Robotics and Computer-Integrated Manufacturing 24 (2008) 699–708

Contents lists available at ScienceDirect

Robotics and Computer-Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim

Strategic advantages of interoperability for global manufacturing using CNC technology

S.T. Newman[a,*], A. Nassehi[a], X.W. Xu[b], R.S.U. Rosso Jr.[c], L. Wang[d], Y. Yusof[e], L. Ali[f], R. Liu[g], L.Y. Zheng[h], S. Kumar[a], P. Vichare[a], V. Dhokia[a]

[a] Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, UK
[b] Department of Mechanical Engineering, University of Auckland, Auckland 1142, New Zealand
[c] Department of Computer Science, State University of Santa Catarina (UDESC), Joinville SC, Brazil
[d] Integrated Manufacturing Technologies Institute, NRC, London, Ontario, Canada
[e] University of Tun Hussein Onn Malaysia (UTHM), Parit Raja, 86400 Johor, Malaysia
[f] National Engineering and Scientific Commission Pakistan, Islamabad, Pakistan
[g] School of Mechanical Engineering, Shandong University, Jinan, Shandong Province 250061, China
[h] Department of Industrial and Manufacturing System Engineering, Beihang University, Beijing 100083, China

ARTICLE INFO

Keywords:
CNC
Interoperability
Global manufacturing
STEP-NC

ABSTRACT

In the domain of manufacturing, computer numerically controllers (CNC) technology is a major contributor to the production capacity of the enterprises. The advances in CNC technology coupled with enhancements in computing systems have provided the basis to re-examine the way in which computer-aided systems (CAx) can be used to enable global manufacturing. Interoperability of the various components of the CAx chain is therefore a major prerequisite for manufacturing enterprises for becoming strategically agile and consequently globally competitive. Being interoperable, resources can be utilized interchangeably in a plug-and-produce manner. Over the last 8 years the eminence of a STEP standard for machining entitled STEP-NC (numerical control) has become a well-known vehicle for research to improve the level of information availability at the CNC machine tool. In this paper, the authors introduce the background to the evolution of CNC manufacturing over the last 50 years and the current standards available for programming. A review of the literature in interoperable CNC manufacturing is then provided relating to milling, turn–mill and other NC processes. The major part of the paper provides a strategic view of how interoperability can be implemented across the CAx chain with a range of standards used to regulate the flow of information. Finally, the paper outlines the advantages and major issues for future developments in interoperability, identifying future key requirements and limiting factors.

1. Introduction

Since the first NC (numerical control) machine was developed in the 1950s, computer numerically controllers (CNC) technology has had a radical effect on the growth of manufacturing across the globe. From this humble beginning, today's CNC multi-process workstation configurations have evolved to support production from high-volume car engine manufacture to low-volume volatile component production. These configurations provide enormous manufacturing flexibility with modular options to produce an enormous range of geometrically complex components, from micro- to multi-metre sized parts, from materials such as aluminium to titanium alloys. Modern multi-process machines not only provide milling or turning capabilities but also allow drilling, milling, turning, laser hardening and grinding to be used on a single machine in one part setup.

In parallel with these machine tool and process developments, CNC vendors have built their proprietary versions and brands of controllers based on programmable logic controllers (PLCs) and PC hardware and software designs. From the early 1980s, CNC vendors started to develop extended programming extensions together with 2D manual data interface (MDI) programming capabilities. These systems were the forerunner of today's 3D feature based machine tool programming systems which incorporate the machine tool vendor's specific programming capabilities. These machine-programming systems provided valuable assistance in enabling SMEs to program simple parts at the machine, but the programming was specific to a machine controller type. In contrast, more complex parts were programmed using computer aided design (CAD)/computer aided

* Corresponding author. Tel.: +44 1225 386934; fax: +44 1225 386928.
E-mail address: S.T.Newman@bath.ac.uk (S.T. Newman).

0736-5845/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rcim.2008.03.002

manufacturing (CAM) or CAM systems using post-processors which translated the high-level CAPP/CAM commands of such systems to G and M codes for a particular machine. Parts programmed using these systems enabled manufacturers to store geometry and tool paths in a vendor-specific format, and using purchased post-processors gave users quality-assured consistent NC output for their machines.

Though machine programming systems and CAD/CAM systems provide good solutions to program modern CNC machines, they can still be considered as bespoke approaches and islands of information with little or no ability to transfer information between the systems. Thus, users become bound and tied into a system for programming specific part types (i.e. simple contours and holes, feature based, sculptured surface), and then limited to particular machines by controllers or system post-processors. This lack of interoperability provides the driver for research reported in this paper, and the outlined standardized solutions for this paradigm shift in the CNC domain.

The paper provides a strategic view on how interoperability can be implemented for the programming of CNC machine tools. In the initial part of the paper the background and arguments for interoperability in CNC manufacture are outlined, together with a review of NC information standards and their impact. The major part identifies the possible solutions and scenarios for interoperability together with the shortcomings of the approaches. The latter parts provide a view of the advantages of interoperability in a global manufacturing together with the future challenges for its implementation in CNC environments.

2. A historical background of interoperability in CNC manufacturing

The standard of programming NC machine tools has remained fundamentally unchanged since the early 1950s when the first NC machine was developed at M.I.T. (Massachusetts Institute of Technology), USA. The early NC machines and today's CNCs utilize the same standard for programming, namely G&M codes formalized as the ISO 6893 standard [1]. Starting in the 1970s, significant development has been made towards automatic and reliable CNC machines with new processes such as punching & nibbling, laser cutting, and water jet cutting, which are now commonplace. The invention of minicomputers, and later microcomputers, has brought a massive improvement in the capabilities of CNC machines with the ability of multi-axis, multi-tool, and multi-process manufacturing. These ever-growing capabilities have made the programming task more and more difficult and complex. The complexity of required programs to utilize the capabilities of the latest machines requires off-line software tools for CAD, computer aided process planning (CAPP) and CAM for efficient and proven NC code generation.

The Software evolution for NC programming has seen a number of generations, from the beginning of hardwired machines, with manual block to block programming, to automated programming tool (APT), ADAPT [2], AUTOMAP, COMPACT II, and UNIAPT [3] and extensions of APT such as EXAPT, EXAPT II, and EXAPT III [2] to modern graphical interactive CAM systems. Today, the software and hardware available at machine tools make it possible to graphically simulate the tool motion and the material removed, and to use adaptive control for on-line improvement of manufacturing process parameters. The current trends are towards open architectures such as OSACA [4] and OMAC [5], where third party software can be used at the controller, working within a standard PC operating system. One further industrial development is the application of software controllers, where PLC logic is captured in software rather than hardware. Such systems, for example the commercial MDSI CNC architecture [6], provide many opportunities to implement open control capabilities, but they are predominantly used in retro-fitting applications for older CNC and conventional NC machines.

Although these developments have improved software tools and the architecture of CNC machine tools, vendors and users are still seeking a common language for CAD, CAPP, CAM, and CNC, to integrate the knowledge generated at each stage. With the current range of proprietary standards for computer aided systems (CAx), translating a program written for a specific CAx resource to work on another CAx resource requires tremendous effort. As a result, an enterprise's responsiveness to market changes and its ability to cope with resource relocation or alterations are severely hindered.

Since the inception of CAD and CAM software, the problem of a model's portability from system to system was one of the key issues in the use of these tools. Many solutions have been proposed to standardize the exchange of data. These standards include SET, VDA, and IGES, which have been successful in specific domains but have failed to address the industry-wide CAD/CAM data portability issues [7]. Thus, the international community has developed the ISO10303 set of standards [8], better known as STEP, which have their foundations in many of the earlier aforementioned standards. To eliminate the problems resulting from multiple standards for information exchange along the CNC manufacturing chain from design to production, an extension to the STEP standards has been developed for CNC manufacture, namely ISO14649 [9] and ISO 10303-AP238 [10], commonly known as STEP-NC. These are the results of an international effort to achieve full interoperability and bi-directional information exchange throughout the CAx manufacturing network.

The EXPRESS language ISO10303-11 [11] is the main description method for the data models within the STEP framework. EXPRESS is a data-modelling language that utilizes object-oriented-like concepts to allow modelling of domains within the field of product data. The application protocols or APs models are defined using EXPRESS schemas. Part 21 [12] of STEP is the implementation method that describes how a valid population of a specific domain within the standard can be presented using an ASCII file. The file starts with a header section followed by a data section. The header contains information about the creation of the file: names of the creators and dates of modifications. The data section contains the instances of the entities representing the population. Each entity instance is preceded by a hash number that is used to refer to that instance where needed. Table 1 shows an excerpt of a part 21 file for an ISO14649 data. The figure illustrates the major constructs of ISO14649, namely the workplan, workingsteps and features which represent the process plan, machining operations and geometry for a component.

ISO10303-28 [13] specifies the extensible markup language (XML) representation for EXPRESS-driven data and is officially known as STEP-XML. Similar to ISO10303-21, this implementation method specifies the representation of a valid population of STEP entities. Instead of encoding the instances in a text file, however, in part 28 the information is captured using XML. Some of the major current implementations of these standards relating to interoperability are classified and outlined below.

3. Review of STEP-NC-based interoperable CNC manufacturing research

This section outlines specific areas of STEP-NC-based interoperable research and developments for the various CNC manufacturing processes. The authors recognize that this list is not comprehensive, but can be used as a representative example of STEP-NC-based interoperable manufacturing research:

Table 1
An excerpt from ISO10303 part 21 representation of an ISO 14649 data model

DATA
#1 = PROJECT('SAMPLE PROJECT',#2,(#3),$,$,$);
#2 = WORKPLAN('MAIN WORKPLAN',(#6,#7,#8,#9,#10,#11,#12,#13,#14,#15),$,$,$);
#3 = WORKPIECE('SIMPLE WORKPIECE',#4,0.010,$,$,#52,());
#4 = MATERIAL('ST-50','STEEL',9#5));
#5 = PROPERTY_PARAMETER('E = 200000/M2');
#6 = MACHINING_WORKINGSTEP('WS ROUGH POCKET 1',#53,#16,#21,$);
#7 = MACHINING_WORKINGSTEP('WS FINESH POCKET 1',#53,#16,#22,$);
#8 = MACHINING_WORKINGSTEP('WS ROUGH POCKET 2',#53,#17,#23,$);
#9 = MACHINING_WORKINGSTEP('WS FINESH POCKET 2',#53,#17,#24,$);
#10 = MACHINING_WORKINGSTEP('WS DRILL HOLE 1',#53,#18,#25,$);
#11 = MACHINING_WORKINGSTEP('WS REAM HOLE 1',#53,#18,#26,$);
#12 = MACHINING_WORKINGSTEP('WS DRILL HOLE 2',#53,#19,#27,$);
#13 = MACHINING_WORKINGSTEP('WS REAM HOLE 2',#53,#19,#28,$);
#14 = MACHINING_WORKINGSTEP('WS DRILL HOLE 3',#53,#20,#29,$);
#15 = MACHINING_WORKINGSTEP('WS REAM HOLE 3',#53,#20,#30,$);
#16 = CLOSED_POCKET('POCKET 1',#3,(#21,22),#60,#54,(),$,#36,$,#37);
#17 = CLOSED_POCKET(('POCKET 2',#3,(#23,24),#62,#55,(),$,36,$,$,#38);
#18 = ROUND_HOLE('HOLE 1',#3,(#25,26),#64,#56,#31,$,#35);
#19 = ROUND_HOLE('HOLE 2',#3,(#27,28),#66,#57,#32,$,#35);
#20 = ROUND_HOLE('HOLE 3',#3,(#29,30),#68,#58,#33,$,#35);

3.1. Milling

The major body of STEP-NC research can be categorized based on the researchers' main focus in terms of manufacturing technology and processes. The most popular area of research has been milling. Suh et al. [14] started their integration research by retrofitting a CNC machine with a PC-based controller to allow graphical simulation, a rarity at the time, and direct machining with no G&M codes. Hardwick [15] provided one of the first outlooks on STEP-NC compliant manufacturing with regard to milling technology. The research was supported by Hardwick's earlier work on virtual enterprises [16].

Based on Hardwick's research, Venkatesh et al. [17] utilized tool centre programming (TCP) provided by AP238 in a joint effort between Boeing and NIST to illustrate an interoperable manufacturing scenario. Hardwick and Loffredo [18] published a paper on this implementation documenting the presentation with 4 CAM vendors and 2 CNC controls on two 5-axis machines with different axes configurations. Cutter center locations were utilized to interpret a single AP238 file for the two machines. While this demonstrates interoperability, the fact that the AP238 file needs to be processed and converted into controller-specific formats for each machine reduces the flexibility of this approach to that of using post-processors with G&M codes.

Suh and Cheon [19] suggested a framework for an intelligent CNC based on ISO 14649. This included the framework for a Shop-Floor programming system. This framework was extended to include an implementation method for a milling machine controller [20]. The modular design relied on CORBA as the facilitator in internal information exchange. The toolpath generator was presented as a flow chart that checked for resource capabilities while interpreting the STEP-NC code automatically. This implementation was then realized in the form of a STEP-NC compliant prototype-milling machine [21]. Suh et al. [22] then designed and implemented the complete shop-floor programming system based on STEP-NC. The system can recognize the features in an AP203 [23] file and then generate ISO14649 manufacturing features. A process plan is then generated and finally the complete STEP-NC file is shown as the output.

Newman et al. [24] provided a view on how the development of ISO14649 and ISO10303-238 can affect the evolution of CAD/CAM systems. An agent-based CAM system capable of generating STEP-NC milling code was used to demonstrate the capability of STEP-NC in manufacturing prismatic parts.

Lee and Bang [25] designed and implemented an ISO14649-compliant CNC milling machine. A proprietary XML coding of the STEP-NC file (i.e. non-STEP-XML) was used as the input for the software CNC controller, a PC attached to a motor controller and the stepper motors on the machine. The controller then interpreted the file and toolpaths were generated internally for the various workingsteps. Lee et al. [26] later expanded the paper to present the work on an embedded controller.

Allen et al. [27] utilized agent technology to develop an automated ISO14649 compliant process planning system for prismatic components named AB-CAM. In the presented approach, a hierarchical decision-making system was in place. Whenever a decision could not be made automatically, the AB-CAM would ask the user to provide input. Such input, however, was not stored to provide a basis for future decision making. Fichtner et al. [28] also created an agent-based system for interpretation and machining of STEP-NC part programmes. The system based on cooperative agents can monitor information on the shopfloor while machining is taking place and represent information from different local knowledge bases. This work on agents was extended by Nassehi et al. [29] in the development of a multi-agent system for computer-aided programming termed MASCAP, where the use of agents in STEP-NC planning and machining of prismatic components with interacting features was demonstrated. The further application of agents in the form of mobile agent systems to select tooling information and other data from distributed data sources was described by Nassehi et al. [30]. In later research, a STEP-NC process planning approach for adaptive global manufacturing was presented by Nassehi et al. [31].

Liu et al. [32] presented a framework for an AP238 STEP-NC controller for milling machines. The controller was comprised of four modules: an interpretation module, a planning module, a simulation module and a CNC kernel. In the paper, only the interpretation module was implemented using the SDAI C++ bindings. The AP238 interpreter reads the STEP compliant data into native data structures. It is noteworthy that only the ISO14649 data elements were actually populated in the native data structures.

Xu et al. [33] compared STEP-NC and function blocks IEC 61499 [34] as two methods for interoperable milling. Advantages and disadvantages of the two approaches with regard to the different aspects of interoperability were then documented. It was identified that no research has combined function blocks with STEP-NC.

Amaitik and Engin Kilic [35] developed an intelligent process planning system based on ISO14649. The system employs an inference engine based on a hybrid artificial intelligence approach composed of neural networks, fuzzy logic and rule-based decision-making systems. The input is taken in the form of manufacturing features compliant with the ISO10303-224 [36] format and an ISO14649 compliant XML process plan is generated. Table 2 provides a summary of the research conducted with milling as its main focus.

3.2. Turning and turn–mill

A number of turning and turn–mill machining oriented papers have been published as well: Rosso et al. [37] investigated the use of STEP-NC in manufacturing of asymmetric rotational components. It was the researchers' conclusion that the ISO14649 part 10 [38] milling standard milling features are capable of supporting the features that these complex components require.

Table 2
STEP-NC research with focus on milling technology

Paper reference	Technology			Standard		Data stovrage	
	Mill	Turn	Other	AP238	ISO14649	XML	TEXT
Suh et al. [14]	☑						
Hardwick [15]	☑			☑			
Venkatesh et al. [17]	☑			☑			
Hardwick and Loffredo [18]	☑			☑			☑
Suh and Cheon [19]	☑				☑		
Suh et al. [20]	☑				☑		
Suh et al. [21]	☑				☑		
Suh et al. [22]	☑				☑		☑
Newman et al. [24]	☑				☑		☑
Lee and Bang [25]	☑				☑	☑	
Lee et al. [26]	☑				☑	☑	
Allen et al. [27]	☑				☑		☑
Fichtner et al. [28]	☑				☑		
Nassehi et al. [29]	☑			☑			☑
Nassehi et al. [30]	☑			☑			☑
Nassehi et al. [31]	☑			☑			☑
Liu et al. [32]	☑			☑			☑
Xu et al. [33]	☑				☑		
Amaitik and Engin Kilic [35]	☑				☑	☑	
Zhao et al. [53]			☑		☑		☑

Xu and Wang [39] developed a G-Code free lathe based on STEP-NC. Xu [40] describes the approach where the STEP-NC file is converted into 6K programs (a machine native format) and passed on to the retrofitted lathe. This low-level language, while not G&M code, is still low-level and interpretation of STEP-NC code into this axis movement language is not that different from translating STEP-NC into G&M codes. Chen et al. [41] proposed an RTCORBA-based soft-bus to realize a framework for turning based on STEP-NC. The CORBA-oriented data transfer would enable generic definition of STEP-NC resources. Suh et al. [42] proposed a novel architecture for an intelligent turning CNC controller that can interpret STEP-NC. The architecture is similar to those developed for milling by the same team. Choi et al. [43] presented the implementation in the form of TurnSTEP, a STEP-Compliant CNC system for turning. In the paper, an XML schema was defined and mapped to the EXPRESS schema to support web-based manufacturing. The XML schema does not appear to be STEP-XML (ISO10303-28) [13] compliant. Heusinger et al. [44] present a methodology for implementation of a CAx chain for rotational asymmetric parts. The necessary data models were created and tested through a prototype system. This research has now been extended by Yusof [45] with the development of an interoperable STEP-NC compliant data model and CAM system for representing and machining of turn–mill components.

Shin et al. [46] investigated the translation of G-code programs written for lathes into STEP-NC compliant code. Utilizing extra information such as the original CAD model, tooling information and machine instruction schema, algorithms for deriving geometric features, operations, etc. were provided. A complete implementation of this research together with the earlier STEP-NC to G&M code interpretations can be combined to allow non STEP-NC compliant machines to be interoperable with each other. Table 3 enumerates the STEP-NC research with the main focus on turning and turn/mill.

3.3. Other CNC processes

Inspection and online monitoring of the machining process has been another area of interest in the STEP-NC research. One of the first frameworks for STEP-NC-based inspection was in geometric error measurement of spiral bevel gears [47]. While the paper does not present any STEP-NC-specific material, it does suggest that the on-line inspection can be added to ISO14649. Ali et al. [48] developed such a STEP-NC-compliant inspection framework for discrete components, where an interoperable inspection process plan would be interpreted for on-machine probing as well as probing on a CMM. Brecher et al. [49] positioned ISO14649-16 [50], the inspection part of STEP-NC, within the domain of inspection standards such as ISO10303-219 [51], dimensional measuring interface standards (DMIS), dimensional markup language (DML) among others. Part 16 of STEP-NC was then utilized to create a closed-loop inspection system. The results were, however, stored in additional entities in the original STEP-NC file. When a single STEP-NC file is used to manufacture a large batch of parts and the results of measurements need to be put back into the file, which already contains manufacturing information, it creates redundancy. Wosnik et al. [52] suggested an approach based on digital servo drives in machine tools for enabling feedback of process data in a STEP-NC compliant machining facility. ISO14649 was extended to accommodate the extra entities that were needed to support the information model for online monitoring of the execution of the workingsteps. Zhao et al. [53] extended the on-line STEP-NC compliant research by supporting real-time, closed-loop machining with the integration of machining and inspection workingsteps within the same STEP-NC program.

There have been a number of STEP-NC papers on other processes as well. Garrido Campos and Hardwick [54] defined a traceability model for CNC manufacturing based on an extension to AP238. It is proposed that traceability data be stored in separate files for each instance of the manufactured product. The files would be ISO10303-21 [12] compliant files based on a new EXPRESS schema designed by the authors.

Sokolov et al. [55] described the implementation of wire electro discharge machining (EDM) algorithms for STEP-NC, namely ISO14649-13 [56]. Ho et al. [57] presented an information model for wire electrical discharge machining in compliance with STEP-NC ISO14649-13. The research was tested by using a prototype system supported by JAVA programming language and

Table 3
Turning and turn/mill STEP-NC research

Paper reference	Technology			Standard		Data storage	
	Mill	Turn	Other	AP238	ISO14649	XML	TEXT
Rosso et al. [37]		☑			☑		☑
Xu and Wang [39]		☑			☑		☑
Xu [40]		☑			☑		☑
Chen et al. [41]		☑		☑			
Suh et al. [42]		☑			☑	☑	☑
Choi et al. [43]		☑			☑	☑	
Heusinger et al. [44]		☑			☑		☑
Yusof 2006 [45]		☑			☑		☑
Shin et al. [46]		☑			☑		☑

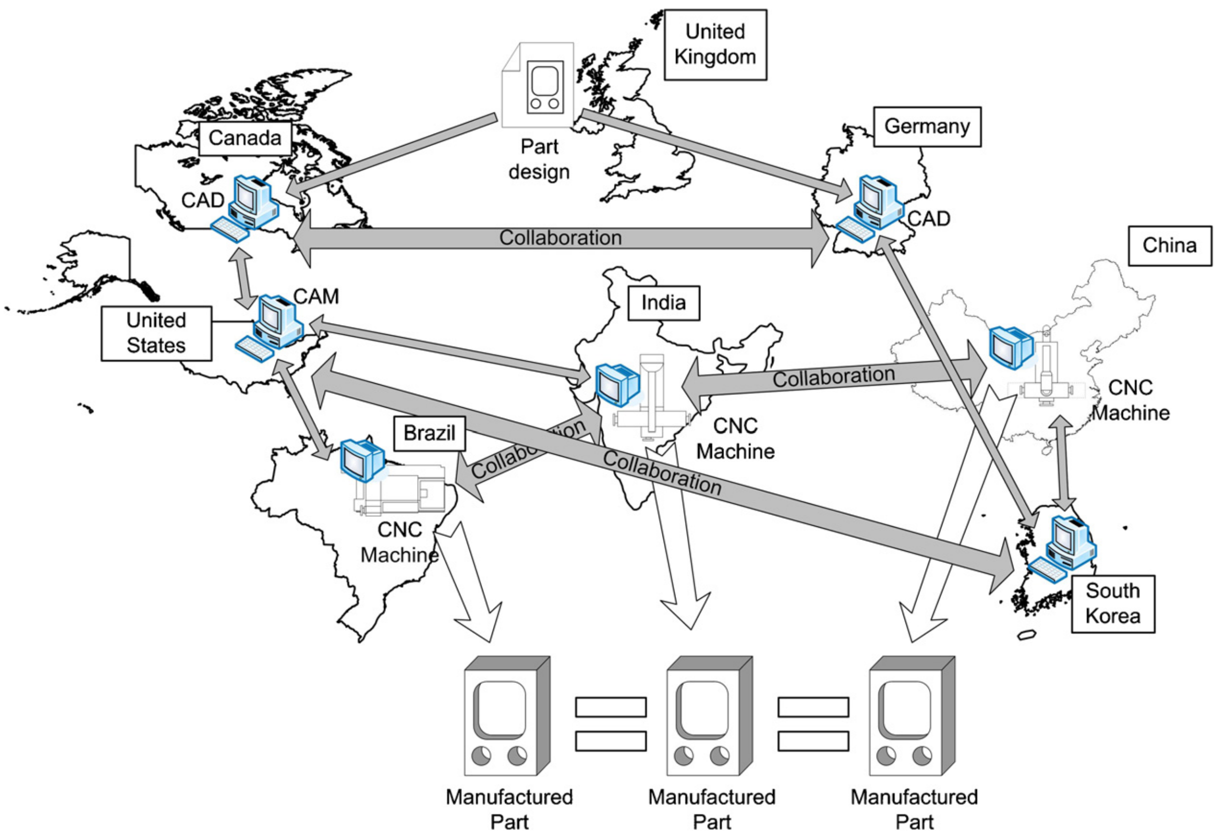

Fig. 1. A vision of global interoperable manufacturing.

an object-oriented database managements system (OODBMS). Ryou et al. [58] proposed an EXPRESS data model as an extension to ISO14649 to represent layered manufacturing (LM) processes. The proposed model, however, does not utilize the existing manufacturing features in ISO14649 and ignores program control entities such as workplan and workingsteps.

Bi et al. [59] introduced a new type of CNC, named intelligent integrated numerical control (I2NC), that proposed an approach to create a unified platform oriented to CNC manufacturing. The implementation of the platform would allow the move from distributed work to collaborative manufacturing.

4. Enabling interoperability in the CAx manufacturing chain

Interoperability is defined as the ability of computer-based systems to exchange information seamlessly [60]. Martin [61] further defines three levels of connectivity between various systems: unified systems where essentially all information is transferred with no requirement for alterations, integrated systems where information is exchanged in accordance to predefined standards and interoperable systems where dynamic information exchange rules are created as required. A CNC manufacturing enterprise requires a highly interoperable CNC manufacturing chain in order to maintain its strategic flexibility in meeting changing market demand. Fig. 1 represents the vision for a global manufacturing network supported by interoperable manufacturing systems.

4.1. Interoperability in the state-of-the-art CNC manufacturing

In the state-of-the-art CAx manufacturing chain, the manufacturing information flows along the chain in a manner similar to Fig. 2. The CAD system is used to create a digital model of the

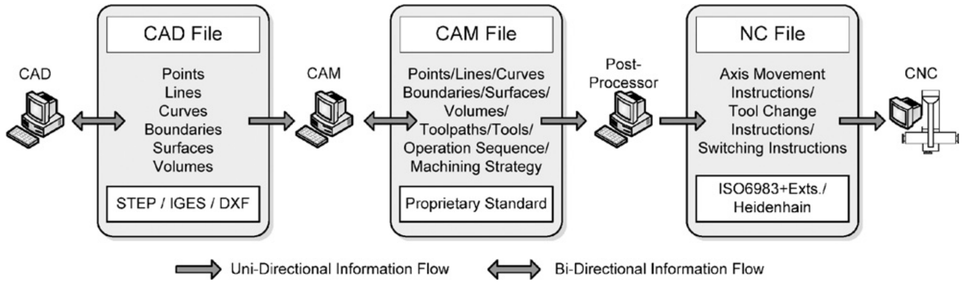

Fig. 2. Manufacturing information flow in the state-of-the-art CAD/CAM/CNC chain.

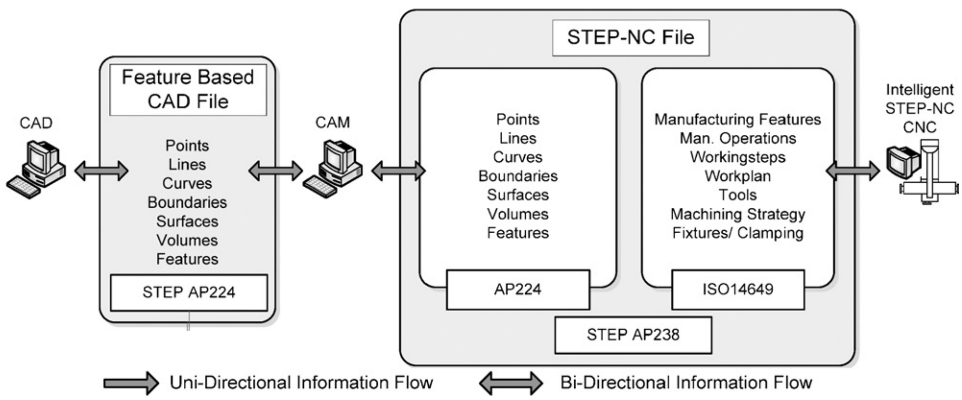

Fig. 3. Information flow in a STEP-NC CAD/CAM/CNC chain.

product. This model is created using geometric primitives such as points, lines and curves. Modern CAD packages also allow the definition of surfaces and volumes as well boundaries as a set of these geometric primitives. The digital design information is then stored in a CAD file. While the CAD file is mostly stored in a proprietary format, nearly all commercial CAD packages are capable of importing and exporting files defined according to the number of standards, namely STEP, IGES and DXF.

The design information presented as a standard CAD file is then passed onto a CAM software package. The CAM software, through user input, adds information about cutting strategies, tools and operation sequences to the existing geometric data. The information is then used to calculate toolpaths to machine the part. The information at this stage is stored in a CAM file with a proprietary format. The CAM system is capable of reading, modifying and writing this information. Next, the CAM file is loaded into a postprocessor. The postprocessor, designed for a unique machine configuration, uses the toolpaths in the CAM file to generate axis movement instructions in addition to some simple switching commands that, when interpreted on the CNC machine, initiate operations such as tool changes and coolant control. The postprocessor outputs the generated instructions in an NC file. This file is usually created according to the ISO6983 (G&M Codes) standard with proprietary vendor extensions.

The overall flow of information in the enterprise is predominantly uni-directional. The design is basically pushed down the manufacturing chain and the necessary information is added at each stage. In cases where the NC program is edited on the shop-floor, it is impossible to capture the knowledge from the shop floor and pass it back through the chain. Changes in design or tools for example will not be reflected in the CAD or CAM files. Consequently, modifications at the later stages of the manufacturing process will create discrepancies in the various views of the manufacturing model that exist within the various resources. This in turn breaks the integrity of the overall information model and will require considerable manual effort to re-integrate the manufacturing information.

Thus, significant changes in resources will have a substantial effect on this type of manufacturing chains. The use of a new CAM package for example will require postprocessors to be obtained for all of the CNC machines available in the resource pool. Likewise, acquiring a new CNC controller requires possession of the postprocessors for that controller for all of the CAM packages in use along the CAD/CAM/CNC chain.

A possible answer to these problems is to use solutions from a single vendor to ensure compatibility. This solution, however, hampers a manufacturing company's capability to function as part of a supply chain in modern virtual enterprises. For a virtual enterprise to function effectively, it is imperative for the various systems used by the different components of the supply chain to be able to exchange information reliably and rapidly regardless of their make and models.

4.2. STEP and STEP-NC, enablers of interoperability

ISO 10303, i.e. STEP, was developed as a means to allow computer systems to exchange information with each other without using proprietary translation filters. Fig. 3 shows the concept of a STEP-NC compliant manufacturing chain. The chain starts with a CAD system generating not only the geometrical primitives such as points, lines and curves but also features such as pockets, slots and holes. These geometrical features are linked to points, lines, curves and surfaces that are used in the CAD system to represent them. Application Protocol 224 (ISO10303-224) [36] in the STEP standard defines data structures for such a feature-based CAD model.

The feature-based CAD model is then passed on to the CAM system, which adds manufacturing information to the geometry and stores the extended information in an AP238 file. The AP238 file contains the AP224 geometry with the addition of manufacturing operations, manufacturing features, tools and machining strategies organized in "workingsteps" and "workplans". The structures that contain these items of information are defined in ISO14694. The data in the workingsteps are linked to the geometry using indigenous AP238 constructs. The resulting STEP-NC file can be a mammoth hierarchical data structure containing every bit of information about the product. This file is then passed on to an intelligent controller that is capable of interpreting the complex data structure and deriving the necessary axis movements and tool changes automatically.

The information flow in the AP238 manufacturing chain can be considered as bi-directional since complete product information is carried onto the CNC controller itself. In this scenario the CNC controller would need to have considerable computing power as changes in manufacturing features (i.e. changing the diameter of a hole on the shop floor by assigning a different drill to the drilling operation) would need to be reflected in the geometric features as well as the geometric primitives used to represent the features in the AP224 portion of the AP238 file.

While several research groups have made some headway into creating a STEP-NC controller [21,25,39], such a controller has not been commercially materialized. This is perhaps due to the complexity involved in developing such a controller. In addition, as adopting AP238 would make the use of proprietary extensions to the NC code obsolete, controller manufacturers who often promote these extensions as additional functionalities have not been enthusiastic in becoming STEP-compliant. A STEP-compliant CAx manufacturing would be interoperable if all of the CAx resources are STEP compliant. Addition of a non-STEP-compliant CAM system or a non-STEP-compliant CNC to the manufacturing resource pool would be nearly impossible. The authors believe that such a restriction limits the actual field of achievable interoperability in the manufacturing enterprise.

4.3. *Shortcomings of current STEP and STEP-NC compliant implementations as enablers of interoperability*

In the absence of a controller that accepts STEP-NC data directly, an intermediate approach has been chosen by some researchers (Fig. 4). In this CAD/CAM/CNC chain, the CAD system generates the geometry primitives and stores them in a CAD file. This file is then imported into a CAM system or passed onto the CAM module of the same CAD/CAM system where toolpaths are calculated and expressed in the form of cutter location (CL) data [17]. The resulting CAM file is then post-processed to give axis movement data in the form of G-codes.

In this approach, toolpaths are still generated off-line and the full potential of employing STEP-NC is not realized. The process chain is almost identical to that of the state-of-the-art chain as shown in Fig. 2. The translator is essentially a type of "STEP-NC post-processor". However, if the translator can be embedded in a CNC controller as indicated by the dotted line, this approach can be seen as a "stepping stone" in achieving a "genuine" STEP-NC controller.

Interoperability in a system such as the one presented in Fig. 4 can be considered as inadequate. The CAM system only generates STEP-NC files; it is not capable of handling the feedback information. More importantly, changes on the shop floor are made at the CNC controller at the G-code level. The changes, therefore, cannot be passed back to the CAD/CAM models and the problems with information integrity remain unresolved. Recently researchers have started to investigate the possibility of creating bi-directional information exchange in these links [46–62], but for the time being the level of interoperability is similar to that of the chain discussed in Section 3.1.

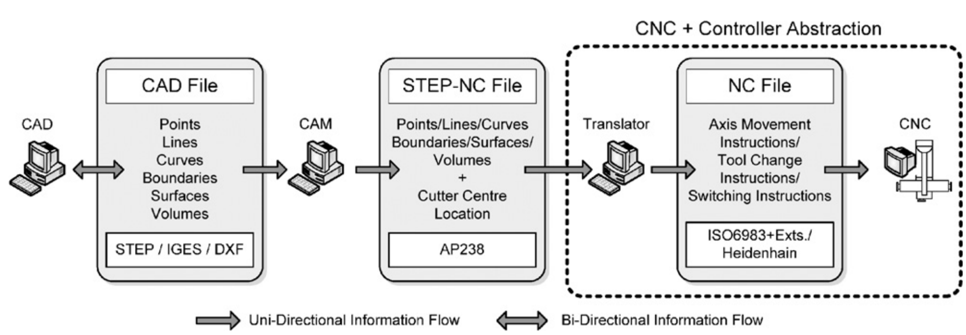

Fig. 4. Information flow in a modified AP238 chain.

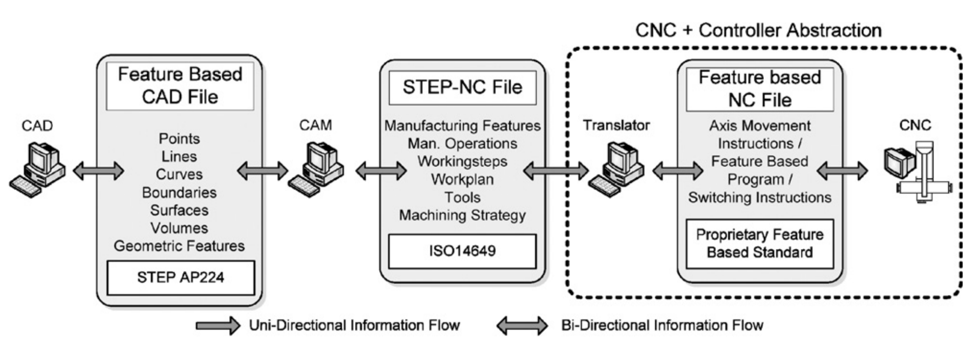

Fig. 5. Information flow in a modified ISO14649 chain.

Another approach depicted in Fig. 5 involves using CNC controllers that employ feature-based data structures that closely resemble those of STEP-NC [30]. One such controller is the 840D from Siemens equipped with ShopMill, a Siemens proprietary feature-based shop floor programming system.

As the controllers usually manipulate geometry on the level of manufacturing features, only the ISO14649 part of the STEP-NC is used to convey information to the controller. Here, the chain starts in the CAD system where feature-based CAD files are created. The ISO14649 STEP-NC file is then created by the CAM system. Manufacturing features are derived from geometrical features and operations, workingsteps and workplans are generated. The STEP-NC file is then transferred to a translator, where the file is converted to the proprietary format of the feature-based controller.

Again, an abstraction of the translator and the CNC controller can be seen as a step in realizing the intelligent STEP-NC controller. The advantage of this approach is that as any changes on the shop floor are carried out on the feature level it is possible to transfer the information back through the translator to the STEP-NC file and from there to the CAD system. In this system, as the translation between CAD geometry and manufacturing features is handled in the CAM system, it would not be necessary to have a CNC controller with a very high computational capacity.

5. Strategic advantages of interoperability for global businesses

The implementation of interoperability has an enormous impact on all manufacturing sectors from large global businesses to the small or even micro manufacturing enterprise as described below.

(i) At the global level, aerospace and automotive worldwide companies will not only have the added ability to transfer component manufacture not only to identical duplicate plants with identical equipment, but also will be able to use equivalent equipment/machine tools and controllers with the confidence and traceability from the information integrity of manufacture that the products produced will be to specification.

(ii) Interoperability will enable manufacturing businesses to produce legacy components, based on the original process planning knowledge, on modern and future machine tools without the overhead of re-planning the fixturing, tooling and tool paths. This will enable future parts to be manufactured with confidence, as and when required without having to rely on the original equipment, past tooling and part programs which would be typically obsolete.

(iii) For the small manufacturing enterprise (SME), individual machining workstations will no longer have to be dedicated to specific jobs/components. Interoperability will provide an enormous increase in the flexibility of production across the shopfloor with parts being interchangeably manufactured and even shared across workstations with different CNC controllers and configurations. This enables SMEs to become even more responsive with the added capability of (i) and (ii) above of traceable manufacturing information.

6. Challenges in implementation of interoperability in CNC manufacturing environments

Though these advantages are tremendously encouraging, a number of issues relating to CNC manufacturing interoperability have been formulated based on the requirements identified by Newman [63] and Xu et al. [64]. These issues relate to the directions of current and future research and are outlined below:

(i) Business factors: The sole beneficiary of enabling interoperability across the CAx chain is the manufacturing user. The advent of manufacturing interoperability for the first time gives these users the opportunity to integrate information systems across the total product data and manufacturing divide together with reverse data capture from the CNC to the CAD system regardless of the vendor of the CAx resource. There has been some support from vendors to these user pressures. Most vendors, however, recognize that with the implementation of interoperability their business advantage and niche will be lost, as users are no longer obliged to buy solutions from a single company to minimize compatibility issues. The authors believe that manufacturing interoperability is still in its infancy, but with a continued market pull from the users it will soon materialize into reality. Support from a global vendor in the role of system integrator can significantly facilitate the transition from the current technology-oriented CAx market to the user-oriented market required in the future.

(ii) Manufacturing information standards: With the development of CAD/CAM and CNC technologies in the last 20 years, a plethora of bespoke information systems and languages now exist for programming CNC machines. It is with this belief that there is a need to research and develop homogenous software platforms that enable standards to be used to integrate these systems across the CAx chain. Though STEP-NC has given the opportunity for machining process information to be standardized, the lack of a semantic and ontology representation makes it almost impossible to inter-relate the existing systems and languages.

(iii) Product models for sculptured components: The majority of research in STEP compliant manufacturing up till now has concentrated on the machining of prismatic parts predominately from billets. If industrial users are to fully engage with the interoperable R&D and standards community, there is a need to consider benchmark components representing a broad spectrum of industries and sectors. In addition, it is also vital the components are manufactured interoperably with commercial machines at different company locations.

(iv) Modelling manufacturing resource capability: The major focus in the area of manufacturing information modelling is in the area of product modelling combined with the processes to make the part. The STEP-NC standards committee has identified the need to develop information models to represent the capabilities of the CNC manufacturing resources. This is a major area of research, as such a model needs to be completely reconfigurable to represent the enormous variety of machine tool configurations on the market.

(v) CNC machining simulation: Though the CNC community has been able to simulate CNC machines toolpath movement for many decades through off-line programming, the ability to accurately simulate and measure the surface finish of the virtual part is limited. This is due to each controller and machine tool having their unique linkages and the interpolation procedure in the CNC being an unknown factor. This area of machine simulation is critical if interoperable manufacturing is to be established and needs to be combined with (iv) above to enable users to have standard simulate machine toolpaths.

(vi) Intelligent CNCs: The developments in STEP-NC controllers have shown the way forward for automatic interoperable

CNC manufacture of parts from CAD models. Though this ability enables models to be manufactured based on feature-based CAD representations, there is still a long way to go. It is possible to imagine a self-aware machine tool that will identify whether it can make a part to tolerance, know when services are required and self-diagnose a problem. Thus, a new area of intelligent/smart machines needs to be explored, leading to development of machines that are able to make autonomous, intelligent manufacturing decisions based on their process capability.

(vii) Interoperable manufacturing platforms: The foundation of the STEP-NC research has provided the manufacturing community with the basis to define a resource independence process plan for machining applications. Coupled with the developments of manufacturing resource models outlined above and intelligent STEP-NC compliant CNC machines, it paves the way forward for the development of "plug and produce" interoperable platforms. It should be recognized that these platforms need to be based on standards to enable interoperability across vendor-based products. Though these platforms are technically feasible, the major challenges, as identified previously, will be to convince vendors and system integrators that integrating their products will provide them with major future business opportunities and also produce a global interoperable manufacturing network.

7. Conclusions and future work

The changing economic climate has made global manufacturing a growing reality over the last decade, forcing companies to design, manufacture and assemble products across the world. The standards ISO10303 and ISO14649 (STEP and STEP-NC) have been developed to introduce interoperability into manufacturing enterprises. Current implementations of these standards, together with the inherent complexity of STEP compliant CNC controllers, have demonstrated that a global interoperable STEP-NC system is still a long way away. A major barrier to the development of these platforms is the resistance from software/hardware vendors who see the current lack of standards as an opportunity to maintain their market advantage through system lock-in. Interoperable manufacturing will only become a reality if user pressures force vendors to integrate their products across common platforms. The authors believe that STEP-NC is one of the enablers for such integration. The challenge is to create the equivalent of a "manufacturing operating system with plug-and-produce CAx device drivers" based on the standard which can provide the foundation for the future of global interoperable manufacturing.

References

[1] International Standards Organization, ISO6983-1—Numerical control of machines—program format and definition of address words—Part 1: data format for positioning, Line motion and contouring control systems, 1982.

[2] Groover MP. Automation, production systems, and computer-integrated manufacturing. Prentice Hall Int. Publ; 2001.

[3] Seames WS. Computer numerical control: concepts and programming. 3rd ed. Albany: Delmar Publishers; 1995.

[4] Lutz P, Sperling W. OSACA—The vendor neutral control architecture. In: Fichtner D, et al., editors. Facilitating deployment of information and communications technologies for competitive manufacturing. Proceedings of the European conference on integration in manufacturing IiM'97. Dresden: Selbstverlag der TU Dresden; 1997.

[5] OMAC, Open Modular Architecture Controls, 〈http://www.omac.org/〉, 2007.

[6] MDSI, Open CNC, 〈http://www.mdsi2.com/〉, 2007.

[7] Kemmerer SJ, editor. STEP The Grand Experience Manufacturing Engineering Laboratory. Gaithersburg (MD): National Institute of Standards and Technology; 1999.

[8] International Standards Organization. ISO10303-1—Industrial automation systems and integration—Product data representation and exchange, Part 1. Overview and fundamental principles, 1994.

[9] International Standards Organization. ISO14649-1—Industrial automation systems and integration—Physical Device Control—Data model for computerized numerical controllers—Part 1: Overview and fundamental principles, 2003.

[10] International Standards Organization. ISO10303-238—Industrial automation systems and integration—Product data representation and exchange—Part 238: Application protocol: Application interpreted model for computerized numerical controllers, 2004.

[11] International Standards Organization. ISO10303-11—Industrial automation systems and integration. Product data representation and exchange. Description methods: the EXPRESS language reference manual, 1994.

[12] International Standards Organization. ISO10303-21—Industrial automation systems and integration. Product data representation and exchange. Implementation methods. Clear text encoding of the exchange structure, 1994.

[13] International Standards Organization. ISO10303-28—Industrial automation systems and integration. Product data representation and exchange—Implementation methods: XML representations of EXPRESS schemas and data, 2003.

[14] Suh S, Noh S, Cho Y. A PC-based retrofitting toward CAD/CAM/CNC integration. Comput Ind Eng 1995;28(1):133–46.

[15] Hardwick M. Digital manufacturing using STEP-NC. Tech. Paper, Society of Manufacturing Engineers, MS02-242, 2002.

[16] Hardwick M, Morris K, Spooner D, Rando T, Denno P. Lessons learned developing protocols for the industrial virtual enterprise. CAD Comput Aided Des 2000;32(2):159–66.

[17] Venkatesh S, Odendahi D, Xu X, Michaloski J, Proctor F, Kramer T. Validating portability of STEP-NC tool center programming. In: Proceedings of the ASME international design engineering technical conferences and computers and information in engineering conference—DETC2005; 2005. p. 285–90.

[18] Hardwick M, Loffredo D. Lessons learned implementing STEP-NC AP-238. Int J Comput Integrated Manuf 2006;19(6):523–32.

[19] Suh SH, Cheon SU. A framework for an intelligent CNC and data model. Int J Adv Manuf Technol 2002;19(10):727–35.

[20] Suh SH, Cho JH, Hong HD. On the architecture of intelligent STEP-compliant CNC. Int J Comput Integrated Manuf 2002;15(2):168–77.

[21] Suh SH, Chung DH, Lee BE, Cho JH, Cheon SU, Hong HD. Developing an integrated STEP-compliant CNC prototype. J Manuf Syst 2002;21(5):350–62.

[22] Suh SH, Lee BE, Chung DH, Cheon SU. Architecture and implementation of a shop-floor programming system for STEP-compliant CNC. CAD Comput Aided Des 2003;35(12):1069–83.

[23] International Standards Organization. "ISO10303-203—Industrial automation systems and integration—Product data representation and exchange—Part 203: Application protocol: configuration controlled 3D designs of mechanical parts and assemblies, 1994.

[24] Newman ST, Allen RD, Rosso Jr. RSU. CAD/CAM solutions for STEP-compliant CNC manufacture. Int J Comput Integrated Manuf 2003;16(7–8):590–7.

[25] Lee W, Bang YB. Design and implementation of an ISO14649-compliant CNC milling machine. Int J Prod Res 2003;41(13):3007–17.

[26] Lee W, Bang YB, Ryou MS, Kwon WH, Jee HS. Development of a PC-based milling machine operated by STEP-NC in XML format. Int J Comput Integrated Manuf 2006;19(6):593–602.

[27] Allen RD, Harding JA, Newman ST. The application of STEP-NC using agent-based process planning. Int J Prod Res 2005;43(4):655–70.

[28] Fichtner D, Nestler A, Dang TN, Schulze A, Carlsen U, Schreiber S. Use of agents and neural networks for acquisition and preparation of distributed NC information to support NC planning. Int J Comput Integrated Manuf 2006;19(6):581–92.

[29] Nassehi A, Allen RD, Newman ST. The application of multi-agent systems for STEP-NC computer aided process planning of prismatic components. Int J Mach Tools Manuf 2006;46(2):559–74.

[30] Nassehi A, Allen RD, Newman ST. Application of mobile agents in interoperable STEP-NC compliant manufacturing. Int J Prod Res 2006;44(18–19):4159–74. 2006.

[31] Nassehi A, Newman ST, Allen RD. STEP-NC compliant process planning as an enabler for adaptive global manufacturing. Robotics Comput Integrated Manuf 2006;22(5–6):456–67. 2006.

[32] Liu R, Zhang C, Newman ST. A framework and data processing for interfacing CNC with AP238. Int J Comput Integrated Manuf 2006;19(6):516–22.

[33] Xu XW, Wang L, Rong Y. STEP-NC and function blocks for interoperable manufacturing. IEEE Trans Autom Sci Eng 2006;3(3):297–307.

[34] Wang L, Jin W, Feng HY. Embedding machining features in function blocks for distributed process planning. Int J Comput Integrated Manuf 2006;19(5):443–52.

[35] Amaitik SM, Engin Kilic S. An intelligent process planning system for prismatic parts using STEP features. Int J Adv Manuf Technol 2007;31:978–93.

[36] International Standards Organisation. ISO10303-224—Industrial automation systems and integration—Product data representation and exchange—Part 224: Application protocol: Mechanical product definition for process planning using machining features, 2006.

[37] Rosso Jr. RSU, Newman ST, Rahimifard S. The adoption of STEP-NC for the manufacture of asymmetric rotational components. Proc IMechE Part B: J Eng Manuf 2004;218(11):1639–44.

[38] International Standards Organization. ISO14649-10—Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 10: Data model for computerized numerical controllers—Part 10: General process data. 2002.
[39] Xu XW, Wang J. Development of a G-Code free, STEP-compliant CNC lathe. American Society of mechanical engineersComput Inf Eng Div, CED 2004: 75–82.
[40] Xu XW. Realization of STEP-NC enabled machining. Robot Comput Integrated Manuf 2006;22(2):144–53.
[41] Chen X, Zhang C, Lan H, Zhai P, Wu H. A framework for CNC turning system based on STEP-NC. Proceedings of SPIE Int Soc Opt Eng, 2005.
[42] Suh SH, Chung DH, Lee BE, Shin S, Choi I, Kim KM. STEP-compliant CNC system for turning: data model, architecture, and implementation. CAD Comput Aided Des 2006;38(6):677–88.
[43] Choi I, Suh SH, Kim K, Song M, Jang M, Lee BE. Development process and data management of TurnSTEP: a STEP-compliant CNC system for turning. Int J Comput Integrated Manuf 2006;19(6):546–58.
[44] Heusinger S, Rosso Jr. RSU, Klemm P, Newman ST, Rahimifard S. Integrating the CAx process chain for STEP-compliant NC manufacturing of asymmetric parts. Int J Comput Integrated Manuf 2006;19(6):533–45.
[45] Yusof Y, Rosso Jr RSU, Case K, Newman ST. The design of a STEP-NC compliant CAD/CAP/CAM system for the manufacture of rotational parts on a CNC turning centre. In: Innovations in manufacturing, Proceedings of the 23rd international manufacturing conference. Northern Ireland: Ulster; 2006. p. 19–28.
[46] Shin SJ, Suh SH, Stroud I. Reincarnation of G-code based part programs into STEP-NC for turning applications. Comput-Aided Des 2007;39:1–16.
[47] Suh SH, Lee ES, Kim HC, Cho JH. Geometric error measurement of spiral bevel gears using a virtual gear model for STEP-NC. Int J Mach Tools Manuf 2002;42(3):335–42.
[48] Ali L, Newman ST, Petzing J. Development of a STEP-compliant inspection framework for discrete components. Proc IMechE Part B: J Eng Manuf 2005;219(7):557–63.
[49] Brecher C, Vitr M, Wolf J. Closed-loop CAPP/CAM/CNC process chain based on STEP and STEP-NC inspection tasks. Int J Comput Integrated Manuf 2006;19(6):570–80.
[50] International Standards Organization. ISO14649-16WD—Industrial automation systems and integration—Physical Device Control—Data model for computerized numerical controllers–Part 16: Data for touch probing based inspection, 2004.
[51] International Standards Organization. ISO10303-219—Industrial automation systems and integration—Product data representation and exchange–Part 219: Application protocol: Dimensional inspection information exchange, 2005.
[52] Wosnik M, Kramer C, Selig A, Klemm P. Enabling feedback of process data by use of STEP-NC. Int J Comput Integrated Manuf 2006;19(6):559–69.
[53] Zhao F, Xu X, Xie S. STEP-NC enabled on-line inspection in support of closed-loop machining. Robot Comput Integrated Manuf 2008;24(2):200–16.
[54] Garrido Campos J, Hardwick M. A traceability information model for CNC manufacturing. CAD Comput Aided Des 2006;38(5):540–51.
[55] Sokolov A, Richard J, Nguyen VK, Stroud I, Maeder W, Xirouchakis P. Algorithms and an extended STEP-NC-compliant data model for wire electro discharge machining based on 3D representations. Int J Comput Integrated Manuf 2006;19(6):603–13.
[56] International Standards Organization. ISO14649-13—Industrial automation systems and integration—Physical device control-data model for computerized numerical controllers–Part 13: Process data for Wire-EDM, 2003.
[57] Ho KH, Newman ST, Allen RD. STEP-NC compliant information modeling for wire electrical discharge machining component manufacture. Proc Inst Mech Eng Part B J Eng Manuf 2005;219(10):777–84.
[58] Ryou MS, Jee HS, Kwon WH, Bang YB. Development of a data interface for rapid prototyping in STEP-NC. Int J Comput Integrated Manuf 2006;19(6): 614–26.
[59] Bi J, Yu T, Li Q. I2NC: a new type of computer numerical control. In: Proceedings of the 2006 IEEE international conference on mechatronics and automation; 2006. p. 803–8.
[60] Ray SR, Jones AT. Manufacturing interoperability. J Intelligent Manuf 2006; 17:681–8.
[61] Martin RA. International standards for system integration. Rochester, NY: International Council on Systems Engineering (INCOSE2005); 2005.
[62] Liu Y, Guo X, Li W, Kashihara YK, Fujishima M. An intelligent NC program processor for CNC system of machine tool. Robotics Comput Integrated Manuf 2007;23(2):160–9.
[63] Newman ST. Integrated CAD/CAPP/CAM/CNC manufacture for the 21st century. In: Proceedings of the 14th flexible automation and intelligent manufacturing conference; 2004. p. 1–8.
[64] Xu XW, Wang H, Mao J, Newman ST, Kramer T, Proctor F. STEP-compliant NC research: the search for intelligent CAD/CAPP/CAM/CNC integration. Int J Prod Res 2005;43(17):3703–43.