed. In some cases, indecision of the suiting process to machine an area of the part can lead to further simulations. This is the exploration field for the Multi-process Planning Simulation Space (E_{mpp}). The object of E_{mpp} is to find the optimal machining features and process plan.

2) Process simulation space (E_p)

The workplan is composed of several workingsteps associated with the manufacturing features. The process simulation space (E_p) gathers all the computations and choices concerning process data and machining parameters selection. E_p is involved for high level manufacturing data selection in STEP-NC file but also integrates shop-floor simulation in the interpreter. This shop floor simulation can

be performed offline or online. Typically, an offline simulation will be privileged in the STEP-NC interpreter for tool paths programming, tool paths optimizations, machining parameters adaptation, etc. Real time optimizations, simulations from sensors feedback in the CNC are to be done online and are part of Ep.

3) Inter-process simulation space (Ei)

Relations between processes take a central position in a totally integrated multi-process context. The Inter-process relations and optimizations are fully integrated in the numerical chain with a large consideration of the Inter-process simulation space (Ei), which is new here. In the traditional G-code based numerical chain, a large part of the simulations concern the process (Ep), manufacturing experts choose the well adapted workplan based on their experience and knowledge (Empp), but inter-process simulation (Ei) is hardly possible due to different data standards and expert communication languages.

In the STEP-NC numerical chain, Ei is the missing link between Empp and Ep when several processes are required. Relations and communication channels between the different processes are enabled with a direct effect on the machining features, the workplan and the process data.

B. Interactions and place for optimized solutions

1) Process and process planning interaction

The intersection between Empp and Ep spaces is the place for process simulations in close link with process planning, and reciprocally. $Empp \cap Ep$ includes the bidirectional relations between CAPP and each selected process. Relations between machining entities and process parameters are important. For example, in pocket milling, the tool diameter is limited by the corner radius for finishing operations. On the other way around, characteristics of a process can also lead to select a feature more than another one. For instance, using a step drill to machine a hole and the associated counter bore results in forcing the two features to be merged in one workingstep.

2) Process planning and inter-process relations Interaction

The constraints of each process must be taken into account when creating machining features and workplan. These interactions are simulated in $Ep \cap Ei$. For example, the thermal effects of Direct Laser Manufacturing (DLM) with powder injection [21] constrain the selected features to be manufactured very early in the workplan, before the finishing operations of high speed milling. Reciprocally, machining features sometimes constrain the choice of the process sequence and consequently of the inter-process relations. For example, if a flat must be milled after a turning operation, inter-process interactions are ordered by process planning.

3) Process and inter-process Interaction

The process simulation space Ep, directly linked with the machine tool functional model, can provide the simulation results associated with a selected process. The results can

have consequences on the other processes machining parameters. For example, the finishing cutting conditions in milling process (feedrate, cutting speed, etc.) can be adapted due to thermal effects after DLM machining a feature.

A multidirectional data exchange enables a workingstep associated with a process to be carried out in an intelligent multi-process context, taking other processes into account.

4) A global and optimized solution in the comprehensive $Empp \cap Ep \cap Ei$ simulation space

The goal to reach is the simulation of a totally integrated manufacturing environment that considers in the same time relevant multi-process planning, inter-process relations and process attributes simulations. However, simulation in $Empp \cap Ep \cap Ei$ involves complex reasoning and simulation methods. Processing the three presented simulation spaces in the same time is certainly not the best way to initiate a solution. In this paper, the bases for a discretization of the simulation space are presented. The objective is to help the different expert along the numerical chain to make their choices, not only by considering their own specific area but by integrating the requirements of the whole manufacturing numerical chain. This is made possible by the use of a data exchange standard supporting multi-process planning information and process data.

To validate the main principles involved in multi-process manufacturing, a STEP-NC platform has been developed.

VI. MULTI-PROCESS INTEGRATED PLATFORM

A. STEP-NC Multi-Process Manufacturing Concept

To implement and validate the proposal of an integrated multi-process STEP-NC numerical chain, a comprehensive multi-process supervision platform is proposed, in which the digital model of the part can include cross interactions between the different processes (Fig.5).

CNC based processes as milling, turning, rapid manufacturing (DLM for example) and incremental sheet forming are well adapted to be integrated in a comprehensive STEP-NC manufacturing environment. However, very few CNC controllers are able to read STEP-NC files today. Some specific STEP-NC interpreters were developed, mostly as development tools for laboratory applications. They are reviewed by Xu et al. in [22]. Recent works at IRCCyN on high level STEP-NC tool path programming lead to develop a first basic version of an STEP-NC interpreter, dedicated to industrial machine tools [23]. These first concrete works on STEP-NC standard showed the real necessity of a STEP-NC development platform to validate and demonstrate the new programming approaches. Then, a first version of a STEP-NC enabled industrial CNC was developed. It was presented in the frame of the participation of IRCCyN to the normative ISO TC184/SC1/WG7 working group of STEP-NC ISO 14649 standard [24]. This STEP-NC Platform for Advanced and Intelligent Manufacturing (SPAIM) is now under implementation for multi-process machining supervision.

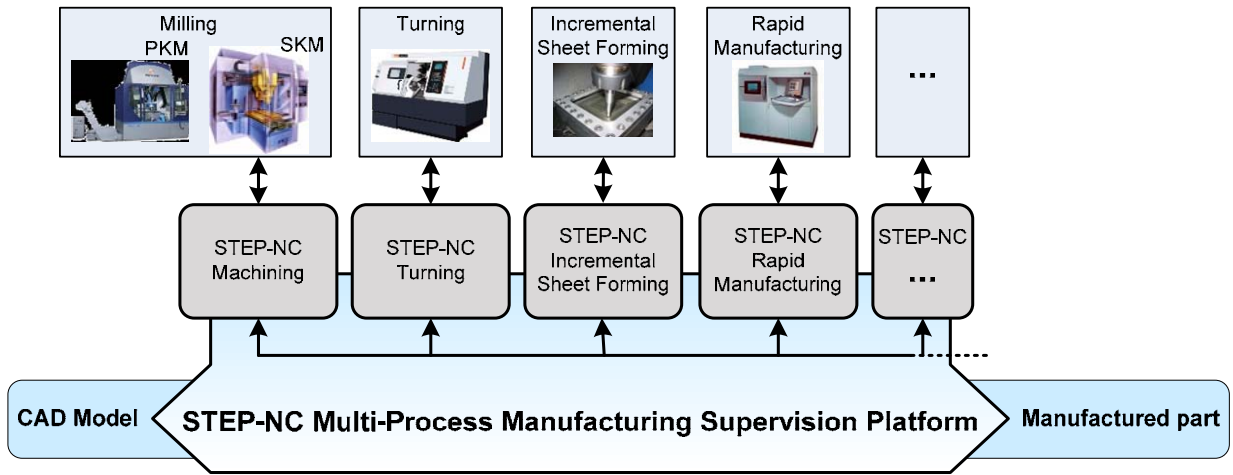


Fig. 5. STEP-NC multi-process manufacturing concept

B. Presentation of SPAIM platform

STEP-NC Platform for Advanced and Intelligent Manufacturing (SPAIM) is composed of a human/machine interface and several Delphi based modules for translating STEP-NC data into an explicit workplan and tool paths for each operation [25]. SPAIM has already been implemented and validated on a HSM machine tool of the laboratory [26]. This machine was designed by the Fatronik Company and is called VERNE [27]. It has parallel kinematics architecture and is equipped with a Siemens Sinumerik 840D NC controller (Fig. 6). Another version of SPAIM has been developed for a Hermle C30U high speed machining centre equipped with a Heidenhain CNC controller.



Fig. 6. SPAIM platform at IRCCyN

C. Multi-process manufacturing and simulation in SPAIM

To achieve intelligent multi-process manufacturing in a STEP-NC numerical chain, it is proposed here to use a three level method.

1) First level: a multi-process manufacturing platform

The first level consists in developing a multi-process integrated manufacturing platform able to read multi-process STEP-NC file and execute it on machine tools (Fig 7.). The current developments aim to extend SPAIM capabilities to other processes. Turning applications are developed based on the already existing architecture of SPAIM platform and will allow to machine parts from a STEP-NC file on turning machine tools. Recent works also focus on rapid

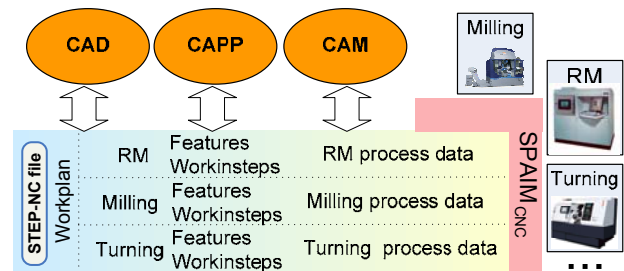


Fig. 7. SPAIM_{CNC}: a multi-process STEP-NC enabled CNC

manufacturing (RM) parts, with new feature definitions. RM involves a new way of building tool paths for material adding processes. These works open the way for multi-process manufacturing in a totally integrated STEP-NC platform.

Fig. 8 shows the first results of multi-process manufacturing by using SPAIM. Test part 1 is manufactured from the STEP-NC file by first using RM because of its internal slot. The finishing of the upper plan, holes and pocket involves HSM. Test part 2 is machined using a RM process and then turning.

In its current version, SPAIM works as a STEP-NC enabled CNC controller (SPAIM_{CNC}) which processes workplans made of multi-process workingsteps. Works are lead to develop it as a totally integrated manufacturing platform for multi-process supervision.

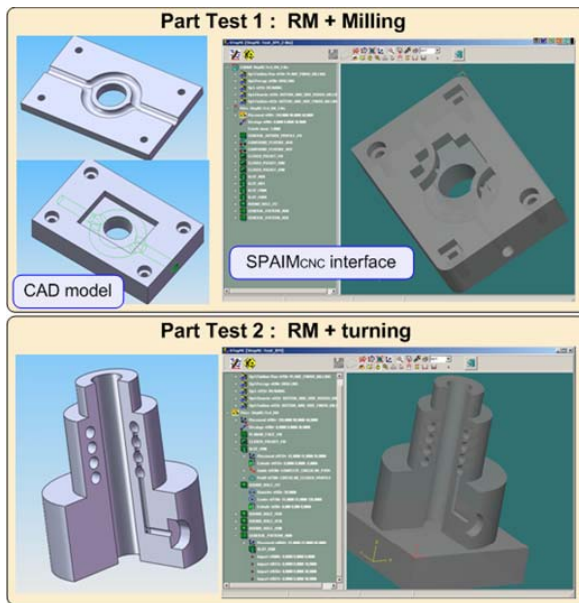


Fig. 8. Multi-process manufacturing parts processed in SPAIM_{CNC}

2) Second level: integration of simulation modules

The second level consists in integrating simulation tools for multi-process planning and process simulations (Fig. 9).

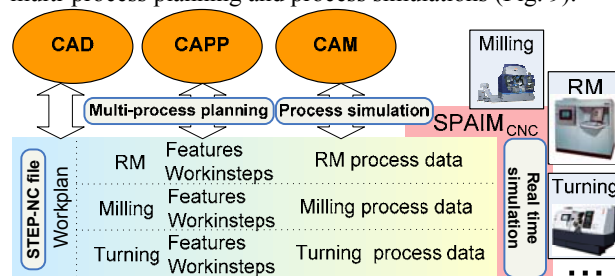


Fig. 9. Simulation modules in SPAIM numerical chain

Today, several process simulation tools are ready to be implemented. The next two examples illustrate the use of simulation tools for milling applications.

In the first example, a real feed rate simulation module and a tool deflection compensation module can be added according to works already done at IRCCyN on 3D solid simulation [28] and tool deflection compensation [29]. These simulations associate cutting tools and machine tools functional models to benefit from the most accurate image of the real machining. These simulations can be performed offline for choosing well adapted process data in the STEP-NC file. They can also be performed in SPAIM_{CNC} controller for a machining operation (for example after on-machine inspection). The simulated machining parameters or tool paths will enable to avoid tracking errors and to compensate tool deflection during the real machining operation.

In another example, real time optimizations can also be performed by using process data feedback in the CNC

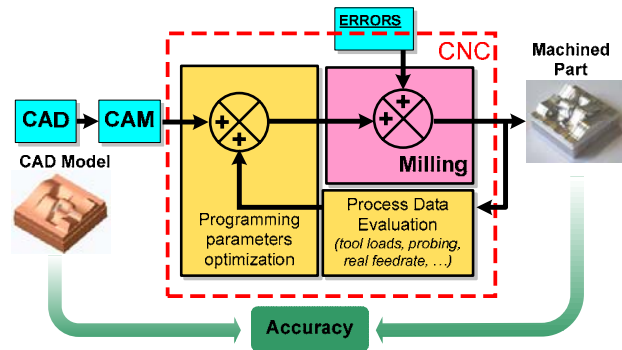


Fig. 10. ICAM approach principles

controller. The ICAM (Intelligent Computer Aided Manufacturing) concept is a method to optimize the machining parameters and tool paths by using the available data in the CNC [30] to control the process (Fig. 10). A previous application of this approach enabled real time feed rate optimization based on cutting forces estimation from the NC controller data (motors amperage, delivered power, articular coordinates of the joints, etc.). In another application, tool paths are regenerated after online machine inspection. The presented tools are examples of the process simulation capabilities in SPAIM (SPAIM_{SIM}).

3) Third step: an intelligent STEP-NC multi-process supervision platform

The third level consists in integrating a new layer for inter-process simulation (Fig. 11). This will stand as a link between multi-process planning and process simulation for an intelligent supervision of the manufacturing processes.

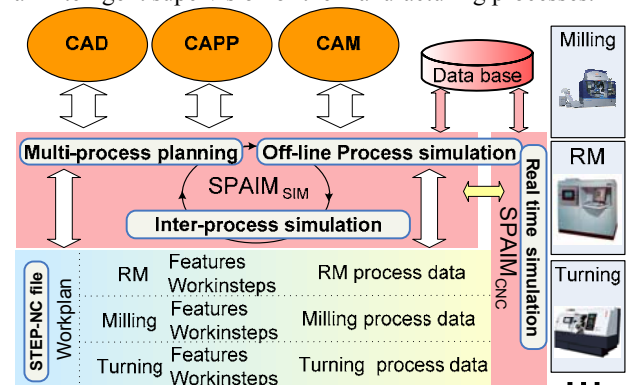


Fig. 11. SPAIM multi-process supervision

As SPAIM_{CNC} enables CNC to read and interpret multi-process STEP-NC files, SPAIM_{SIM} will integrate simulation tools including inter-process simulation. This is made possible thanks to the large range of high level data available in the STEP-NC file for all the processes involved in the workplan. Cross interactions between the different processes will be possible by integrating the associated requirements in the workplan or for process data choice. A database will gather manufacturing data warehouse and knowledgebase. SPAIM_{SIM} and SPAIM_{CNC} will merge to develop an intelligent and advanced STEP-NC multi-process

supervision platform. Further works will lead to develop the multi-process supervision SPAIM_{SIM} but needs time to be implemented for concrete validation.

VII. CONCLUSION

The STEP-NC standard presents a range of new possibilities for intelligent manufacturing. This object oriented standard is well adapted for exchanging high level manufacturing data. It provides a new vision of the numerical chain with multidirectional exchange possibilities. In this paper, the STEP-NC multi-process manufacturing concept is presented. Multi-process manufacturing associates the advantages of several processes to increase productivity, possibilities for part manufacturing and interoperability but often leads to complex scenarios. In this context, simulation tasks take a central part for intelligent supervision. Thus, the simulation spaces concept is introduced as a performing approach to model simulations fields for multi-process manufacturing. A STEP-NC enabled platform for milling, turning and rapid manufacturing has been developed. This STEP-NC Platform for Advanced and Intelligent Manufacturing (SPAIM) aims at validating the new concepts involved in STEP-NC multi-process manufacturing. Test parts are presented as well. This new multi-process manufacturing approach needs a high level data standard, such as STEP-NC, to be efficiently implemented at large scale. Indeed, the technological improvements conveyed by STEP-NC appear to be obvious when carrying out innovative manufacturing approaches such as those proposed here. The purpose of STEP-NC is not only to overtake the deep-rooted G-code programming for usual machining operations, but to develop a new intelligent, integrated and interoperable manufacturing environment.

REFERENCES

- [1] B. P. Erdel, High-speed machining, 2003, Soc. of Manuf. Engineers.
- [2] N. Hopkinson, R. Hague and P. Dickens, Rapid Manufacturing: An Industrial Revolution for the Digital Age, 2006, John Wiley & Sons.
- [3] K. H. Ho and S. T. Newman, State of the art electrical discharge machining (EDM), International Journal of Machine Tools and Manufacture, Vol 43, 2003, pp. 1287-1300.
- [4] J. Jeswiet, F. Micari, G. Hirt, A. Bramley, J. Duflou and J. Allwood, Asymmetric Single Point Incremental Forming of Sheet Metal, CIRP Annals - Manufacturing Technology, Vol 54, 2005, pp. 88-114.
- [5] K. L. Edwards, Designing of engineering components for optimal materials and manufacturing process utilisation, Materials & Design, Vol 24, 2003, pp. 355-366.
- [6] X. W. Xu and S. T. Newman, Making CNC machine tools more open, interoperable and intelligent—a review of the technologies, Computers in Industry, Vol 57, 2006, pp. 141-152.
- [7] J. Balic, Intelligent CAD/CAM system for CNC programming - an overview, Advances in Production Engineering & Management, Vol 1, 2007, pp. 13-21.
- [8] T. Kurita and M. Hattori, Development of new-concept desk top size machine tool, International Journal of Machine Tools and Manufacture, Vol 45, 2005, pp. 959-965.
- [9] J. P. Michael, Introduction to ISO 10303—the STEP Standard for Product Data Exchange, Journal of Computing and Information Science in Engineering, Vol 1, 2001, pp. 102-103.
- [10] ISO 14649 Part 1 - Industrial automation systems and integration -- Physical device control -- Data model for computerized numerical controllers - Overview and fundamental principles, TC184/SC1, 2003.
- [11] ISO 10303-238 - Industrial automation systems and integration -- Product data representation and exchange -- Part 238: Application protocol: Application interpreted model for computerized numerical controllers, TC 184/SC 4, 2007.
- [12] S. T. Newman, A. Nassehi, X. W. Xu, R. S. U. Rosso Jr, L. Wang, Y. Yusof, L. Ali, R. Liu, L. Y. Zheng, S. Kumar, P. Vichare and V. Dhokia, Strategic advantages of interoperability for global manufacturing using CNC technology, Robotics and Computer-Integrated Manufacturing, Vol 24, 2008, pp. 699-708.
- [13] ISO 14649 Part 10 - Industrial automation systems and integration - physical device control - data model for computerized numerical controllers - Part 10: general process data, ISO TC 184/SC1, 2004.
- [14] ISO 14649 Part 11 - Industrial automation systems and integration -- Physical device control -- Data model for computerized numerical controllers -- Part 11: Process data for milling, TC 184/SC 1, 2004.
- [15] ISO 14649 Part 12 - Industrial automation systems and integration -- Physical device control -- Data model for computerized numerical controllers -- Part 12: Process data for turning, TC 184/SC 1, 2005.
- [16] R. S. U. Rosso, S. T. Newman and S. Rahimifard, The adoption of STEP-NC for the manufacture of asymmetric rotational components, *In proceedings of the Institution of Mechanical Engineers Part B-Journal of Engineering Manufacture*, 2004, pp.1639–1644,
- [17] ISO14649 Part13 - Industrial automation systems and integration— Physical device control-data model for computerized numerical controllers—Part 13: Process data for Wire-EDM, TC 184/SC 1, 2003.
- [18] A. Sokolov, J. Richard, V. K. Nguyen, I. Stroud, W. Maeder and P. Xirouchakis, Algorithms and an extended STEP-NC-compliant data model for wire electro discharge machining based on 3D representations, International Journal of Computer Integrated Manufacturing, Vol 19, 2006, pp. 603 - 613.
- [19] R. Bonnard, P. Mognol and J.-Y. Hascoët, Rapid Prototyping Project Description in STEP-NC Model, Proceedings of 6th CIRP International Seminar on Intelligent Computation in Manufacturing Engineering, 2008, Naples (Italy).
- [20] B. Babic, N. Nestic and Z. Miljkovic, A review of automated feature recognition with rule-based pattern recognition, Computers in Industry, Vol 59, 2008, pp. 321-337.
- [21] S. Barnes, N. Timms, B. Bryden and I. Pashby, High power diode laser cladding, J. of materials processing technology, 138, 2003, pp. 411-416.
- [22] X. W. Xu, H. Wang, J. Mao, S. T. Newman, T. R. Kramer, F. M. Proctor and J. L. Michaloski, STEP-compliant NC research: The search for intelligent CAD/CAPP/CAM/CNC integration, International Journal of Production Research, Vol 43, 2005, pp. 3703-3743.
- [23] R. Laguionie, M. Rauch and J.-Y. Hascoët, Toolpaths programming in an intelligent STEP-NC manufacturing context, Journal of Machine Engineering, Vol 8, 2008, pp. 33- 43.
- [24] J. Y. Hascoët and R. Laguionie, STEP-NC research at the IRCCyN, 56th ISO TC 184/SC1 Plenary Meeting, 29-31 October 2008, Busan.
- [25] R. Laguionie, J.-Y. Hascoët and S.-H. Suh, A new STEP-NC based CNC interface for High Speed Machining, *In proceedings of the 12th Conference on Modelling of Machining Operations*, 2009, pp.443-450, San Sebastian (Spain).
- [26] M. Rauch, R. Laguionie and J.-Y. Hascoët, Achieving a STEP-NC Enabled Advanced NC Programming Environment, in "Advanced Design and Manufacturing Based on STEP", Springer London, editions Xu X., Nee A. Y. C., 2009, pp. 197-214, in press.
- [27] Y. S. Martin, M. Gimenez, M. Rauch and J.-Y. Hascoët, VERNE – A New 5-Axes Hybrid Architecture Machining Centre, *In proceedings of the 5th Chemnitz Parallelkinematik Seminar*, 2006, pp.657-676, Chemnitz (Germany).
- [28] A. Dugas, J. J. Lee, M. Terrier and J.-Y. Hascoët, Development of a machining simulator considering machine behavior, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol 217, 2003, pp. 1333-1339.
- [29] S. H. Suh, J. H. Cho and J. Y. Hascoët, Incorporation of Tool Deflection in Tool Path Computation: Simulation and Analysis, SME J. of Manufacturing Systems, Vol 15, 1996, pp. 190-199.
- [30] J.-Y. Hascoët and M. Rauch, A generic method for real time adaptive force control in manufacturing operations using CNC data, *In proceedings of the International conference on High Speed milling*, 2006, pp.101-113, Suzhou (China).