STEP-NC, advanced CNC programming
CAD/CAM/CNC data interoperability,

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ENHANCING CNC MANUFACTURING INTEROPERABILITY WITH STEP-NC

Despite substantial improvements CNC manufacturing is still based on dated practices and habits. This is mostly due to the use of ISO 6983 standard (G-codes) combined with vendor specific formats to exchange CAD/CAM/ CNC information. The manufacturing sector is consequently made of a collection of disconnected elements that are difficult to make communicate together. On the contrary STEP-NC approach offers many opportunities to overtake the current situation and rethink CAD/CAM/CNC numerical chains. However, the actual integration of STEP-NC in industrial concerns is quite limited. It is essential to couple this innovative approach with existing equipments. This paper shows how STEP-NC can be an efficient way to reconcile today's interoperability and efficiency demands by introducing the association of two manufacturing platforms: SPAIM, developed at IRCCyN (France), and which controls current industrial machine tools directly from STEP-NC files and IIMP from the University of Auckland (New Zealand), which realizes data portability between heterogeneous proprietary formats, process interoperability. As a result, both approaches lead to improved supervision and integration of the machining systems.

1. INTRODUCTION

The manufacturing area has benefitted from various progresses over the last decades: the equipment has become faster, smarter and safer to face today's global challenges. However, CNC programming is somehow still based on dated practices and habits. This mostly comes from the use of ISO 6983 data standard, as known as G-codes [1]. The manufacturing data chain is consequently composed of disconnected elements that are using vendor specific formats to exchange CAD/CAM/ CNC information and that are difficult to make communicate together [2]. In contrast, STEP-NC programming approach rethinks CAD/CAM/CNC numerical chains [3]. It stands therefore as a viable solution to overtake the current situation.

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Among many substantial improvements [4], STEP-NC standards enables the development of advanced NC programming approaches and the improvement of CAD/CAM/CNC interoperability, which are central in today's global and high competitive manufacturing industry. However, the actual integration of STEP-NC in industrial concerns is very limited and these industrials need to be convinced. It is consequently essential to couple STEP-NC innovative approach with existing equipments to demonstrate the benefits.

This paper discusses these central issues and introduces an association of two manufacturing platforms, which have been proposed to meet manufacturing efficiency and interoperability needs. The first approach stands at shop-floor level: SPAIM developed at IRCCyN makes true intelligent STEP-NC programming approaches. The second approach positions at business level: IIMP project from the University of Auckland realizes data portability between heterogeneous proprietary formats and process interoperability. In a word, both approaches lead to an improved supervision and integration of the machining systems.

2. STEP-NC CAD/CAM/CNC PROGRAMMING APPROACHES

Based on a STEP concept, STEP-NC objective is to significantly enhance the communication between CAD/CAM systems and NC controllers. It allows the use of modern NC functionalities and simplifies the programming (CAM, CAPP…) by a feature-oriented description [5]. The manufacturing stage is fully included in the whole product development process: the modifications made on the shop-floor stage can be saved and fed back to the design stage, as ISO 14649 is fully STEP-compliant [6]. Another important aspect is that using STEP-NC means working with a unique NC formalism for any machine tool software, as no post-processing operation is needed (Fig. 1). The communication language used by STEP-NC is a high level one; the data exchanged relate to the machining features rather than to simple axis coordinates control [7].

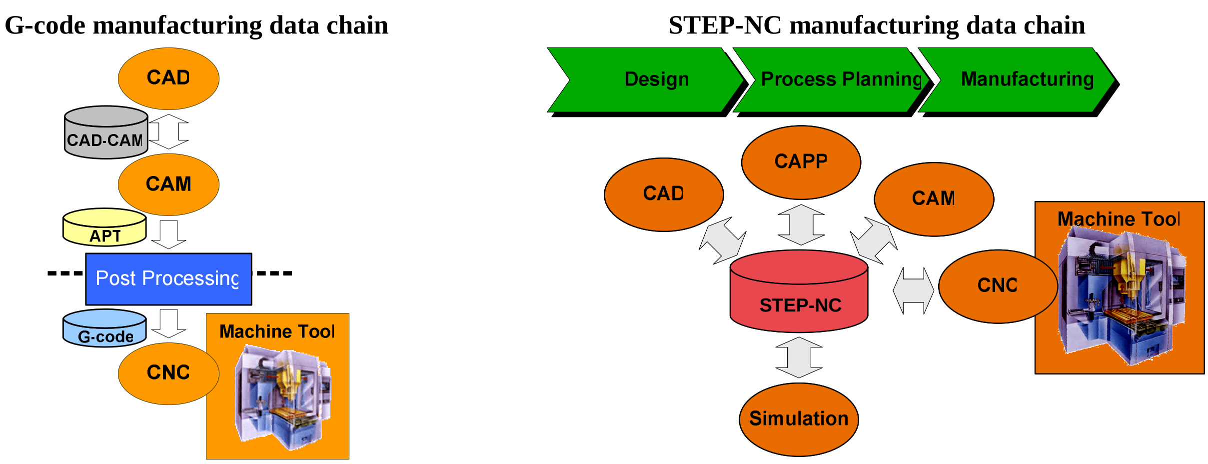

Fig. 1. Manufacturing data chains with G-code and STEP-NC

STEP-NC formalism consequently enhances the manufacturing equipment effectiveness by developing intelligent programming approaches and making these equipment and software tools more interoperable by exchanging seamlessly high level data all along the manufacturing data chain.

2.1. INTELLIGENT NC PROGRAMMING

STEP-NC object-oriented programming helps to shift the tool-path generation to the shop-floor level. As a result, some intelligent and decision-making power can be transferred into the CNC controller. Self learning algorithms begin to be developed to produce better quality parts to compensate controlled errors [8]. Thanks to its high level object-oriented data model, STEP-NC approach opens the path to advanced programming methods [9], new simulation and optimization approaches can be implemented in order to have a better control of the manufacturing process and to optimize CAM and CNC parameters (Fig.2).

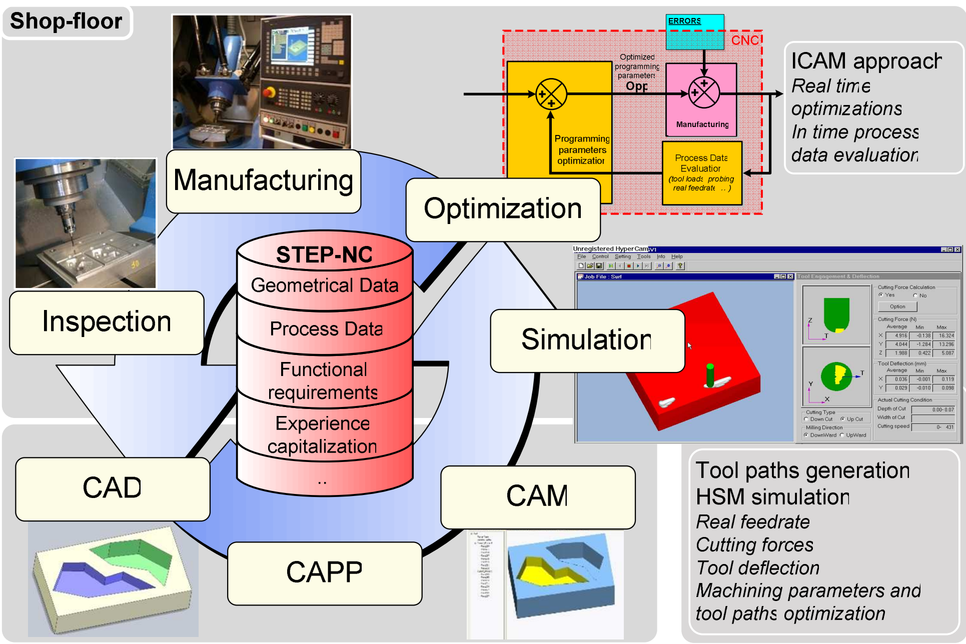

Fig. 2. Advanced NC programming enabled by STEP-NC

In addition to that, by moving the CNC controller into the CAD/CAM data chain, information feedback, tool-paths adaptations and “on the fly” modifications can be send from CNC to the other elements [6]. Consequently, the CNC controller has a central role because it interprets STEP-NC manufacturing data and generates explicit tool-paths by using manufacturing feature geometrical characteristics and programming parameterization of each manufacturing step. SPAIM project described in this paper stands as an example of the numerous intelligent NC programming possibilities offered by STEP-NC approach.

2.2. INTEROPERABILITY

In previous part of this paper, STEP-NC capabilities to support intelligent NC programming applications have been proved. By being independent from any commercial software tool, STEP-NC format is well suited for achieving collaborative environment too. Indeed, a major issue in today's global manufacturing context lies into the data portability between the links of a manufacturing data chain that can include distributed partners [10].

STEP-NC can stand as a valid solution to reconcile these interoperability needs, as proposed by various research projects: the Universal Manufacturing Platform developed at the University of Bath [11] and the UbiDM (Design and Manufacture via Ubiquitous Computing Technology) of Pohang University of Technology [12]. However, today's implementations of STEP-NC standard are still limited to research purposes and feasibility demonstrations. A major barrier to the development of interoperable platforms in the industry is the defiance from software vendors who see the current situation as an opportunity to maintain their market advantage through system lock-in [10]. Moreover, it is central to propose hybrid manufacturing environments which are able to make existing software cohabitate with the new STEP-NC programming approaches.

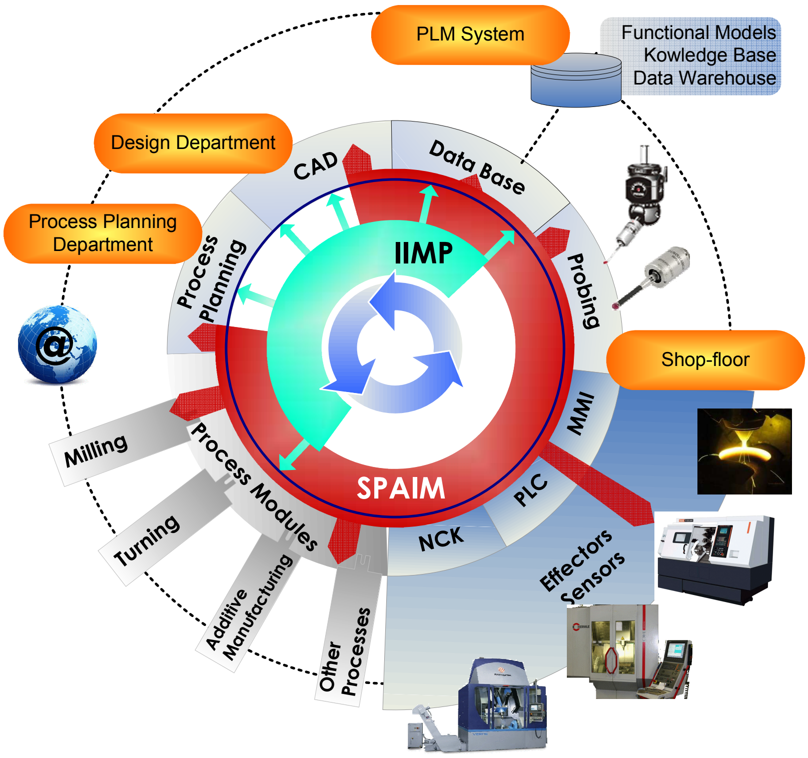

Fig. 3. Complementarities of SPAIM and IIMP in for advanced CNC manufacturing

The CAD/CAM/CNC platforms presented in this paper are an illustration of such system. SPAIM is shop-floor oriented, invests into programming and process methods and enables STEP-NC compliant advanced manufacturing while IIMP stands at business level, makes manufacturing data flows easy among CAD/CAM/CNC systems. Although they can be implemented individually, they collectively form a comprehensive framework that covers the whole manufacturing data chain by interacting with every link (Fig. 3).

3. STEP-NC PLATFORM FOR ADVANCED AND INTELLIGENT MANUFACTURING (SPAIM)

STEP-NC Platform for Advanced and Intelligent Manufacturing is based on a STEP-NC Interpreted Programming approach and can be implemented on most industrial CNC controllers. Two main objectives are attached to the development of such platform. First it stands as a demonstrator of the benefits of STEP-NC and applies on industrial machines; secondly it serves as a development platform for future research and validations concerning the STEP-NC standard.

3.1. ARCHITECTURE OF SPAIM

STEP-NC Platform for Advanced and Intelligent Manufacturing (SPAIM) is composed of a Human/Machine Interface and several Delphi based modules for interpreting STEP-NC data into an explicit workplan and tool paths for each machining operation [13]. SPAIM has already been implemented and validated on a HSM machine tool in Nantes (France). This machine was designed by the Fatronik Company (Spain) and is named VERNE [14]. It has parallel kinematics architecture and is equipped with a Siemens Sinumerik 840D NC controller Other versions of SPAIM have been developed for a Hermle C30U high speed machining centre equipped with a Heidenhain CNC controller and for a CLAD machine equipped with a Siemens 840D CNC controller.

Although the explicit machining tool-paths are generated automatically, a validation from the user is still needed before sending the tool-paths to the machine tool. This stage is considered as compulsory because it informs the user of the movements that the machine tool will execute. Furthermore, the user can check whether proposed tool-paths meet the requirements. If not, the user can modify the 3D model, or the tool-path parameters. After user validation, the appropriate output file (G-code) is automatically executed by the controller.

In practice, SPAIM modules can be installed on the CNC controller of the machine tool, or on an external computer to save the computation power of the CNC hardware (Fig. 4). However, all the modules running on the external PC can be implemented in the CNC computer if its computing capacity allows it. The adopted solution is totally transparent to the user. The external PC can be seen as an extension of the capacities of the CNC hardware. The main modules of SPAIM are:

- *Human Machine Interface*: the user can control the CNC platform using this module. It displays the results of the interpreter and of the simulation module.
- *Master module*: set up on the PC part of the NC controller, this program is directly linked with the HMI and sends the data to other modules at the user’s request. For

parameter modification tasks, it locates and replaces the corresponding elements in the STEP-NC file.

- *Execution module*: distributes orders from the Master module via a local or an Internet network. This module analyses the STEP-NC data through the master module and sends the requested information for processing to the tool-path generation module and to the simulation module.
- *CAD reconstruction module*: updates the CAD geometry from the feature description in the STEP-NC file. This automatic tool sends corresponding commands to a CAD modeller for geometry reconstruction. The CAD model is used by the tool-path generation module to generate common process strategies. This module provides feedback from the STEP-NC file to the CAD model as well.
- *Tool-path generation module*: divided into two components which are run in parallel. The first component handles every common strategy related to the ISO 14649 standard (e.g. contour parallel, bidirectional, etc.). It is based on a generic tool-path generator, so that industrial parts can be supported. The second component has been developed at IRCCyN and handles pattern strategies in the case of trochoidal milling and plunging tool-paths. According to the manufacturing data, the execution module collects the corresponding tool-path generation module for each machining operation and merges the tool-paths results before sending the NC code to the controller for execution.
- *Simulation module*: sends back the results of the different computations (e.g. STEP-NC file analysis, 3D geometry and explicit tool-paths as a VRML file, etc.) to the HMI for visualization.

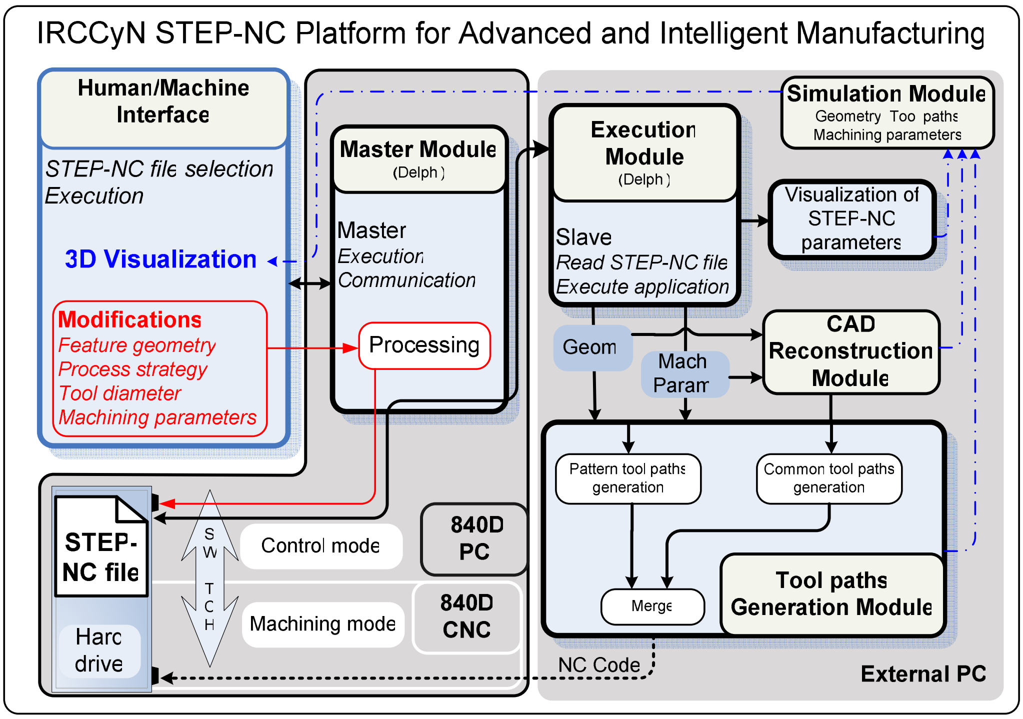

Fig. 4. Architecture of SPAIM

IRCCyN SPAIM platform can benefit from the skills and performance of industrial CAM software. It shows that even if the numerical chain is redistributed, all the current knowledge is still needed.

3.2. CNC PROGRAMMING WITH SPAIM

IRCCyN SPAIM platform shows the feasibility to use STEP-NC standard to achieve intelligent NC programming applications with the existing machine tools and NC controllers [15].

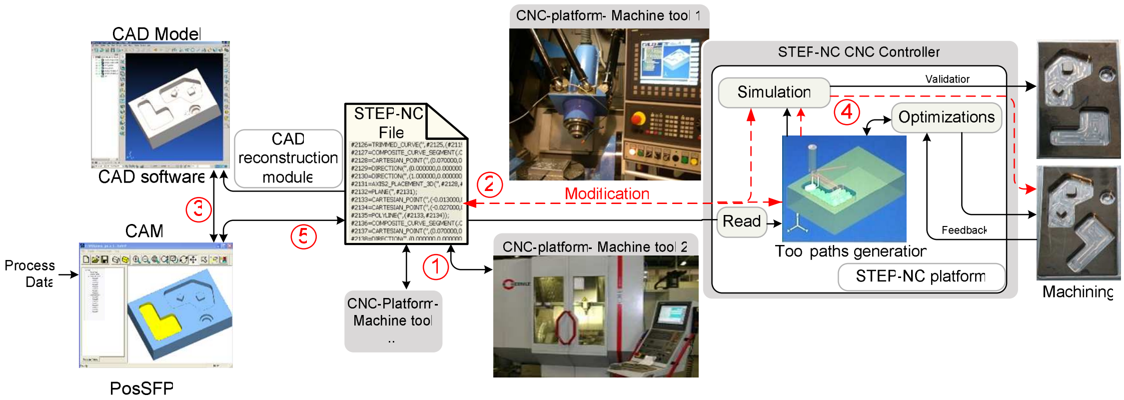

Fig. 5. Advanced NC programming applications enabled by SPAIM

Indeed, most advantages of STEP-NC at the CNC level are already enabled, as shown on Fig. 5:

1. A STEP-NC file can be directly read and executed on several machine tools without any modification. This compatibility is enabled by the high-level description of geometry and process data. All machine tool information and functional models are provided by the CNC platform. For example, the execution of the same STEP-NC file on different machine structures would use different spindle speeds, feed-rates or tool-paths, because each NC controller would compute the most suitable and efficient parameterization, according to the target equipment.
2. Modifications of the geometry and the machining parameters can be achieved at the shop-floor level directly on the CNC controller HMI. These modifications lead automatically to a regeneration of the tool-paths, the geometry displays and the STEP-NC model tree. The corresponding STEP-NC files and a CAD model are updated as well.
3. Feedback from CNC to CAD/CAM software is possible since the STEP-NC file is always up-to-date. Modifications can be done at shop-floor level during the first manufacturing phase of a part. This knowledge feedback enables process planning level to learn and improve the future manufacturing phases.

4. Optimizing the machining parameters and the tool-paths is easier at CNC level. SPAIM provides new ways of optimization based on the STEP-NC data model.
5. STEP-NC file has a small size because of its high-level data ("what to do" instead of "how to do"). This situation reduces the transfer time and is well suited for the Internet-based collaborative manufacturing.

Architecture and use of SPAIM suggest that all elements involved in the present NC chain have a role to play in the development of STEP-NC, although the NC programming approaches are very different. As the major interest is to improve data exchange between all the modules involved in the NC chain, it would be wrong to state that all elements of the NC chain have to be reinvented (e.g. CAD modellers, tool-path generators, etc.). This is because the knowledge is available already. STEP-NC is a data model standard that extends this knowledge. It calls for fundamental, organisational and even cultural changes in the industry. Yet, it still relies on existing capabilities and know-how in the manufacturing industry. In addition to that, SPAIM proves that NC programming can clearly benefit from STEP-NC data models and methods: intelligent NC programming approaches are made possible with the existing CNC controllers.

4. INTELLIGENT AND INTEROPERABLE MANUFACTURING PLATFORM (IIMP)

The Intelligent and Interoperable Manufacturing Platform aims at achieving a collaborative environment among existing and future CAD/CAM/CNC systems. The purpose is to demonstrate how STEP-NC approaches can improve interoperability inside the manufacturing data chain made of various existing commercial CAD/CAM/CNC software suites. Starting from the assumption that CAD/CAM/CNC data are relevant to their own context, a common language may not be necessary to design the IIMP. There is indeed no need to convey all information from one activity (e.g. CAD) to another (e.g. CAM) but only a subset accurately defined and selected. Consequently, a process-centric approach has been chosen to design the IIMP, based on requests and tasks. There is heterogeneity at activity level (data models, software suites, programming languages…) but homogeneity at platform level. Moreover, STEP and STEP-NC will be used as backup and exchange formats in order to ensure the continued existence of the manufacturing data. Although mostly still at a concept level, IIMP promises to propose an efficient architecture to make heterogeneous systems work together. In particular, the introduction of STEP-NC compliant systems within existing environment is made easy.

4.1. ARCHITECTURE OF IIMP

An overview of IIMP is proposed in Fig. 6. The platform is composed with three main groups of elements: an orchestrator, an application module pool and an execution core.

The orchestrator stands as the main decision centre of the platform. That consists in getting the user's requests, generating the roadmap of the project and controlling the information flow among the modules and execution core. The HMI of IIMP is supported by the orchestrator too. This element has consequently a central role and its capabilities have a direct impact on the efficiency of the platform. Except the HMI, two other elements constitute the orchestrator: the roadmap generator and the event-driven supervisor.

Thank to its direct link with the application module pool, the roadmap generator translates the user's request into a list of list of events and tasks that have to be carried out by the application modules within a predefined order. Later on, the user's request is fulfilled by following this "roadmap". Preloaded scenarios are available as well in order to make use of previous jobs and optimize the running of usual tasks and projects.

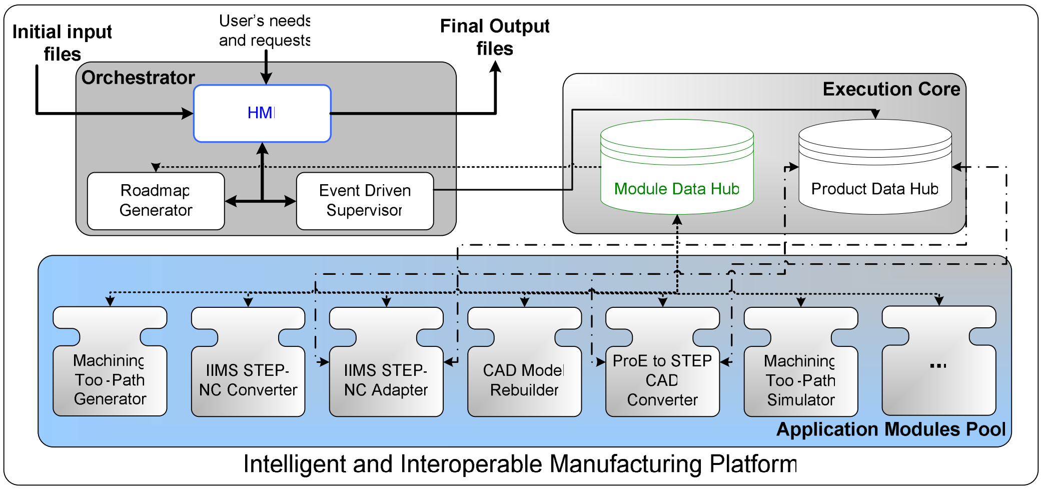

Fig. 6. Overview of Intelligent and Interoperable Manufacturing Platform

As soon as the roadmap has been generated, the job of the event-driven supervisor is to call the application modules accordingly and to store the appropriate data and information thanks to the execution core. The supervisor controls the information flow within the platform modules and .the product data hub.

The application module pool gathers all the activity modules of the platform. These modules have different natures (tool-path generator, CAD file converter, CAM software suite…) and are made of standalone applications that can be run autonomously. The role of each module is to carry out one or several tasks, as required by the roadmap.

In order to be as flexible and tailorable as possible, it has been decided to encapsulate these existing software tools with an event-and data-driven layer and to control their input and output data. As a result, there are no internal interactions between the modules and there is no restriction concerning the number and the nature of the modules. The structure of each module is inspired from the function blocks concept, a new IEC standard (IEC-61499) for distributing industrial-process measurement and control systems [16] (Fig. 7). By proposing an explicit event driven model for data flow and finite state automata-based control, the Function Block (FB) concept has several advantages for the IIMP such as robustness, as the same FB can be used in a wide range of applications, and easy implementation, as there is no need to understand how a FB works internally to make use of it [17].

The running of each FB is triggered by event-in and event out-variables. This means that, as soon as the appropriate event-in signal is sent to the FB, the input data are read from the execution core and the enwrapped software (CAD system, tool path generator…) starts its computations. When the appropriate output files are ready, an event-out variable is sent to the orchestrator, so that the roadmap can jump to its next step. For example, when the module refers to a commercial software suite, the user can use the software HMI to carry out the selected tasks. Once they are completed, the output data are saved to the execution core and the software tool is closed.

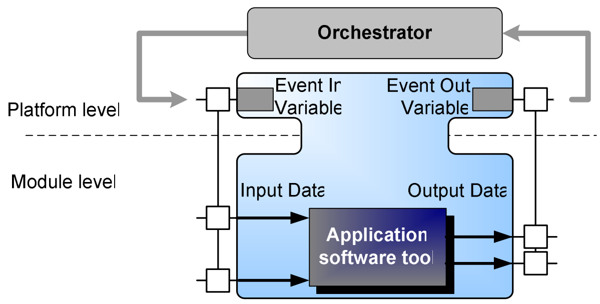

Fig. 7. Function Block concept employed for the application module pool

From the platform point of view, each module is identified by its input and output data formats and by the supported task and activity. This information is made available to the user and the orchestrator thanks to an execution core which gathers these data.

Data hubs are useful to the platform for storage, backup and management purposes. In practice, two data hubs are needed: a module data hub and a product data hub. The module data hub focuses on the application module pool. Its objective is to store all the relevant data for the orchestrator to generate the roadmap and control the information flow during the process. For each module the data stored are as following: module name, input formats, output formats, and module summary.

The product data hub controls the intern information during the running of a project. Input and output files of each module are stored for later use and the final CAD/CAM/CNC data are saved for backup. In addition to that all CAD/CAM data are saved into STEP and STEP-NC formats into the product data hub. The objective is to ensure their continued existence and to maintain their compatibility with future application modules.

4.2. AN EXAMPLE OF IMPLEMENTATION

A case study has already been developed based on existing research works carried out at the University of Auckland [18]. This practical implementation consists of using a generic STEP-NC file as an input to a legacy CNC controller: the main input file is a STEP-NC file and the main output file is the corresponding G-code file. As shown on Table 1, two application modules are necessary, the IIMS STEP-NC adapter, which adapts the generic STEP-NC file into a native STEP-NC file (that includes accurate machining parameters for the selected machine tool) and the IIMS STEP-NC converter which converts this latest file into a G-Code file.

Table 1. Roadmap for the case study

Task	Event In Trigger	Event out Trigger	Application Module
Start Work	HMI Message Displayed	File Loaded	
Generic STEP-NC file =>Native STEP-NC file	Generic STEP-NC file loaded	Native STEP-NC file created	IIMS STEP-NC Adapter
Native STEP-NC File => G-Code file	Native STEP-NC File loaded	G-code file created	IIMS STEP-NC Converter
Arrived at Destination	G-code file present in Product Data Hub	HMI Message displayed	

Then, according to the roadmap, the project is run as proposed by Fig. 8. All STEP-NC and G-code files are stored by the execution core for backup and future use.

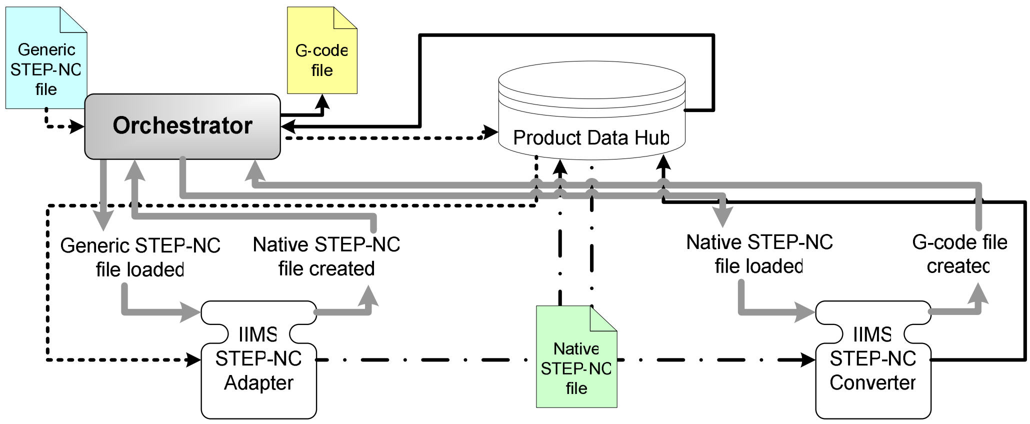

Fig. 8. Running of IIMP case study

As shown by the case study, the major role of IIMP is to gather and synchronize various CAD/CAM/CNC activities. The use of a FB concept makes it tailorable and flexible because the addition of new application modules is made easy. Existing works and software suites can be employed without modifying their internal algorithms. In addition to that, IIMP is well suited for web-based applications as the application module pool can be distributed among several sites.

However, some drawbacks can be observed as well. Thus, the efficiency of IIMP is heavily dependent on the orchestrator. As the user's needs are formalized into a set of tasks, it may be difficult to answer some 'original' requests. Moreover, there is no global optimization as all modules are independent and several modules may provide same services. As a result the total platform can be enormous. This situation is nevertheless not critical: it is the price to pay to dispose of high customisable and high flexible platform architecture.

IIMP still lacks of practical feedback to measure its real effectiveness. By positioning at the crossroads of CAD, CAM, CAPP and CNC systems, it meets nevertheless the actual interoperability needs in the manufacturing industry.

5. CONCLUSION

By offering a new vision of CAD/CAM/CNC data chain, STEP-NC has clear benefits for the manufacturing industry in terms of efficiency and interoperability. This promising but demanding more research approach needs nevertheless industrial buy-in. As companies cannot get rid of their existing CNC Controller and CAD/CAM solutions, the implementation of STEP-NC has to be achieved "step by step".

This paper consequently introduced the combination of two complementary manufacturing platforms aiming to an improved supervision and integration of the machining systems with STEP-NC standard. By enabling STEP-NC programming for existing commercial CNC controllers, SPAIM platform demonstrates the current advantages of STEP-NC data model and shows its performances with industrial manufacturing equipment. SPAIM also proves to be a powerful equipment to implement advanced CNC programming methods. It is also open for further development. Although still mostly at concept level, IIMP promises to be an efficient tool to work with heterogeneous systems and make them interoperable. It is well suited to distributed environment and adapts to any CAD/CAM/CNC software tool. The use of STEP and STEP-NC standards enables a sustainable management and control of these data. SPAIM and IIMP collectively design an inclusive framework for interoperable and advanced CNC manufacturing.

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