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ORIGINAL ARTICLE

Research into integrated design and manufacturing based on STEP

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Abstract This paper discusses a typical STEP-compliant manufacturing environment, which effectively integrates two systems. The first generates native data that retain the information needed to machine a part on a particular machine tool, whereas the second carries out optimization for machining parameters using the dispatched information from the first system. The related research work is divided into four areas, feature generation, macro process planning, micro process planning, and machining execution. The main part of the paper is devoted to reviewing the most recent research publications. The publications have been organized into the four areas as mentioned above. The discussion section that follows looks at the STEP-compliant research from the perspectives of industrial adoption, feature recognition for process planning, challenges in STEP-enabled inspection and STEP-NC controllers.

Keywords Design · Manufacturing · Integration · STEP · STEP-NC

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1 Introduction

In today's industry, product data throughout the lifecycle is often managed in different systems. Each of these systems has its own data format, so the same information is entered multiple times into different systems at different design phases leading to possible data redundancy and error. Industry vendors and users have since been seeking a common language to be used in an integrated system that can describe the entire product data throughout its lifecycle. Many solutions were proposed, the most successful being the STandard for Exchange of Product data model (STEP) [1]. STEP provides a mechanism that is capable of describing product data, independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing, sharing, and archiving product databases.

For various types of product data, STEP uses Application Protocols (APs). APs are formal documents that cover a set of activities in the lifecycle of a product. Every AP defines a set of activities, information requirements and a formal schema that is tied to an integrated product model shared between all APs. An AP is developed through three phases: (1) Application Activity Model (AAM) identifies and analyses process requirements in an application domain; (2) Application Reference Model (ARM) describes the pieces of product information described in the AAM in terms of basic Application Objects (AO); and (3) Application Interpreted Model (AIM) is formed by using an EXPRESS information model to capture everything in the ARM and to tie it to a library of pre-existing definitions (e.g., Integrated Resources).

ISO 10303-AP203 [2] is the first and perhaps the most successful AP developed to exchange design data between different CAD systems. After the initial release of AP203, other APs have been developed to support their particular industries. For example, AP 214 [3] defines the core data for automotive mechanical design processes, AP 219 [4] defines dimensional inspections, AP223 [5] defines exchange of design and manufacturing product information for cast parts, AP 224 [6] defines mechanical product definitions for process planning using machining features, AP 229 [7] defines exchange of design and manufacturing product information for forged parts, AP 238 [8] is the application interpreted model for computerized numerical controllers, and AP 240 [9] defines process plans for machined parts.

Figure 1 describes an integrated STEP-compliant manufacturing system. The geometric representation data described in AP203 or other formats are translated into machining features defined in AP224. The machining feature definitions are used as inputs to macro process planning applications (e.g., AP240 for machining, AP223 for casting, and AP229 for forging). Micro process planning for machining (AP238) and inspection (AP219) are then carried out for each of the aforementioned application processes. In such a system, the need for data conversion is eliminated.

Despite all the efforts in developing APs, harmonizing these APs is still an on-going process. Implementation of the APs in an integrated manufacturing system is also being researched. As shown in Fig. 1, there are four areas in which intensive research has been observed. These four areas of research are discussed in the remaining part of this section, and are elaborated in Fig. 2.

The development works in area A focus on feature recognition. Translation of geometric data (as in AP203) to features (as in AP224) is an important step toward having the right type of data in a STEP-based CAD/CAM system. The development work in area B focuses on STEP-based process planning, where STEP-NC data models are used to retain information about manufacturing features and associated manufacturing parameters in an object-oriented manner via the concept of Workingstep [10]. The development work in area C looks at building a comprehensive inspection data model that can be integrated with machin-

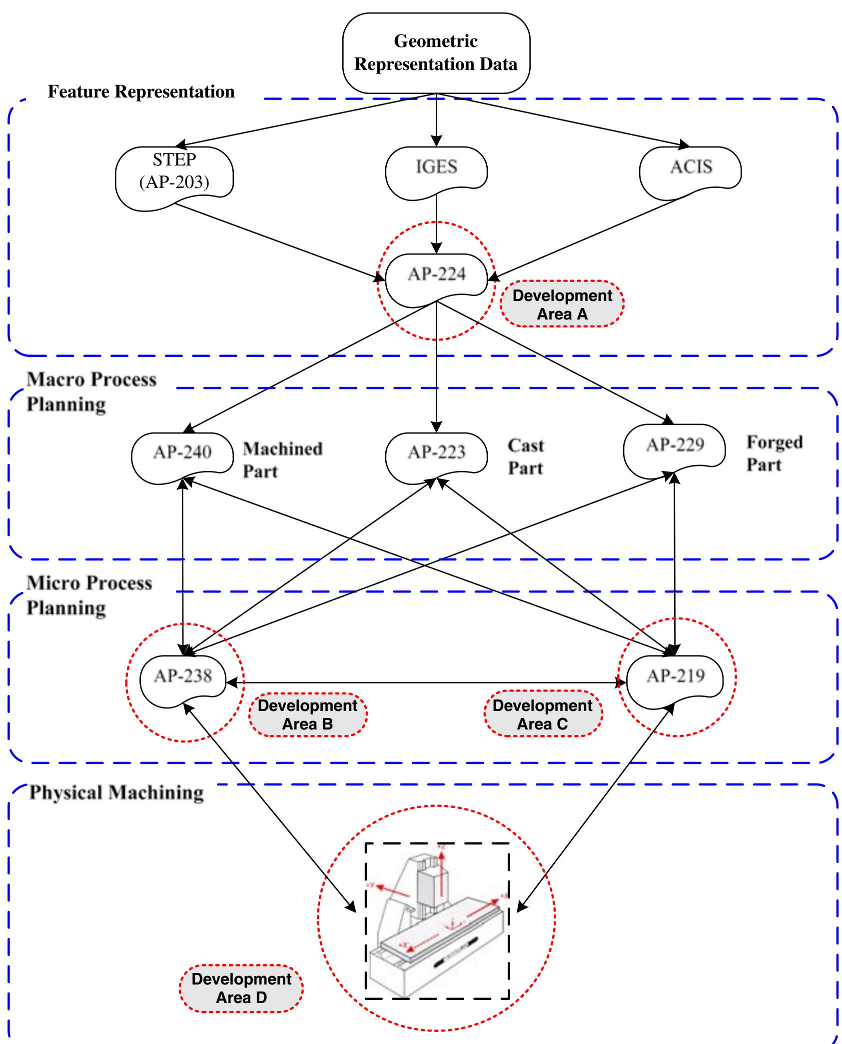


Fig. 1 An integrated STEP-compliant manufacturing system

ing process as well as for higher-level quality controls. Current inspection data model (AP219) describes inspection information that can be utilized on a Coordinate Measuring Machine (CMM) for micro inspection process planning purposes. Other inspection-related standards such as Dimensional Measurement Interface Standard (DMIS) [11], ISO 14649 Part 16 [12], and I++ DME [13] may also be used. Research work on the execution of STEP APs (STEP-NC) data models (development area D) has been the main focus of many research groups, consortiums, and industrial partners [14, 15]. The development work involves essentially utilizing the implementation methods described in STEP to devise a standard method capable of converting the high-level STEP data to low-level machining instructions such as G-codes [15].

This paper presents an overview of an integrated, STEP-compliant manufacturing environment and discusses the requirements for such system to be developed. Then, the ongoing research in each of the aforementioned development areas is reviewed. This paper can be seen as a continuation of

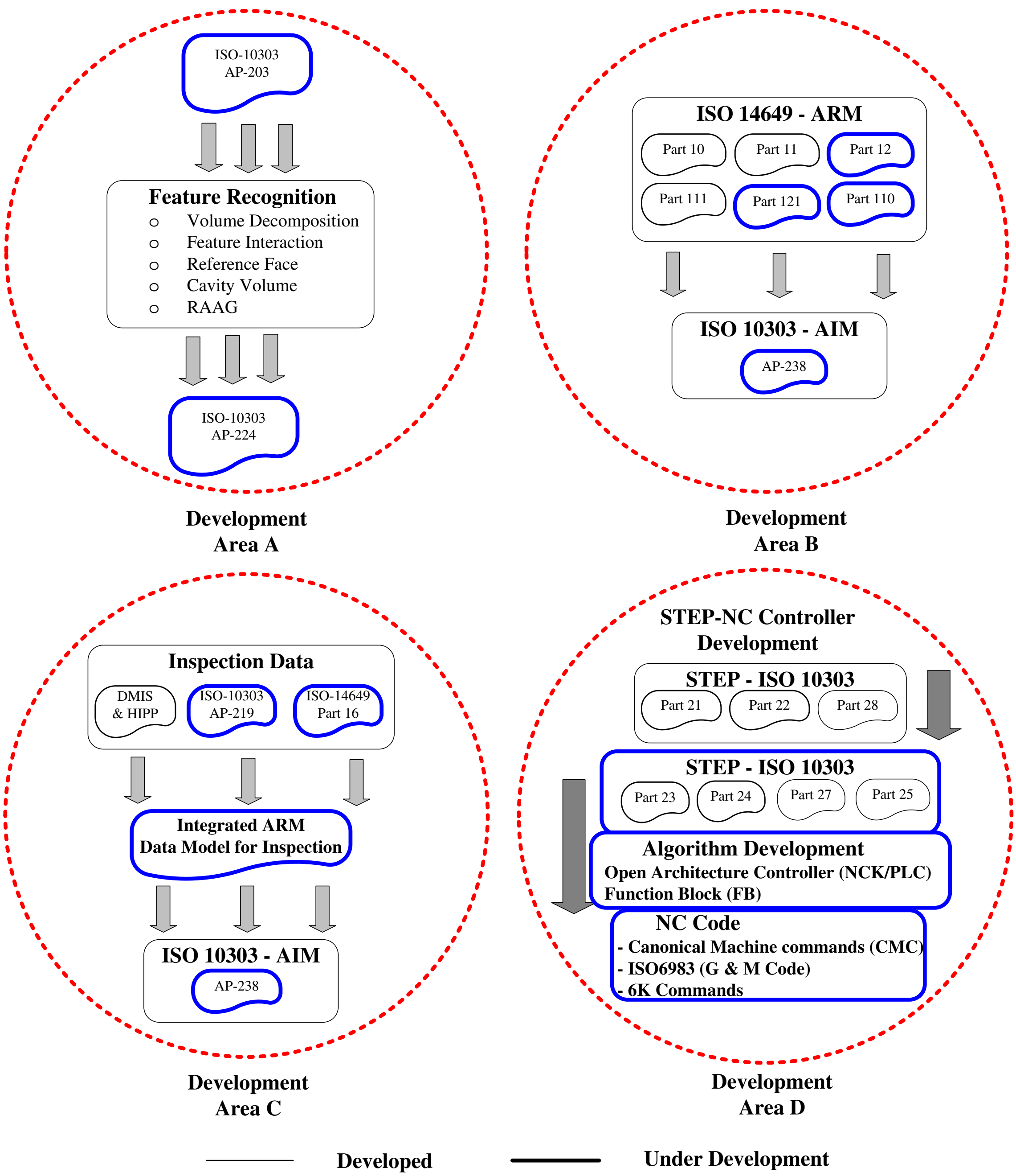


Fig. 2 Areas of research in an integrated STEP-compliant manufacturing system

the review work carried out by Xu et al. [30] in 2005, which reviewed the major developments in the similar fields prior to 2004.

2 An integrated, STEP-compliant manufacturing environment

An integrated STEP manufacturing environment can be sub-divided into two systems (Fig. 3). The first subsystem is responsible for generating a native program that retains all the information needed to machine a part on a particular machine tool. The second subsystem carries out optimization for the machining parameters using the dispatched information from the first subsystem. Hence, the second system is responsible for generating tool paths, instructing a machine tool and inspecting the machined part.

The first subsystem utilizes the geometry data given from a CAD system that outputs STEP AP203 data. The information in the STEP file is then interpreted into AP224 manufacturing feature. These features are used as inputs for process planning. Some general production requirements and manufacturing resources are then defined for each feature so that Workingsteps [10] are formed and saved into a STEP-NC part program (generic program).

The generic STEP-NC program acts as an input to the resource-driven process planning system, which is linked to a machine tool database (preferably developed using EXPRESS) that provides the necessary data for machining optimization. Consequently, the generic STEP-NC program is converted to a native STEP-NC program. The integrated process planning (including generic and native process planning) is shown in Fig. 4.

The native STEP-NC program is then sent to a manufacturing system. This system performs two activities (Fig. 5). The first activity is to generate a tool path based on the STEP-NC native program. The tool-path generator interprets the native STEP-NC information to low-level machining commands such as G-code or any other NC languages. This system is directly connected to the machine tool, where manufacturing execution (the second activity) takes place.

A possible activity after machining is inspection. A *C*omputer *A*ided *I*nspection *P*rocess *P*lanning *S*ystem (CAIPPs) can carry out this task. The native STEP-NC inspection program is inputted to the CAIPPs and transformed into a native probing path, which is then executed to drive the probe and take the necessary measurements. The data collected by the probe is analyses to determine if the tolerances are met and if not what remedial decisions should be made to rectify the error.

3 Review of STEP-related research

Relatively intensive research in the areas of STEP-compliant CAD/CAPP/CAM/CNC has been reported in the

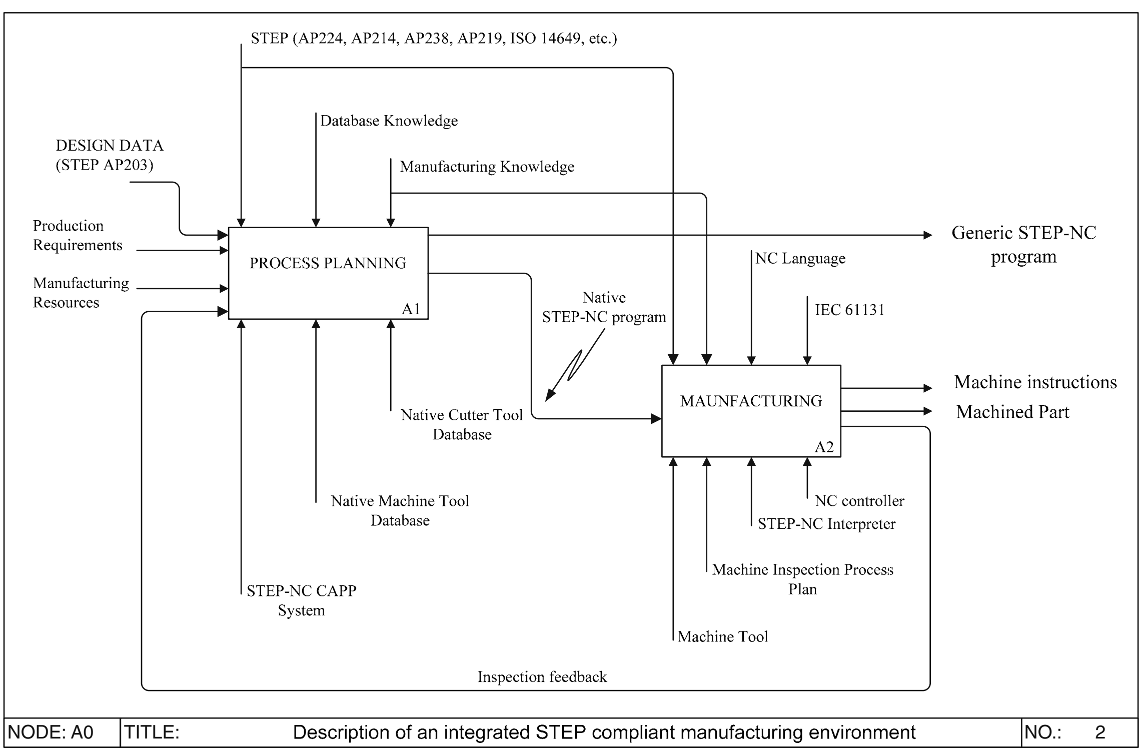


Fig. 3 IDEF0 diagram for process planning and manufacturing

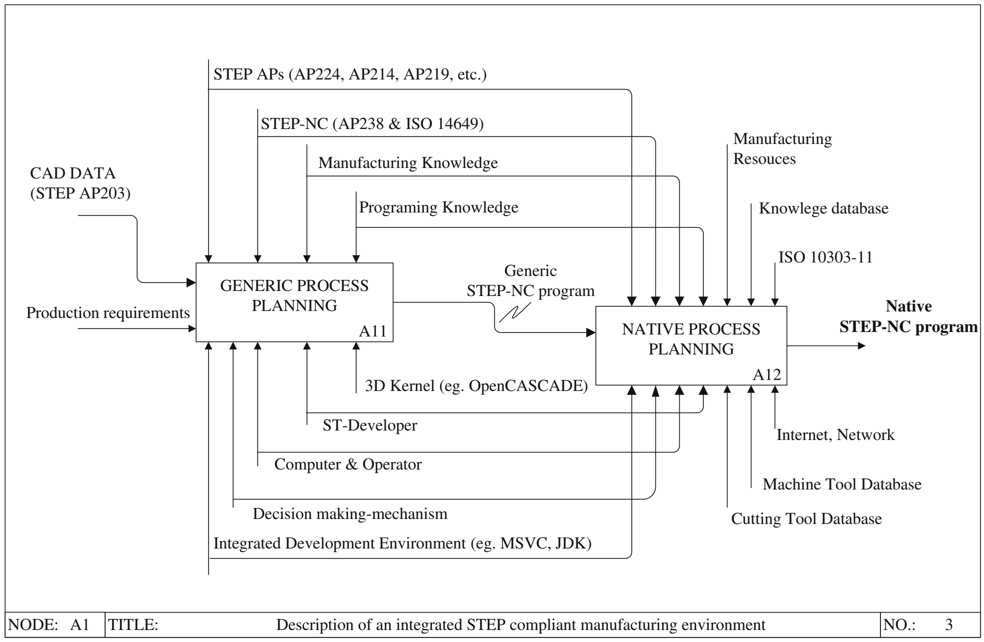


Fig. 4 IDEF0 diagram of the integrated STEP-NC process plan

literature. This paper aims to review the most recent research outcomes, i.e., post-2004.

3.1 STEP-related feature recognition (Development area A)

The first major challenge in STEP-based manufacturing system is to establish a concurrent engineering environment across all manufacturing activities. A key element in this environment is feature which allows integration between CAD (as in AP203) and CAPP (as in AP224 and AP238) data. However, recognizing AP224 features from an AP203 model is still being researched [31]. This section reviews the recent effort in STEP-related feature recognition.

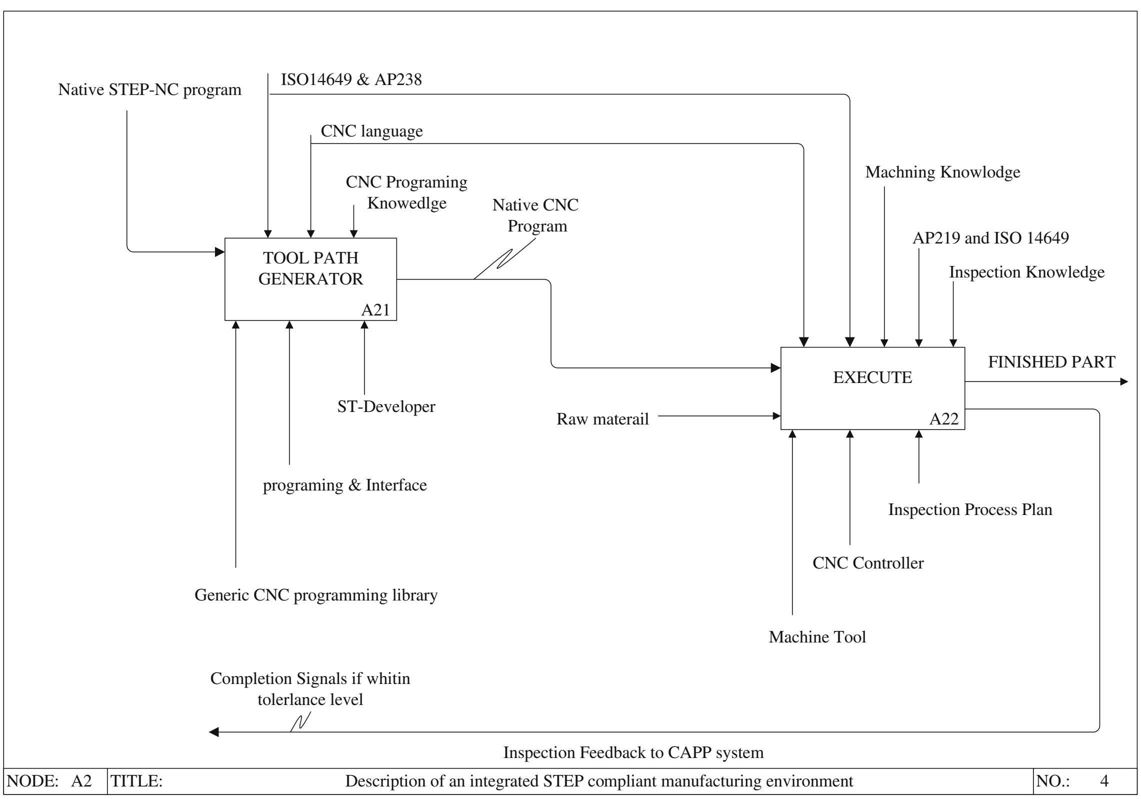


Fig. 5 IDEF0 diagram of an integrated STEP-NC manufacturing

Holland et al. proposed a process orientated feature recognition system to assist the development of a CAD-linked, standalone computer-based metal-forming system [32]. This system converts AP203 data to simple features such as boss, cylinder, pocket, and external transition features. The system uses pattern recognition to transform the surface boundary model of a component into an Attributed Adjacency Graph (AAG). In an AAG, each face is represented as a node, with connection edges shown as lines. Form features are then extracted through geometric pattern matching from a nodal plot.

Nassehi et al. developed a STEP-NC Multi-Agent System for Computer Aided Process Planning (MASCAPP) [33]. The MASCAPP employs a collection of classic interaction detection algorithms. These algorithms help determine if a feature represented by a feature agent has interaction(s) with other features by using methods such as a bounding box, line interaction, and feature-enclosure methods. While the algorithms are capable of determining overlap and enclosure types of interactions in a prismatic part, they are limited to two features: general closed pocket and round hole.

Ong et al. at the National University of Singapore proposed a manufacturing feature recognizer for the Unigraphics system [31]. It integrates feature recognition with design-by-feature approaches to generate a STEP-based manufacturing feature model. The design feature models and feature recognition system are integrated into a concurrent engineering agent environment (Fig. 6). The recognizer detects manufacturing features from a Constructive Solid Geometry (CSG) tree. Then, a neutral file is generated to describe the manufacturing feature model for the downstream manufacturing activities to share. The interacting and inter-relating relationships between features can also be represented.

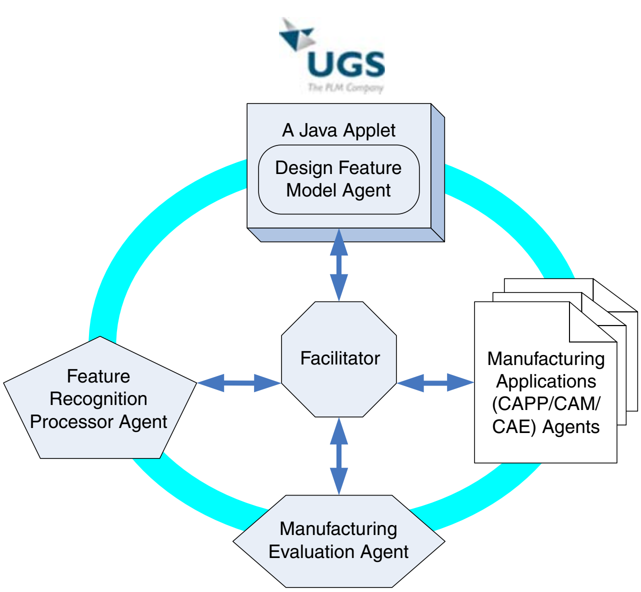


Fig. 6 Concurrent engineering agent environment

Kang et al. at the University of Suwon in Korea proposed an approach to link design with process planning by representing manufacturing information together with part geometry given in the STEP format [34]. Figure 7 shows the data flow of the approach. The STEP AP203 interpreter extracts geometric entities from an AP203 file and converts it into a Parasolid model by the Parasolid translator. The STEP data is then converted into the B-rep data, which are then translated into a Parasolid model by using Parasolid APIs. Tolerance information is also attached to the Parasolid model. Machining features are then extracted making used of the tolerances attached to the Parasolid model through the feature recognition kernel, IF^2.

Similar research has also been carried out for injection-molding processes. Lockett et al. proposed a mid-surface-based feature recognition approach for molded parts [35]. The Attributed Mid-Adjacent Graph (AMAG), which represents the patterns identifying molding features, is parsed by the system. The techniques developed in this research were based on some of the existing graph-base feature recognition techniques, e.g., graph pattern matching and hint-based reasoning for prismatic parts.

3.2 STEP-related process planning (Development area B)

Process planning involves decision-making for selection of process parameters, division of machining stages, and selection of machine and cutting tools. Although many process planning systems have been developed, CAPP systems in support of the STEP-compliant manufacturing environment are still few and far in-between. This section reviews the research work in this area.

Research works have been carried out to explore the capability of STEP-NC in interoperable manufacturing, especially process planning at Loughbough University and the University of Bath. Using agent-based technology, Allen et al. developed a STEP-NC compliant process planning system named AB-CAM (Fig. 8) [36]. In this system, STEP-NC manufacturing features are defined as Manufacturing Feature Agents (MFAs). Simple features are defined as Autonomous MFAs whereas combined features are defined as Cooperating MFAs. Both types of MFAs can require corresponding manufacturing feature information from the Component Model and Manufacturing Resources Model (including cutting tool information). The process planning tasks that are carried out include resource selection, operation selection, machining parameter determination, etc. Afterwards, the operation-related information is written into a corresponding Workingstep. The Workingstep Optimizer agent is then used to optimize the sequence of the Workingsteps and generate an optimal Workplan.

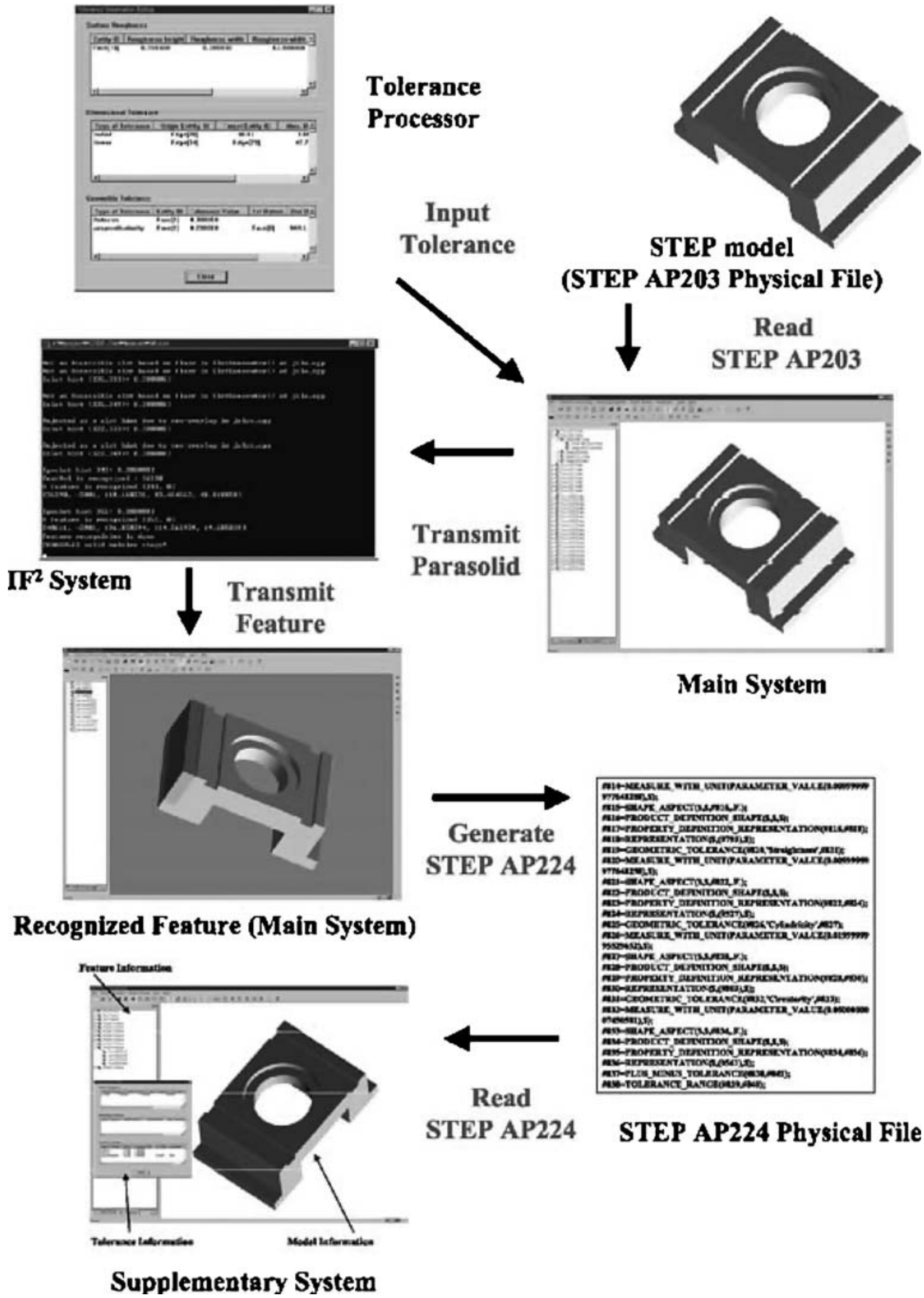


Fig. 7 Workflow in the proposed framework

Nassehi et al. from the same research group analyzed each part of the STEP-NC standard for a potential application in an adaptive manufacturing system [37]. The researchers grouped the STEP-NC model into three main sections, product geometry model (manufacturing features definitions as in Parts 10 and 11) [16, 17], interoperable manufacturing process models (as in Parts 10, 11, 12, 14 and 16) [18, 19] and manufacturing resources models (as in Part 111 and 121) [20, 21]. Based on this work, a Multi-Agent System for CAPP (MASCAPP) was developed [38]. This system employs a collaborative multi-agent approach where each individual agent is charged with the responsibility of identifying manufacturing requirements for a particular manufacturing feature. Continuing with their work, Nassehi et al. demonstrated a software platform entitled the Integrated Platform for Process Planning and Control (IP^{3}AC) [33]. IP^{3}AC was developed using JAVA, and adopted a two-stage strategy for STEP-NC part program generation, namely general Workplan generation and specific Workplan generation.

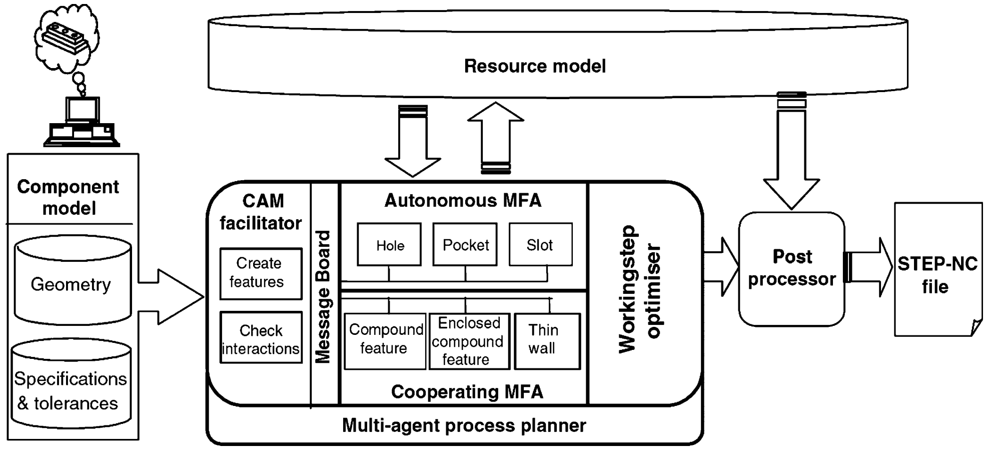


Fig. 8 Framework of AB-CAM system

Stroud and Xirouchakis extended the feature definitions in STEP-NC to support process planning for aesthetic products in stone manufacturing industry such as dry high-speed milling of marble and industrial ceramics [39]. The new aesthetic features are divided into four categories: shell_feature, rebate_feature, runoff_area, and pattern_feature. Machining strategies for these new features were also suggested. Sokolov et al., from the same university, discussed the implementation of the wire-EDM algorithms (surface-based algorithm) [40]. This wire-EDM data model further extends the existing ISO 14649 Part 13 schema [22]. An EDM process plan in the form of STEP-NC Part 21 [23] file can be generated through a commercial CAM system—AlphaCAM. This Part 21 file was then sent to an EDM machine controller.

Amaitik used the STEP-NC concept to develop a process planning system named ST-FeatCAPP (Fig. 9) [42]. ST-FeatCAPP is integrated with a CAD system making use of STEP AP224 XML data. It is part of a large system that also contains a STEP-based feature modeler (STEP-FM). STEP-FM uses STEP features as the basic entities for part design and generates a STEP AP224 XML data. ST-FeatCAPP performs tasks such as integration and preparation of design data, and selection of machining operations, cutting tools, machine tools, and machining parameters.

In the effort of developing an integrated sheet metal system, Xie and Xu proposed a STEP-based prototype system [43]. The system contains a CAD, CAPP, CAM, and common database module. A STEP-compliant information model is utilized to represent the sheet metal product, which includes product geometry information, sheet metal product feature, the nesting planning results (cutting routing information), etc. Yang et al., from the same research group, proposed a resource-driven process planning system in support of collaborative manufacturing by utilizing STEP-NC as a fundamental data model [44].

At the rapid prototyping front, Ryou et al. developed an EXPRESS data model that contains three main categories (i.e., part geometry design, part non-geometry design, and part process history) and one optional category (i.e., part local control) [45]. The part geometry design category is responsible for modeling CAD data and the related geometric features. The part non-geometry design category is responsible for non-geometric property data, such as material, color, roughness, etc. The part process history category contains the knowledge about the previous work history. A prototyping system called CyberRP was developed to test the proposed EXPRESS data model.

3.3 STEP-related inspection research (Development area C)

Inspection is an essential part of machining process that provides quality assurance. Due to the lack of standardized data model for both machining and inspection, inspection process is largely carried out separately from a machining process. Some effort has been spared to achieve optimal inspection process planning utilizing the STEP-NC data model. Most of the work, however, employed CMM for inspection. This section reviews the research works on STEP-NC related inspection process planning systems using both CMMs and On-Machine Measurement (OMM).

Lin and Chow proposed a STEP data model represented in an IDEF0 module for CMM-based inspection process planning [46]. An EXPRESS data module was developed in this research. It was divided into three sub-modules (part, resource, and input data modules). The EXPRESS data module was used in this research to provide an object-oriented measurement data structure.

A number of American organizations collaborated on a STEP-enabled Closed-Loop Machining (CLM) project using ISO 10303 AP238 [26]. Two of the three probing operations defined in ISO 14649 Part 10 were tested in a demonstration, i.e., workpiece_probing and workpiece_complete_probing. The Workpiece was measured on a CMM machine. The inspection results were incorporated into the original input AP 238 data file for modifications. The modified AP238 data was then tested. This demon-

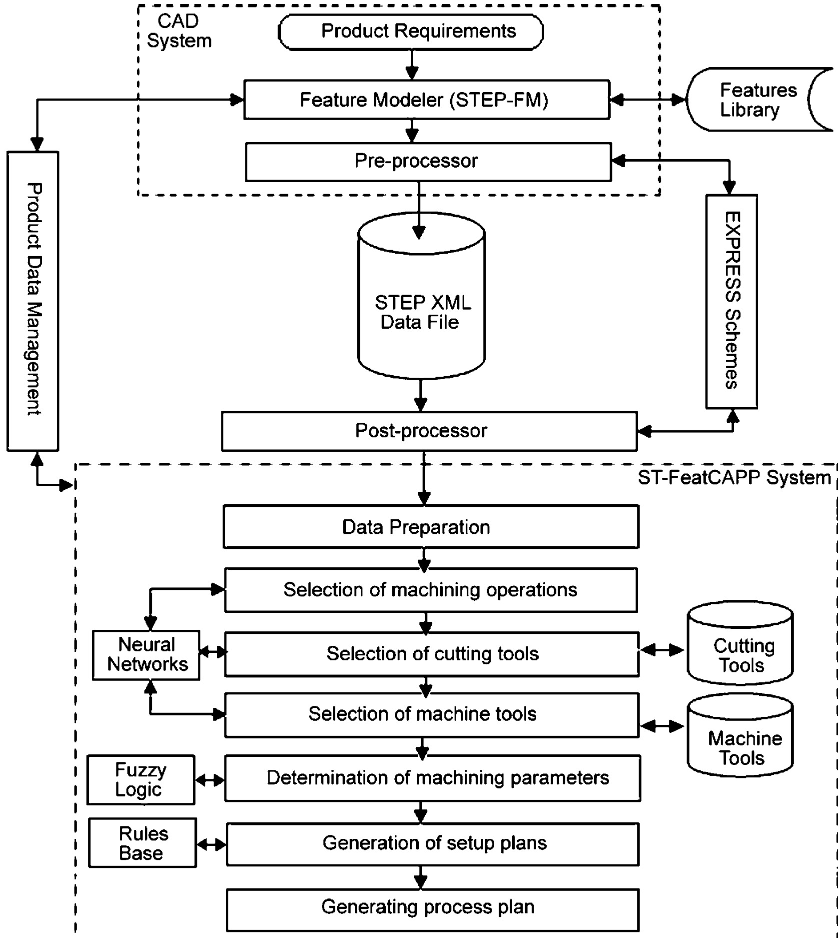


Fig. 9 ST-FeatCAPP architecture

stration is the first attempt to test the inspection operation definitions in the ISO 14649 standards.

Brecher et al. developed a system for a closed-loop process chain which integrated inspections into the STEP-NC machining information flow [47]. The system (Fig. 10) considers milling and uses a CMM for inspections. Two STEP-NC controllers were used for the implementation: (1) Sinumerik 840D plus STEP-NC enabled ShopMill controlling a Chiron machine tool, and (2) a WZL-NC controlled Maho 600E machine tool. Inspection commands are generated for a Zeiss CMM using the Calypso software. The milling operations are defined in an ISO 14649 data file together with inspection Workingsteps. This file is processed by the WZL-SFP program, which has a GUI for

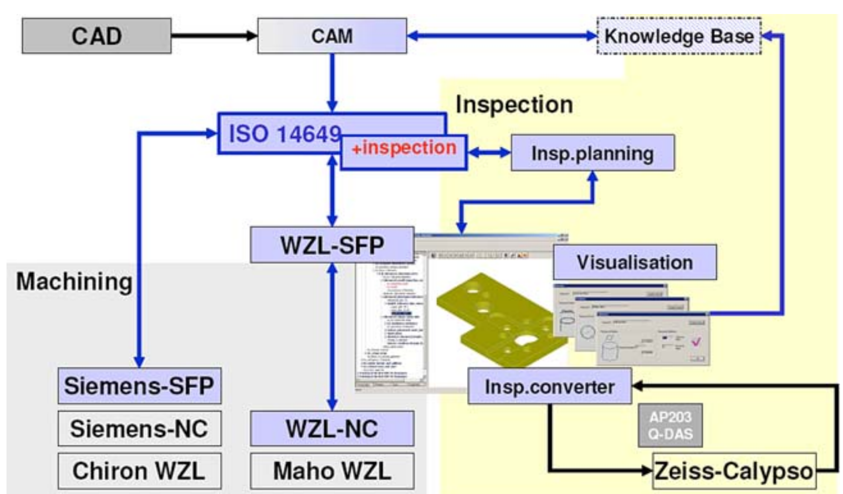


Fig. 10 STEP-NC enabled closed-loop machining chain

part display, tolerance definitions, and inspection Workingstep definitions. Inspection results are stored in a text file that is then parsed and reintegrated into the CAM module for updating.

Ali et al. proposed an inspection framework for closing the inspection loop through integration of information across the CAx process chain (Fig. 11) [48]. The main feature of framework is the inclusion of high-level and detailed information in terms of inspection Workplans and Workingsteps, and a mechanism to feed back inspection results across the entire CAx process chain. STEP-NC (ISO 14649-16), DMIS and AP219 were used. Again, this research mainly focused on the utilization of a CMM.

A piece of more specific work was carried out by Suh et al. [49]. They developed a method of indirect measurement based on the virtual gears model (VGM), obtained by Non-Uniform Rotational B-Spline (NURBS) fitting of the surface points measured by a CMM. By comparing the VGM with the CAD model (soft-master model), errors such as tooth profile error and tooth trace error are automatically identified. The model-based method can be incorporated into an advanced CNC controller based on the new CAM–CNC interface scheme of STEP-NC as an online inspection module.

Zhao et al. proposed a STEP-NC compliant, closed-loop machining (CLM) framework [50]. The work developed and integrated ISO 14649 Parts 10, 11, 12, and 16 to form an integrated data model for CLM. Inspections are done via OMM, providing in-process feedback for the entire machining process chain. Command files containing both machining and inspection commands have been generated. Based on this research, an integrated process planning system for machining and on-machine inspection was proposed [29]. The system consists of a STEP-NC Part 21 data file containing information such as feature, tolerance, measurement resource information and pre-machining process planning. Tolerances and machining-related information are analyzed and measurement features and related measurement operations are generated. These measurement operations are then inserted into the machining operation sequence to perform an in-process on-machine inspection. The inspection result is fed back to the process planning section to update subsequent machining operations.

Standards organizations and industry partners have joint forces to harmonize the existing inspection standards such as DMIS, AP 219, and ISO 14649 Part 16. In 2006, the Automotive Industry Action Group's (AIAG) MEtrology Project Team (MEPT) started to explore STEP-NC enabled solutions in conjunction with the work on Dimensional Markup Language (DML) and the new Quality Measurement Data (QMD) standard. The group believes that the standard/specifications under the oversight of the MEPT, namely, I++ DME, DMIS, DML, QMD, and Scan Data, should generally fit well within the context of the appropriate STEP APs.

In 2007, a STEP-enabled, on-machine inspection demonstration was carried out at a meeting held in Ibusuki, Japan. In this demonstration, a High-level Inspection Planning (HIPP) system was proposed. A new edition of AP238 was also proposed with new inspection features added to the related existing entities. An on-machine inspection operation was carried out on a selected work-

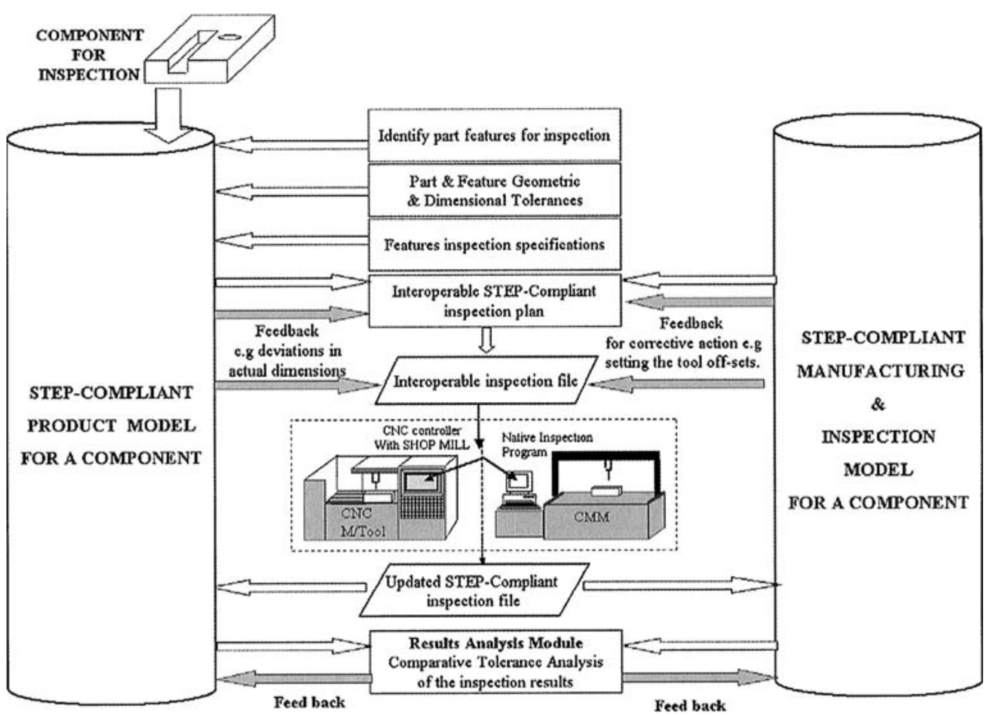


Fig. 11 STEP-NC compliant inspection process planning system

piece. Although no inspection path planning and measurement points optimization were considered in this demonstration, it is considered the first physical demonstration of STEP-enabled on-machine inspection. In a later meeting, NIST proposed a newly developed AP238 ARM model for HIPP. The combined ARM model incorporates the information requirement models for machining defined by ISO 14649 Parts 10, 11, 12, 111, and 121. The ARM model was also augmented with product data management information and information necessary to harmonize the inspection feature descriptions with the STEP manufacturing application protocols and linked to the aforementioned data.

Currently, all inspection-related STEP standards are still under development. The main focus of these standards is still on the use of CMMs. ISO 14649 Part 16 does not have the definitions for inspection features. ISO 10303 AP219 defines inspection features but does not specify the inspection operations and strategies. Due to the low-level information that the current G-code carries, each inspection phase has its own software and using its own standard data format. This hinders interoperability in metrology industry. Figure 12 shows the current metrology interoperability standards landscape. Research in how to harmonize these existing standards into a STEP data model for the entire inspection process is urgently up to us.

3.4 STEP-related controller (Development Area D)

Now that STEP-NC provides a consolidated and comprehensive data model for machining processes, it brings new challenges to CNC controllers in that these controllers will have to be able to process the high-level STEP-NC data and more importantly make intelligent machining decisions at execution. In order to achieve this, work has started to develop a STEP-NC enabled CNC controller that can handle the complex rules and syntax definitions in a STEP-NC data model. No doubt, this type of research is critical in bringing about the true benefits of STEP-NC.

ISO14649 standards were primarily used in the research work in Korea, which aims for intelligent product data processing such as feature recognition, collision-free tool path generation, automatic tool selection, and automatic process parameter selection, machining status, and feedback control.

Suh et al. proposed a conceptual framework for designing and implementing an intelligent CNC-controlled system [51–54]. The proposed system has five modules: Shop Floor Programming system (PosSFP), Tool Path Generator (PosTPG), Tool Path Viewer (PosTPV), Man–Machine-Interface (PosMMI), and CNC kernel (PosCNC). The proposed framework was later validated through the implementation of a prototype system. Figure 13 illustrates the working principle of their system. In 2005, this work was patented under the title, “Intelligent STEP-NC controller” [25]. A STEP-compliant CNC system for turning application was also developed [52]. The system is named TurnSTEP. This system is composed of three subsystems: Code Generating System (CGS), Code Editing System (CES) and Autonomous Control System (ACS). The data models incorporated in TurnSTEP are ISO 14649 Parts 10, 12, 121. Lee, W. et al., in a different group in Korea, developed a PC-based milling machine operated by STEP-NC in the XML format for five-axis machining [55].

NIST has built two STEP-NC interpreters for milling operations, one using STEP-NC AIM (ISO10303-AP238), and the other using STEP-NC ARM (ISO 14649-10,11,111; Fig. 14) [56]. The systems output Canonical Machining

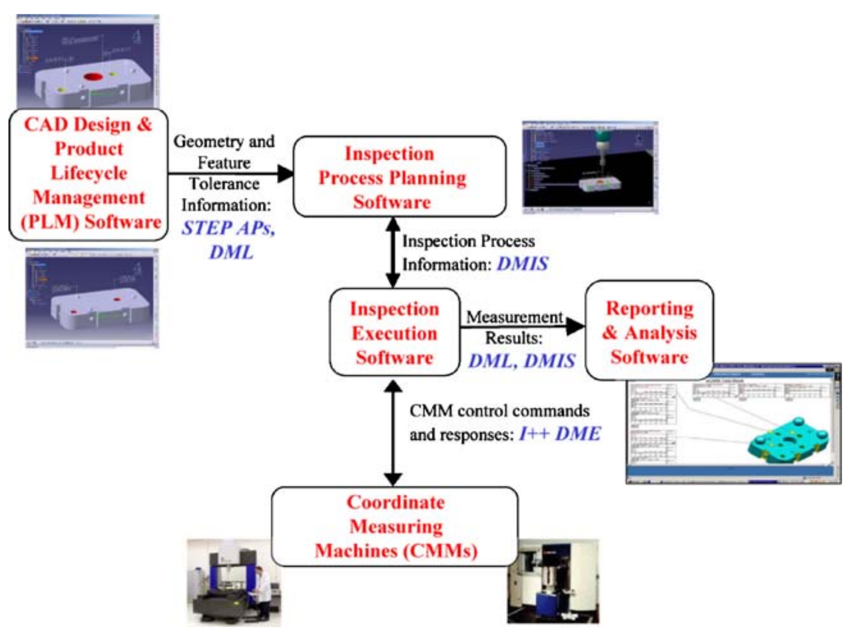
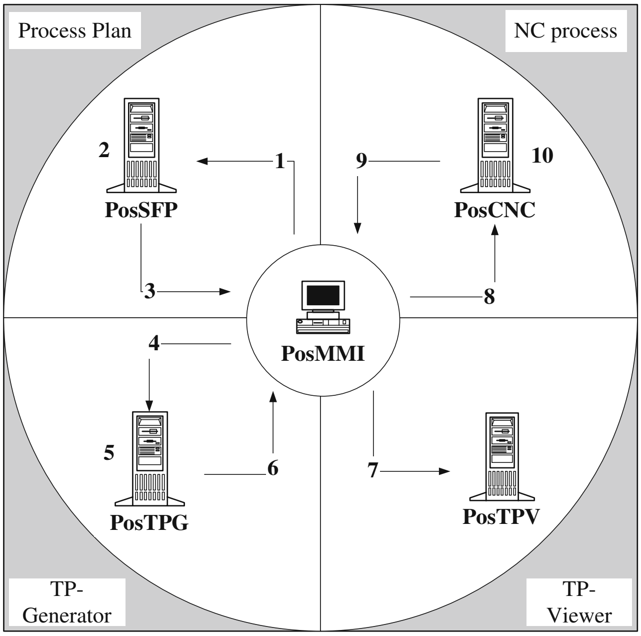


Fig. 12 The current metrology interoperability standards landscape



1-2	PosMMI command PosSFP to generate part program
2-3	Send part program to the main database (PosMMI)
4-5	PosMMI command PosTPG to generate tool path
5-6	Send the tool path to the main database (PosMMI)
6-7	Instruct PosTPV to view the generated tool path
8-10	PosMMI send tool path and commands to PosCNC
9-10	Process within PosCNC (e.g. Machining Instruction)

Fig. 13 POSTECH STEP-NC control strategy

Commands (CMCs). The interpreters include sufficient functionality to generate tool path for an example in the STEP-NC standards.

Fortin et al. proposed a new NC language called "Base Numerical Control Language" (BNCL) in the effort to improve information flow between CAM and CNC [57]. The language is based on a low-level, simple instruction set-like approach. The architecture is conjured around two concepts: the BNCL Virtual Machine (BVM) and the BNCL Virtual Hardware (BVH). The BVM is the virtual microprocessor acting as a compiler of any language or programming tool, whereas is the part of the architecture that makes abstractions of the machine it sits on. The proposed concepts have been validated through computer simulations and physical tests.

The University of Stuttgart presented a generic approach to pre-process and then feed back the process data obtained from servo drives to CNCs and CAPP systems [58]. The approach utilizes open digital servo drives on a machine tool and the design of application-dependent algorithms to process and exchange drive signals for both online and offline optimization of machining processes. Figure 15 shows the proposed open STEP-NC enabled CNC.

Different control strategies have been proposed and implemented by the researchers at the University of Auckland. Xu, in his paper [59], discussed a STEP-Compliant CNC lathe. The work consists of two parts, retrofitting an existing CNC lathe (HERCUS PC200) with the Parker's motion control system and the development of a STEP-NC converter "STEPcNC". The converter processes STEP-NC AIM data. The work was later extended by Habeed et al. who developed a more generic control strategy for CNCs (Fig. 15. Open STEP-NC-enabled CNC Fig. 16) [27]. A strategy supports a bi-directional data flow of three different data forms: STEP-NC data, machine specific language, and low-level machine control commands. The proposed method utilizes the concepts of modularity and database to harmonize and group machining processes. Based on this strategy, the same retrofitted CNC lathe was used for concept approval. This process was achieved through the development of a software tool that can process STEP-NC data and provide an interface with the retrofitted CNC lathe [59].

Also developed in the same research group is a STEP-compliant CNC adapter [60]. It is used as a "front-end" for a CNC controller that supports STEP-NC data models. A major part of the research is the mapping mechanism, which transforms STEP-NC data given in the physical file into the type of G-code specific for a particular controller. The mapping mechanism incorporates the function block technology. The system is therefore based on the concept of 'plug-and-play'.

Applications of Function Blocks [24] have been extended by Mohamed et al who proposed an architecture for a STEP-NC controller based on the Model-View-Control (MVC) design pattern [28]. The system's framework uses a layered structure, each layer responsible for data processing, data storage, and execution respectively. The layers separate the functional units into a hierarchical structure that utilizes the services of the lower layers.

Zhang, C. et al. in China proposed a framework for autonomous STEP-NC machining [41, 61]. The framework consists of two agents, the planning agent and the machining agent. The same group has also proposed a framework [38] that suggests a system consisting of an interpreting module (interpreter), a planning module (planner), a simulation module and a CNC kernel. In a system developed by Chen, X. et al. [62], a RTCORBA-based soft bus was used for communicating among the 18 functional modules.

4 Discussions

The review of the research work in this paper highlights several issues and challenges concerning STEP-compliant manufacturing that are deliberated and still remain open. These issues include the adoption by industry, as well as the outstanding issues in the aforementioned research areas.

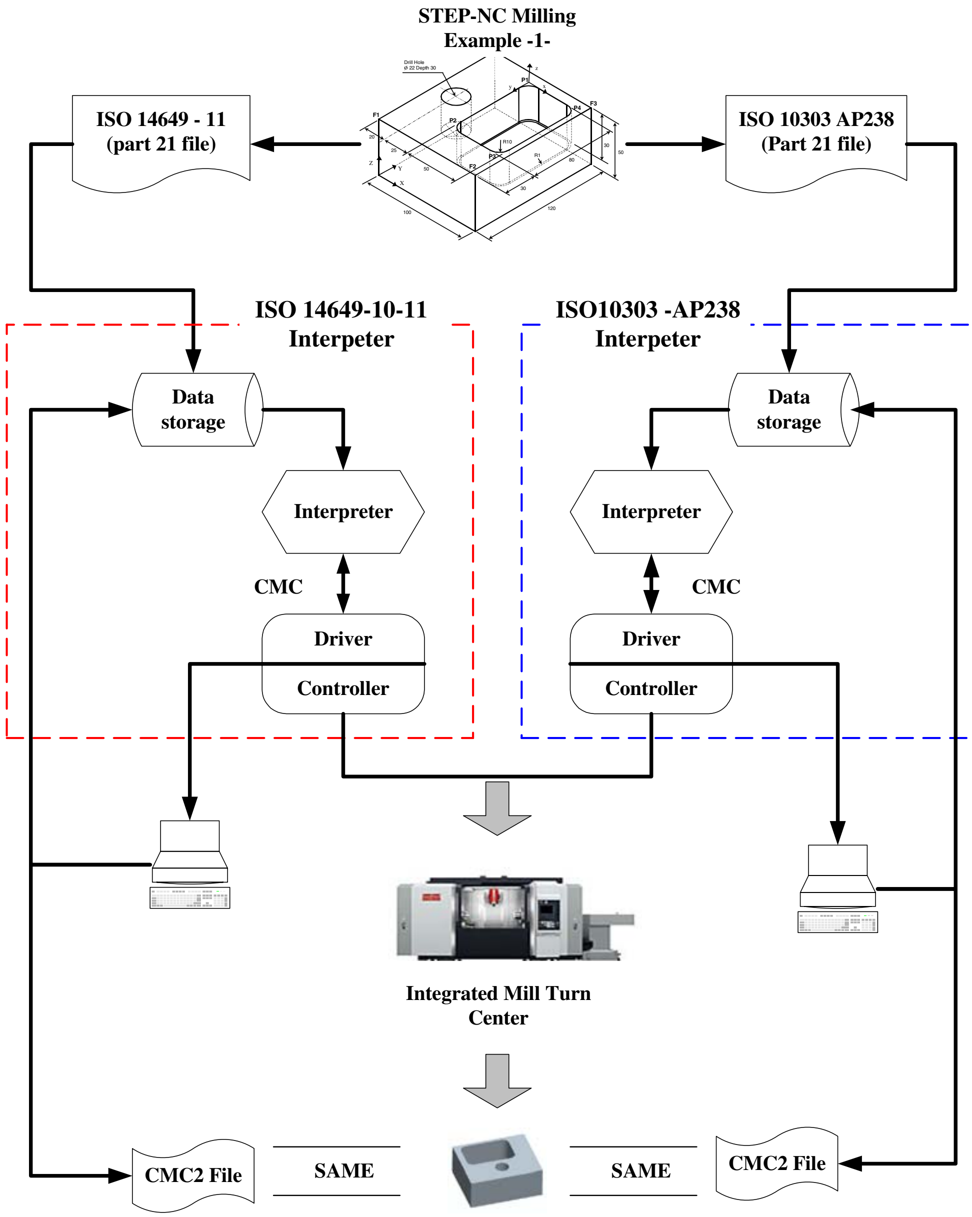


Fig. 14 Schematic diagram of NIST STEP-NC system

4.1 Current status of STEP

The current status of STEP standards development has been on four fronts. First of all, STEP AP 203, the most widely used AP in STEP application protocols, has been worked on for a number of years to produce its second edition. In this edition, construction history and geometric and dimensional tolerancing are, for the first time, included, providing foundation for additional future capabilities. Secondly, there has been some extensive development work undertaken to provide an effective tool for STEP data to be communicated via the Internet. This is evidenced by publication of STEP Part 25 in 2005. Part 25 describes the implementation method from EXPRESS to XMI. Also being worked on is STEP Part 28 Edition 2, which specifies the implementation methods for XML representations of EXPRESS schemas and data. Thirdly, STEP has been extended to reach many other fields in addition to design. This is particularly true with manufacturing. Between 2004 and 2007, five such APs have been published. They are:

- STEP AP 215: ship arrangement
- STEP AP 218: ship structures
- STEP AP 224 ed3: mechanical product definition for process planning using machining features
- STEP AP 238: application interpreted model for computerized numerical controllers
- STEP AP 240: process plans for machined products

How STEP will look in 5 or 10 years time is much dependent on a battle to win a balanced trade-off between

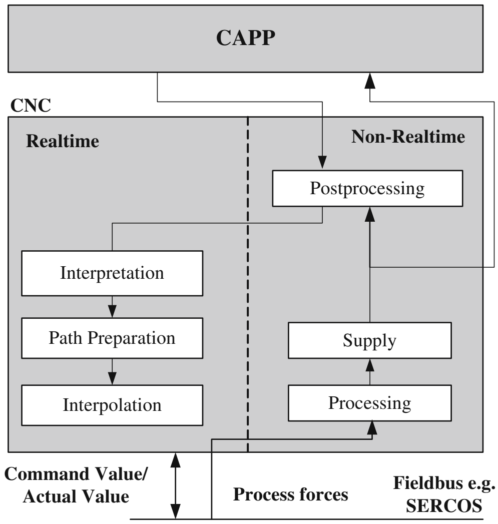


Fig. 15 Open STEP-NC-enabled CNC

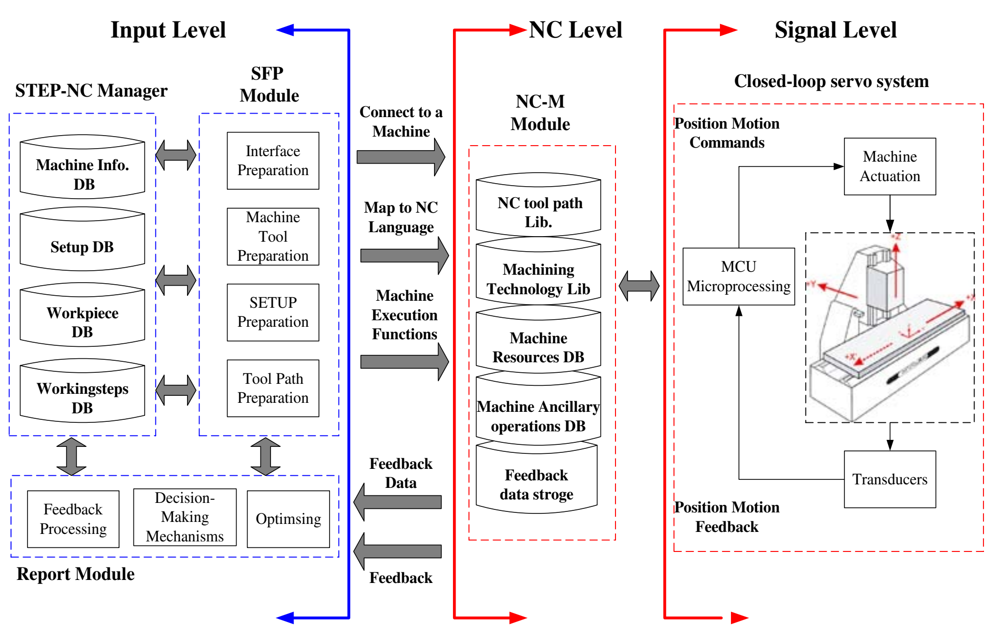
extensibility of its specification and guaranteed interoperability of applications using the specification. In the recent past, and perhaps still so, a major driver for architectural change in STEP is interoperability between APs. On the one hand, it would be naive to think STEP developers would have the foresight to anticipate all data elements of importance for any significant time span. For example, the increasing use of parametric, feature-based design was not supported in the early parts of ISO 10303. There has also been a desire to represent the designer's intent and design history together with the raw design data. Experimental use of STEP for practices such as product lifecycle management (PLM) [63, 64] and e-commerce, is already taking place. Therefore, there is definitely a need for STEP to be able to expand its current data structures and hierarchy. On the other hand, interoperability between APs will be threatened if expanded data structures are added outside the standard. Past experiences with issuing newer versions of a STEP Part to include extra data (e.g., AP 203) have always led to a significant amount of re-development and revamp of the existing tools and systems, which does little to encourage quick adoption of the new standard.

All in all, it is apparent that STEP is much more than an international standard for exchanging product data. It is about enterprise integration, global competitiveness, data archiving, design reuse, and solving challenging manufacturing and business problems.

4.2 Industrial adoption

Some 15 years have lapsed since the first version of STEP became an ISO standard in 1994 and companies such as GE, Boeing, and General Motors began announcing commitments to using STEP in 1995. Industrial use of STEP has now shown evidence of significant cost savings, higher quality, and reduced time-to-market. It may become a major building block in e-economy, the effort to unite manufacturing businesses among corporate partners, distant suppliers, and across diverse computer environments. Such an important function will only gain in importance in this rapidly changing economy that is increasingly globalized, collaborative, distributed, interoperable, and integrated. A typical example of how a sector of industry, e.g., automobile industry, uses STEP can be described as hereafter. An automobile engine designer working with a commercially available CAD system designs an engine block. The CAD system's native representation of the design is proprietary to the vendor of the system, but a

Fig. 16 System control configuration



STEP output module has been included within the CAD system that translates the proprietary representation into a representation using the STEP application protocol for configuration controlled design (AP 203) [2]. The AP 203 representation is saved in a STEP data file using Part 21 of STEP [23]. The engine block design is sent to a manufacturing plant by sending the STEP Part 21 file for the design. At the manufacturing plant, a manufacturing engineer using a CAD (or CAD/CAM) system from a different vendor tells the CAD system to read the STEP file. This is possible because the second CAD vendor has also implemented STEP AP 203. The system reads the STEP file and builds a representation of the design in the second CAD system's native format. With the design now resident in the CAD system, the manufacturing engineer goes to work figuring out how to manufacture the engine block. If the manufacturing engineer wants to suggest a change in the design (and the second CAD system includes a STEP output module), he or she can have the CAD system write a revised STEP AP 203 Part 21 file and send it back to the designer.

However, STEP implementation has only engaged modest industry involvement. A number of benchmark products and interoperable machining benchmark tests are urgently needed across various manufacturing sectors to showcase the capabilities, strengths, and weaknesses of STEP-enabled interoperable manufacturing. Although CAD/CAM software vendors and system integrators have almost all had an embedded STEP interoperable module as discussed in the previous paragraph, the data that are handled are only at very basic level (STEP AP203). There is obvious hesitation in achieving complete interoperable standardization by implementing other STEP APs. They often see a STEP-based universal platform reduce commercial profits competitive advantages of their products. A big test for these software vendors will be their plan to adopt STEP AP 203 2nd Edition that incorporates tolerance data. However, the spread of true interoperable systems based on STEP, once their benefits are recognized, will form a forceful market demand, to which the CAD/CAM vendors may eventually fully embrace STEP.

4.3 Challenges for feature recognition and process planning

Feature recognition is the front-end of any process planning system to be used in an integrated CAD/CAM environment. However, much of the manufacturing knowledge such as manufacturing resources and tooling, typically used in-process planning, is rarely incorporated into feature recognition systems, which in general require more than just geometry data for a part to be manufactured. For example, product geometry defined in AP203 may need to be linked with STEP-NC Workingsteps, the same way as manufacturing features are linked with machining operations. Table 1 lists some of the recent work on feature recognition and process planning based on STEP and STEP-NC.

The current major challenge in STEP-based manufacturing system is to establish a concurrent engineering environment across all manufacturing activities. A key element in this environment is a feature which allows integration between CAD (AP203) and CAPP (AP224) data. However, recognizing AP224 features from a AP203 model is still not an easy task [28]. This section reviews the recent effort in STEP-related feature recognition.

It can be said that research on feature recognition based on AP 203 and AP 224 is limited. Those that are reported seldom consider all features defined in AP224. At the process planning level, there is a need for the STEP standards to provide data structures that can record machine tool configurations, technologies, and capabilities. This is so that a machine tool resource database can be developed and used to map a generic STEP-NC program to a native one. It appears that use of AP 238 may make bi-directional data flow between design and manufacturing easier, which is essential to provide feedback from manufacturing to design.

4.4 Challenges in STEP-enabled inspections

An inspection system often consists of distinct components, each with distinct functions, e.g., CAD, process planning, process execution, inspection hardware, and result reporting and analysis. Multiple vendors offer solutions for each function. The languages used to communicate across the interfaces between these components are typically proprietary. This proliferation of proprietary interface languages has proved to be costly to users, suppliers, vendors, and customers. STEP and STEP-NC would be a "natural" solution to provide the needed interoperability between these interfaces. However, there are a number of major issues to be addressed.

ISO committees, AIAG, and MEPT metrology standard development groups have met to discuss the gaps and overlaps between different inspection data models. The collaboration between these groups in the effort of further developing a harmonized STEP-NC inspection data model is considered a way to move forward. Issues to be addressed include the incompleteness of the inspection-based STEP-NC data model and the harmonization between STEP-NC and some widely used and emerging interface specifications such as DMIS and I++ DME. ISO 14649 Part 16 does not have the definition of inspection features nor geometric tolerances. ISO 10303 AP 219 does not support inspection operations and strategies. Both of these standards are only meant to support inspections carried out on CMMs. Hence, these standards lack definitions of measuring machine functions and technologies, metrology device information,

Table 1 Summary of the research on feature recognition and process planning

	Systems	Capability	Standard I/O	Region
Feature Recognition	Feature recognizer	B-rep geometry abstraction /conversion (simple features only)	CAD data/ ISO 10303 Part 21	UK
	Feature recognition processor	feature interaction, detection, and extraction (simple features only)	CAD data/ ISO 10303 Part 11	Singapore
	AP 203 interpreter	feature interaction, detection, and extraction (simple features only)	AP 203/ AP 224	South Korea
	Molding-feature recognition system	B-rep geometry abstraction/conversion, molding feature extraction (simple prismatic features only)	CAD data/ISO 10303 Part 21	UK
	MASCAPP	Feature interaction/inter-relating detection (closed pocket and round holes only)	Design features/ ISO 10303 Part 21	UK
Process planning systems	AB-CAM system	Resource, cutting tool, machining parameters selection and determination	Design features/ ISO 10303 Part 21	UK
	IP^{3}AC system + MASCAPP system	Machining feature detection/sequencing, machining operation, tool and parameters selection and determination, NC code generation	product design features/ ISO 10303 Part 21 and NC code	UK
	EDM system	Machining feature detection/sequencing, NC code generation	ISO 14649, ISO 10303 Part 21/ NC code	Switzerland
	STEP-compliant process planning agent	Machining operation, cutting tool, and machining parameter selection and determination	ISO 14649/ISO 10303 Part 11	China
	Sheet metal CAPP	Machining feature detection/sequencing, machining operation selection, NC code generation	ISO 10303 Part 21/ NC code	New Zealand
	CyberRP system	Machining feature detection/sequencing	STL/ ISO 10303 part 11	South Korea
	ST-FeatCAPP system	Machining feature detection/sequencing, machining operation, tool and parameters selection and determination,	Design features /AP 224 XML	Turkey

and measuring strategy information. Most of this information is defined in other standards such as DMIS and I++DME.

4.5 Development of STEP-NC-enabled controller

The research into developing a STEP-NC controller can be divided into two levels. The first is the STEP-NC level (high level) in which STEP-NC data is processed, optimized, and ready to be fed to a controller. The second is at the command-level which concerns with translating the STEP-NC data into a form of low-level signals that control for example power amplification equipment to drive actuation components and to produce feedback from transducers of the machine tool.

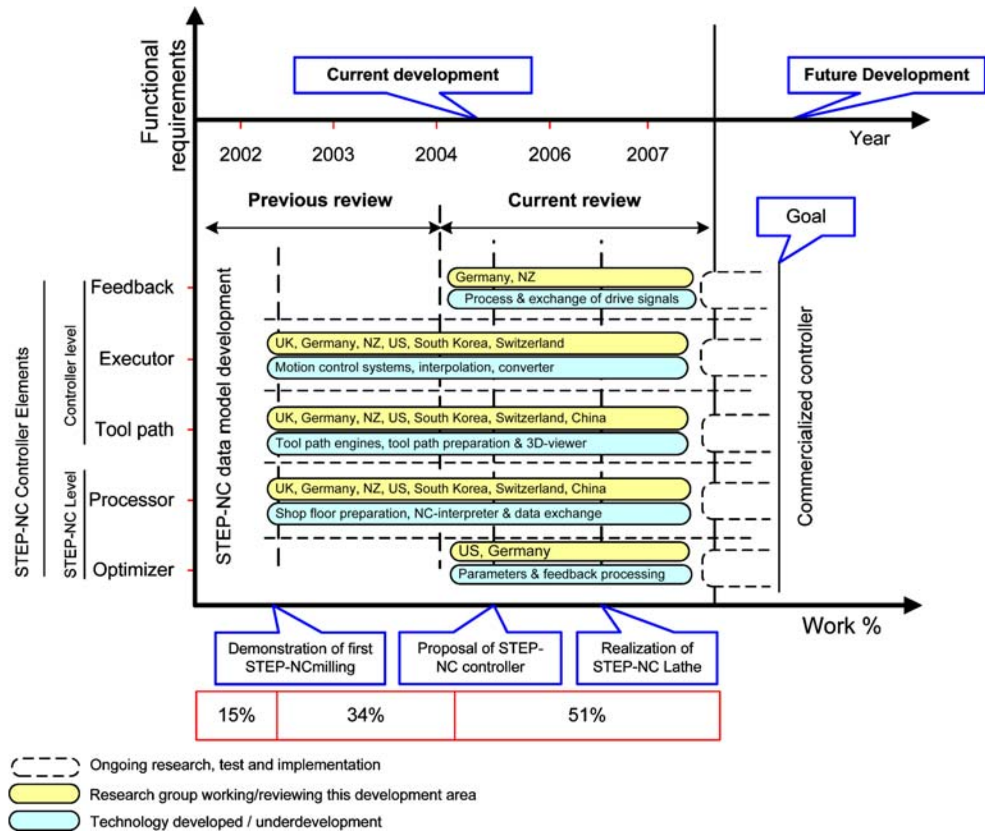
A number of functional prototypes of STEP-compliant CAM/CNC systems and STEP-NC controllers have been developed by research teams from a number of countries. NIST created a software system that can directly read and interpret the information in a STEP-NC file to a machine specific language (i.e., canonical machining commands). Korea proposed an architectural foundation for a STEP-NC controller. Germany on the other hand developed their system for milling application using ARM data model for Shopmill that enhanced Siemens controllers. Research work in New Zealand demonstrated the realization of STEP-NC lathe utilizing 6K4 Parker Motion Controller system. Figure 17 gives a timeline of the progressive development in the field, and also the reviewing work of the research works.

It can be observed that the current research in implementing STEP-NC technologies and developing STEP-NC controllers has yielded some results. However, most of the systems make use of the existing controllers that run on G-codes. Thus, changes made at the actuation components cannot be captured and integrated with up-stream processes. Genuine type of STEP-NC controllers that are capable of real-time and bi-directional machining optimization is yet to be seen. Indeed, STEP-NC data models show superior potential in communicating with a CNC controller at a high level. Mechanisms that enable interoperability between different controllers are altogether another challenging task.

5 Conclusions

After almost 15 years since the first STEP standard formally published, for the first time, we seem to have enough published Application Protocols for the development of a potential integrated, STEP-compliant manufacturing environment. These APs, to list only a few, cater for configuration controlled designs (AP203), data for automotive design

Fig. 17 Shop floor implementation and controller development (2002–2008)



processes (AP214), machining features (AP224), process planning (AP240), computer numerical control (AP238), product data for cast parts (AP223) and forged parts (AP229), and dimensional inspection information exchange (AP219). Added to this list is a newly published ISO 14649 parts that essentially move the STEP standards a step ever closer to be used by computer numerical controllers. The significance of ISO 14649 standards is that its parts are also developed using STEP definitions and EXPRESS languages. All of this has provided a valuable stimulus to raise the awareness of CAx software vendors, controller suppliers, and CNC machine tool manufacturers to develop new CAD/CAM and CNC software products that have the possibility to bring about a new era for integrated manufacturing in the twenty-first century.

In phase with the deliberation of the STEP APs is the relatively high magnitude of funding strength over a number of STEP and STEP-NC-related projects in the past decade, sufficiently demonstrating the importance of the STEP standards. Participation of, and collaboration among, a wide variety of organizations such as end users, academic and research institutions, and manufacturers of CAM systems, controls, and machine tools, echoes the significance and relevance of this work in particular from the industry perspective. Some research has yielded promising results and a number of public demonstrations have taken place.

The STEP-based feature recognition research has the longest history. The goal is to identify STEP-based manufacturing features from a pure geometric model. This is an indispensable step toward integrated design and manufacturing as features are the common thread throughout the integrated process chain. The work in this area is still on-going. The challenge comes from the difficulties in the process of geometric reasoning needed by almost all feature recognition systems. STEP-related process planning research also has a long history. The work in this area is somewhat hampered by the difficulties in obtaining STEP-defined manufacturing features. Since AP224 edition 1 was published in 1999, this problem has been alleviated. However, by then, CAPP work had already been in full swing but using all sorts of feature definitions and taxonomy. There has not been much research work done in relation to STEP-based inspections. The work that has been reported is mainly based on AP219 and there is little integration with machining operations. With AP238 and ISO 14649 Part 16 to be published, there is a good chance that an integrated machining and inspection system may be developed. Some of this work has already led to valuable outcomes. Developing a STEP-compliant CNC controller has proven to be a more difficult task, partly because this would involve hardware re-development for the CNCs. The progress in this direction has been slow. Resistance from the CNC OEMs (original equipment manufacturers) is mainly rooted from the short-term financial benefits, or rather the lack of them being envisaged.

It is believed that the use of STEP requires a paradigm shift in programming together with a culture change for CAD/CAM vendors and machine tool manufacturers. This change will become a reality only if company owners see cost reductions in the design to manufacturing process chain which enable lead times to be reduced with component prove out minimized, part quality improved, and machine utilization increased. Nonetheless, the authors believe that STEP is the right approach; the challenge is to convince the users.

References

1. ISO 10303-1 (1994) Industrial automation systems and integration—Product data representation and exchange—Part 1: Overview and fundamental principles. International Organisation for Standardisation (ISO), Geneva, Switzerland
2. ISO 10303-203 (2005) Industrial automation systems and integration—Product data representation and exchange—Part 203: Application protocol: Configuration controlled 3D design of mechanical parts and assemblies (modular version). International Organisation for Standardisation (ISO), Geneva, Switzerland
3. ISO 10303-214 (2003) Industrial automation systems and integration—Product data representation and exchange—Part 214: Application protocol: Core data for automotive mechanical design processes. International Organisation for Standardisation (ISO), Geneva, Switzerland
4. ISO 10303-219 (2007) Industrial automation systems and integration—Product data representation and exchange—Part 219: Application protocol: Dimensional inspection information exchange. International Organisation for Standardisation (ISO), Geneva, Switzerland
5. ISO10303-223 (2008) Industrial automation systems and integration—Product data representation and exchange—Part 223: Exchange of design and manufacturing product information for cast parts, currently on CD level. International Organisation for Standardisation (ISO), Geneva, Switzerland
6. ISO 10303-224 (2006) Industrial automation systems and integration—Product data representation and exchange—Part 224: Application protocol: Mechanical product definition for process planning using machining features. International Organisation for Standardisation (ISO), Geneva, Switzerland
7. ISO10303-229 (2008) Industrial automation systems and integration—Product data representation and exchange—Part 229: Application protocol: Exchange of manufacturing product information for forged parts. International Organisation for Standardisation (ISO), Geneva, Switzerland
8. ISO 10303-238 (2007) Industrial automation systems and integration—Product data representation and exchange—Part 238: Application protocol: Application interpreted model for computerized numerical controllers. International Organisation for Standardisation (ISO), Geneva, Switzerland
9. ISO 10303-240 (2005) Industrial automation systems and integration—Product data representation and exchange—Part 240: Application protocol: Process plans for machined products. International Organisation for Standardisation (ISO), Geneva, Switzerland
10. ISO 14649-1 (2003) Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 1: Overview and fundamental principles. International Organisation for Standardisation (ISO), Geneva, Switzerland
11. American National Standard Institute (2001) ANSI/CAM-I 104.0-2001, Part 1, Dimensional Measurement Interface Standard-DMIS 4.0 Standard, Part 1. ANSI
12. ISO 14649-16 (2004) Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 16: Data for touch probing based inspection. International Organisation for Standardisation (ISO), Geneva, Switzerland
13. I++DME (2005) Dimensional Measurement Equipment Interface, Version of specification 1.6
14. Xu X, Newman ST (2003) Making CNC machine tools more open, interoperable and intelligent—a review of the technologies. Comput Ind 57(2):141–152
15. Xu X, Wang L, Rong Y (2006) STEP-NC and function blocks for interoperable manufacturing. IEEE Trans Autom Sci and Eng 3 (3):297–307
16. ISO 14649-10 (2004) Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 10: General process data. International Organisation for Standardisation (ISO), Geneva, Switzerland
17. ISO 14649-11 (2004) Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 11: Process data for milling. International Organisation for Standardisation (ISO), Geneva, Switzerland
18. ISO 14649-12 (2005) Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 12: Process data for turning. International Organisation for Standardisation (ISO), Geneva, Switzerland
19. ISO 14649-14 (2004) Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 14: Process data for contour cutting of wood and glass. International Organisation for Standardisation (ISO), Geneva, Switzerland
20. ISO 14649-111 (2003) Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 121: Tools for milling machines. International Organisation for Standardisation (ISO), Geneva, Switzerland
21. ISO 14649-121 (2005) Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 121: Tools for turning. International Organisation for Standardisation (ISO), Geneva, Switzerland
22. ISO 14649-13 (2004) Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 13: Process data for electro discharge machining. International Organisation for Standardisation (ISO), Geneva, Switzerland
23. ISO 10303-21 (2002) Industrial automation systems and integration—Product data representation and exchange—Part 21: Implementation methods: Clear text encoding of the exchange structure. International Organisation for Standardisation (ISO), Geneva, Switzerland
24. IEC 61449 (2000) Function blocks for industrial process measurement and control system, Part 1: Architecture, IEC/PAS 61449-1. Edition 1.0
25. Suh SH, Cheon SU (Inventors) (2005) Intelligent STEP-NC controller (Patent), Agent: Bacon & Thomas, PLLC-Alexandria, VA, US, USPTO Application #: 20050171629-Class: 700159000 (USPTO): [online] available: http://www.freshpatents.com/Intelligent-step-nc-controller-dt20050804ptan20050171629.php, [1 November, 2008]
26. Hardwick M (2005) STEP-NC Probing Demonstration. EASTEC 2005 Exposition & Conference, West Springfield, MA USA. [online] available: http://www.isd.mel.nist.gov/projects/stepnc/ [1 November, 2008]

27. Habeeb S (2007) STEP-NC Enabled Machining with Bi-directional Data Flow, Master Thesis, Department of Mechanical Engineering, the University of Auckland, New Zealand
28. Christensen J (2000) Design patterns for systems engineering with IEC 61499, Verteilte Automatisierung—Modelle und Methoden für Entwurf, Verifikation, Engineering und Instrumentierung, Ch. Döschner, ed. Magdeburg, Germany: Otto-von-Guericke-Universität
29. Zhao YF, Xu XW, Xie S, Kramer TR, Proctor FM (2008) An integrated process planning system for machining and on-machine inspection, Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, USA
30. Xu X, Wang H, Mao J, Newman ST, Kramer TR, Proctor FM, Michaloski JL (2005) STEP-compliant NC research: the search for intelligent CAD/CAPP/CAM/CNC integration. Int J Prod Res 43(17):3703–3743
31. Ong SK, Li WD, Nee AYC (2003) STEP-based integration of feature recognition and design-by-feature for manufacturing applications in a concurrent engineering environment. Int J Comput Appl Technol 18(1–4):78–92
32. Holland P, Standring PM, Long H, Mynors DJ (2002) Feature extraction from STEP (ISO 10303) CAD drawing files for metalforming process selection in an integrated design system. J Mat Process Technol 125–126:446–455
33. Nassehi A, Liu R, Newman ST (2007) A new software platform to support feature-based process planning for interoperable STEP-NC manufacture. Int J Comput Integr Manuf 20(7):699–683
34. Kang M, Han J, Moon JG (2003) An approach for interlinking design and process planning. J Mater Process Technol 139(1–3 SPEC):589–595
35. Lockett HL, Guenov MD (2005) Graph-based feature recognition for injection moulding based on a mid-surface approach. CAD Comput Aided Des 37(2):251–262
36. Allen RD, Harding JA, Newman ST (2005) The application of STEP-NC using agent-based process planning. Int J Prod Res 43 (4):655–670
37. Nassehi A, Newman ST, Allen RD (2006) STEP-NC compliant process planning as an enabler for adaptive global manufacturing. Robot Comput-Integr Manuf 22(5–6):456–467
38. Nassehi A, Newman ST, Allen RD (2006) The application of multi-agent systems for STEP-NC computer aided process planning of prismatic components. Int J Mach Tools Manuf 46 (5):559–574
39. Stroud I, Xirouchakis P (2006) Strategy features for communicating aesthetic shapes for manufacturing. Int J Comput Integr Manuf 19(6):639–649
40. Sokolov A, Richard J, Nguyen VK, Stroud I, Maeder W, Xirouchakis P (2006) Algorithms and an extended STEP-NC-compliant data model for wire electro discharge machining based on 3D representations. Int J Comput Integr Manuf 19 (6):603–613
41. Liu R, Zhang C, Newman ST (2006) A framework and data processing for interfacing CNC with AP238. Int J Comput Integr Manuf 19(6):516–522
42. Amaitik SM, Kilic SE (2007) An intelligent process planning system for prismatic parts using STEP features. Int J Adv Manuf Technol 31(9–10):978–993
43. Xie SQ, Xu X (2006) A STEP-compliant process planning system for sheet metal parts. Int J Comput Integr Manuf 19 (6):627–638
44. Yang W, Xu X, Xie S (2007) Development of STEP-NC compliant machine tool data model, Proceedings of the 35th International MATADOR Conference, pp 35–40
45. Ryou MS, Jee HS, Kwon WH, Bang YB (2006) Development of a data interface for rapid prototyping in STEP-NC. Int J Comput Integr Manuf 19(6):614–626
46. Lin ZC, Chow JJ (2001) Integration planning model of IDEF0 and STEP product data representation methods in a CMM measuring system. Int J Adv Manuf Technol 17(1):39–53
47. Brecher C, Vitr M, Wolf J (2006) Closed-loop CAPP/CAM/CNC process chain based on STEP and STEP-NC inspection tasks. Int J Comput Integr Manuf 19(6):570–580
48. Ali L, Newman ST, Petzing J (2005) Development of a STEP-compliant inspection framework for discrete components. Proc Inst Mech Eng Part B J Eng Manuf 219(7):557–563
49. Suh SH, Lee ES, Kim HC, Cho JH (2002) Geometric error measurement of spiral bevel gears using a virtual gear model for STEP-NC. Int J Mach Tools Manuf 42(3):335–342
50. Zhao F, Xu X, Xie S (2008) STEP-NC enabled on-line inspection in support of closed-loop machining. Robot Comput-Integr Manuf 24(2):200–216
51. Suh SH, Lee BE, Chung DH, Cheon SU (2003) Architecture and implementation of a shop-floor programming system for STEP-compliant CNC. CAD Comput Aided Des 35(12):1069–1083
52. Suh SH, Chung DH, Lee BE, Cho JH, Cheon SU, Hong HD (2002) Developing an integrated STEP-compliant CNC prototype. J Manuf Syst 21(5):350–362
53. Suh SH, Cho JH, Hong HD (2002) On the architecture of intelligent STEP-compliant CNC. Int J Comput Integr Manuf 15 (2):168–177
54. Suh SH, Cheon SU (2002) A framework for an intelligent CNC and data model. Int J Adv Manuf Technol 19(10):727–735
55. Lee W, Bang Y-B, Ryou MS, Kwon WH, Jee HS (2006) Development of a PC-based milling machine operated by STEP-NC in XML format. Int J Comput Integr Manuf 19(6):593–602
56. Kramer TR, Proctor F, Xu X, Michaloski JL (2006) Run-time interpretation of STEP-NC: Implementation and performance. Int J Comput Integr Manuf 19(6):495–507
57. Fortin E, Chatelain JF, Rivest L (2004) An innovative software architecture to improve information flow from CAM to CNC. Comput Ind Eng 46(4 SPEC. ISS.):655–667
58. Wosnik M, Kramer C, Selig A, Klemm P (2006) Enabling feedback of process data by use of STEP-NC. Int J Comput Integr Manuf 19(6):559–569
59. Xu XW (2006) Realization of STEP-NC enabled machining. Robot Comput-Integr Manuf 22(2):144–153
60. Wang H, Xu X, Tedford JD (2007) An adaptable CNC system based on STEP-NC and function blocks. Int J Prod Res 45 (17):3809–3829
61. Jou M, Zhang HW (2006) An interactive web-based learning system for manufacturing technology education. Mat Sci Forum 505–507(2):1111–1116
62. Chen X, Zhang C, Lan H, Zhai P, Wu H (2005) A framework for CNC turning system based on STEP-NC. Proceedings of SPIE—The International Society for Optical Engineering
63. PDM Implementers Forum (2002) Usage Guide for the STEP PDM Schema, V1.2, Release 4.3. January 2002
64. ISO 10303-239 (2005) Industrial automation systems and integration—Product data representation and exchange—Part 239: Application protocol: Product life cycle support. International Organisation for Standardisation (ISO), Geneva, Switzerland