NEW TECHNIQUE FOR THE DEVELOPMENT OF OPEN CNC CELL CONTROLLER BASED ON ISO 14649 and ISO 6983

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ABSTRACT

The aim of modern Computer Numerical Control (CNC) is to be more flexible, interoperable, adoptable, open and intelligent. In the projection towards the development of the next generation of CNC systems, the problem of current International Standards Organization (ISO) data interface model (ISO 6983) limitations was encountered. A new ISO standard known as Standard for The Exchange of Product Data (STEP) or ISO 10303 was introduced to overcome the issues of current data interface model in Computer Aided Design (CAD)/Computer Aided Manufacturing (CAM) systems. After that successful implementation, the standard was further extended to implement the STEP features on the CNC by introducing a new standard known as STEP-Numeric Control (NC) or ISO 14649. The implementation of STEP-NC was firstly initiated on the commercial CNC units by In-Direct STEP-NC programming approach. However, that approach failed to enable all the features of modern CNC systems due to the translation of data from high to low level and vendor specifications dependency of the commercial CNC units. A new controller is need to be developed in order to overcome these issues. In this study a new cell controller has been developed based on Open Architecture Control (OAC) technology and Interpreted STEP-NC programming approach. The aim of the developed system is to provide new techniques for both ISO data interface models (14649 and 6983) interpretation, along with its graphical verification, execution, monitoring and report generation functionalities into the CNC core. The implied system is composed of *ISO data interface models interpretation*, *3D simulation*, *machine motion control*, *live video monitoring* and *automatic document generation* modules. The system has also been validated through manufacturing of case study components. Corresponding experimental results verified the proposed technique with satisfactory outcomes.

ABSTRAK

Pembangunan Mesin Kawalan Berangka Komputer (CNC) yang moden adalah untuk menjadi lebih fleksibel, boleh beroperasi, boleh beradaptasi, system terbuka dan pintar dengan kehendak semasa. Standard Organisasi Antarabangsa (ISO) untuk model antaramuka data sediada yaitu ISO 6983 tidak dapat menampung keperluan sistem CNC di masa depan. Standard ISO baru, yang dikenali sebagai *Standard for The Exchange of Product Data (STEP)* atau ISO 10303 telah diperkenalkan untuk mengatasi masalah penukaran model antaramuka data yang digunakan sekarang kepada sistem dalam Rekabentuk Berbantu Komputer (CAD)/ Pembuatan Berbantu Komputer (CAM). Kejayaan perlaksanaan STEP telah membawa kepada pengembangan penggunaannya kepada CNC dengan memperkenalkan satu standard baru yang dikenali sebagai *STEP-Numerical Control (NC)* atau ISO 14649. Perlaksanaan STEP-NC telah mula digunakan untuk unit CNC komersil secara tidak langsung dalam pengaturcaraan STEP-NC. Walaubagaimanapun, pendekatan tersebut gagal mengataptasi kesemua ciri-ciri yang terdapat dalam sistem CNC moden kerana tidak boleh menterjemahkan data daripada tahap tinggi kepada tahap rendah dan terlalu bergantung kepada spesifikasi pembekal mesin CNC. Sistem kawalan yang baru telah dibangunkan berdasarkan teknologi Kawalan Rekabentuk Terbuka (Open Architecture Control, OAC) dan menggunakan pendekatan pengaturcaraan pentafsiran STEP-NC. Tujuan sistem ini dibangunkan adalah untuk menggunakan teknik baru model antaramuka dan tukaran data dari ISO 14649 ke ISO 6983, berserta verifikasi grafik, operasi pemesinan, pemantauan dan berfungsi untuk penyediaan laporan. Sistem yang dimaksudkan terdiri daripada modul interpretasi antara muka data ISO, simulasi 3D, kawalan pergerakan mesin, pemantauan video secara lansung dan penghasilan dokumen secara automatik. Sistem ini telah disahkan melalui penghasilan komponen dalam beberapa kajian kes. Keputusan eksperimen yang dijalankan telah mengesahkan sistem yang dibangunkan ini mengasilkan keputusan yang sangat memuaskan.

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LIST OF ABBREVIATIONS

2.5D	Two-and-a-half Dimensional
2D	Two Dimensional
3D	Three Dimensional
3DS	Three Dimensional Simulation
AAM	Application Activity Model
AB-CAM	Agent Based Computer Aided Manufacturing
AD	Analog to Digital
ADG	Automatic Document Generator
AI	Artificial Intelligent
AIM	Application Interpreted Model
AM	Application Module
AO	Architecture Object
AP	Application Protocol
API	Application Program Interface
ARM	Application Reference Model
ASC	American Standard Code
ASIC	Application Specific Integrated Circuit
ATC	Automatic Tool Changer
CAA	Component Application Architecture
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CAPP	Computer Aided Process Planning
CAx	Computer Aided Systems
CC	Conformance Classes
CCC or C^3	Conical Code Converter
CE	Compact Edition
CMM	Coordinate Measuring Machine

CNC	Computer Numerical Control
COM	Component Object Model
CPU	Central Processing Unit
DA	Digital to Analog
DBC	Drill Bit Changer
DH	Drill Head
DIO	Digital Input Output
DLL	Dynamic Link Library
DNC	Direct Numerical Control
DRC	Distributed Reconfigurable Controller
DSP	Digital Signal Processing
EMC	Enhanced Machine Controller
ESPRIT	European Strategic Program on Research in Information Technology
EtherCAT	Ethernet for Control Automation Technology
EtherMAC	Ethernet for Manufacturing Automation Technology
EU	European Union
FBICS	Feature Based Inspection and Control System
FBMash	Feature Based Machining
FBTol	Feature Based Tolerancing
FDL	Flowchart Description Language
FM&T	Federal Manufacturing and Technologies
FMS	Flexible Manufacturing System
FPGA	Field Programmable Gate Array
FSMC-OA	FoFdation Smart Machine Controller-Open Architecture
GD&T	Geometric Dimensioning and Tolerancing
GUI	Graphical User Interface
HMI	Human Machine Interface
I/O	Input/Output
IDEF	Integrated DEFinition for function modeling
IEEE	Institute of Electrical and Electrons Engineers
IGES	Initial Graphics Exchange Specification
IIMP	Intelligent and Interoperable Manufacturing Platform
IMAQ	IMage AcQuisition

IMS	Intelligent Manufacturing System
IMSCMI	Intelligent Manufacture for STEP-NC Compliant Machining and Inspection
IP3AC	Integrated Platform for Process Planning And Control
IPC	Intrinsically Passive Controller
IPIM	Integrated Product Information Model
ISO	International Standards Organization
ITP	Integrated Test Platform
JIS	Japanese Industrial Standard
JOP	Japanese Open Promotion group
LabVIEW	Laboratory Virtual Instrument Engineering Workbench
LVM	Live Video Monitoring
MADCON	Multi Agent Distributed Controller
MATLAB	MATrix LABoratory
MCC	Motion Control Card
MDICM	Model Driven Intelligent Control of Manufacturing
MFA	Manufacturing Feature Agent
MIM	Module Integrated Model
MMC	Machine Motion Control
MMI	Man Machine Interface
MPU	Micro Processing Unit
NC	Numerical Control
NCC	NIST-SAI Conical Code
NCK	Numeric Control Kernel
NI	National Instruments
NIST	National Institute of Standards and Technology
NN	Neural Network
NRL-SNT	National Research Laboratory for STEP-NC Technology
NT	New Technology
NURBS	Non Uniform Rational Basic-Spline
OAC	Open Architecture Control
OCEAN	Openness, Conscientiousness, Extroversion, Agreeableness and Neuroticism
OMAC	Open Modular Architecture Control

ORCOS	Organic Reconfigurable Operating System
OS	Operating System
OSACA	Open System Architecture for Controls within Automation Systems
OSEC	Open System Environment for Controllers
OWL	Ontology Web Language
PAPI	Principal Application Programming Interface
PC	Personal Computer
PCI	Peripheral Component Interconnect
PIC	Peripheral Interface Controller
PLC	Programmable Logic Control
PMAC	Packet Media Access Controller
RAMP	Rapid Acquisition of Manufactured Parts
RT	Real Time
RTAI	Real Time Artificial Intelligent
RTOS	Real Time Operating System
SAI	Stand Alone Interpreter
SC	Sub Committee
SDAI	STEP Data Access Interface
SERCANS	Module of Master SERCOS interface-A product from Bosch Rexroth
SERCOS	SErial Real-time COmmunication System
SFP	Shop Floor Programming
SIM	System for Interconnecting of Media
SMS	STEP Manufacturing Suite
SPAIM	STEP-NC Platform for Advance and Intelligent Manufacturing
STEP	Standard for The Exchange of Product Data
STEPcNC	STEP-compliant NC
STEP-NC	Standard for The Exchange of Product Data-Numerical Control
TC	Technical Committee
TPG	Tool Path Generator
TPV	Tool Path Viewer

TTL	Transistor Transistor Logic
UK	United Kingdom
UMI	Universal Motion Interface
UNL	Universal Logic Network
USA	United States of America
USB	Universal Serial Bus
VB	Visual Basic
VDAFS	Verband der Automobilindustri Flachenschnittstelle
VISA	Virtual Instrument Software Architecture
VS	Visual Studio
WEDM	Wire Electric Discharge Machine
WZL	Laboratory for Machine Tools and Production Engineering
XMIS	eXtended Manufacturing Integrated System
XML	Extensible Markup Language

LIST OF APPENDICES

LIST OF AWARDS AND ACHIEVEMENTS

(i). **Silver Medal** in Research and Innovation Festival 2014 [R&I 2014]: Yusri Yusof and Kamran Latif "New ISO 14649 and 6983 based Open CNC Controller".

(ii). **Malaysian International Scholarship (MIS)** under Ministry of Education (MOE) Malaysia.

(iii). **Patent** application in process with ID (PI2014702363) by TRADEMARK2U INTELLECTUAL PROPERTY SDN BHD.

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CHAPTER 1

INTRODUCTION

In this chapter, the basic concept of the traditional Computer Numerical Control (CNC) and its systems are discussed. Then, the shortcomings of the commercial CNC system in terms of modern manufacturing are highlighted. Followed by general discussion about possible remedies over these shortcomings with some previous efforts and proposed approach introduced. At the end of the chapter, the problem statement, aim, scope, objectives and further design of thesis are given.

1.1 Research Background and Motivation

The CNC machine plays a vital role in the growth of manufacturing since its development. This technology uses computers and Computer Aided Design (CAD)/Computer Aided Manufacturing (CAM) software for the generation, parsing and execution of the sequential control. Today, CNC machines are employed in many industries with different controllers and multiple abilities for various applications such as: turning, drilling, milling, packaging, tube welding and robotic cutting (Groover, 2007). The CNC is composed of many parts whereas, the controller is the heart of a CNC unit that is composed of two parts: hardware and software. The hardware part contains various types of hardware namely motor drives, motion control card and others. While, the software part consists of Programmable Logic Control (PLC) and interpreter for executing machine hardware. The interpreter of the CNC controller acquires the International Standards Organization (ISO) data interface model instructions and translates it into internal commands for moving tools and executing auxiliary functions in a CNC system (Ertell, 1969). CNC machines utilize ISO 6983 data interface model, formally known as G M codes, for their operations. The ISO 6983 data interface model program codes are generated by CAM systems that use CAD information. This model defines the information by numerical codes (G, T, M, F, S etc) indicating the movement of a machine and an axis to the controller (ISO 6983-1, 1982).

The demand of flexibility in the CNC systems was increased in the late 1970's and early 1980's. Because of the rapid growth in the manufacturing world to enable low batch manufacturing of the extensive variety of parts. In the progression towards the realization of the flexible manufacturing environment, the CNC machines were found to be a critical resource because of their capability of being reprogrammed to produce different parts (Xu & Newman, 2006). However, in the development of the flexible CNC systems, a number of limitations were found in ISO 6983 data interface model such as: delivering limited information to CNC, transferring one-way information from CAD/CAM to CNC, unable to implement the seamless integration between CAD-CAM-CNC, programs are huge and very difficult to handle and last minute changes are very hard at shop floor (Suh & Cheon, 2002). Apart from that, different manufacturers had also added new supplement commands into G codes for enabling more facilities into the systems but these extensions are not a part of ISO 6983. Due to these additions, the part programs cause interchangeability problems between different machines, which make the G code more machine specific (Xu & Newman, 2006).

In order to overcome these issues, a new ISO standard was developed which is formally known as Standard for The Exchange of Product Data (STEP) or ISO 10303 (ISO, 1991; ISO, 1994b). The objective of STEP is to provide the means of describing product data throughout the life cycle that is independent from any particular computer system. ISO 10303 significantly improved the interoperability between CAD systems and had also created the need of a similar standard for exchange of information between CNC machines as well as CAM systems. Consequently, in 1999 an international project was started to specify a new standard entitled ISO 14649 formally known as STEP-(Numerical Control) NC to bring the benefits of STEP to CAM and CNC (Suh *et al.*, 2002). The ISO 14649 standard is an extension of ISO 10303. It allows the connections between STEP based Computer Aided Systems (CAx) and CNC machines. The concept of Standard for The

Exchange of Product Data- Numerical Control (STEP-NC) is based on "Design anywhere, build anywhere and support anywhere" (Newman *et al.*, 2008). The introduction of ISO 14649 provides a platform to recover the information loss between CAD/CAM/CNC and opens the doors for the development of next generation (modern and flexible) CNC systems (Xu & Newman, 2006).

The implementation of STEP-NC originated on current commercially available CNC controllers. This implementation was known as “In-Direct STEP-NC programming approach” (Hamilton *et al.*, 2014; Rauch *et al.*, 2012) that translates the STEP-NC data into G codes for operations (Xu & Newman, 2006). There are many approaches that had been carried out by various researchers such as Weck *et al.* (2001) Newman *et al.* (2003) Nassehi *et al.* (2006) and Wang *et al.* (2007). During this implementation, it was found that this low level translation is not enough to enable all the features of STEP-NC in the CNC (Xu & Newman, 2006). Also, current commercial CNC machines are found to be of close nature, which not allow the user to implement customs features into CNC core (Mori *et al.*, 2001).

In order to overcome these problems, a new STEP-NC implementation approach “Interpreted STEP-NC programming” (Hamilton *et al.*, 2014; Rauch *et al.*, 2012) was introduced. In this approach, the controller directly reads and interprets the ISO 14649 information as per internal structure of the machine. However, Open Architecture Control (OAC) technology was introduced into the CNC systems in order to tackle the issues of closed nature in CNC machines. The aim of OAC was to develop a controller that is independent from manufacturers technology, allowing the user to buy hardware and software from several different manufacturers and freely assemble the acquired piece of equipment (Asato *et al.*, 2002). Based on this approach and technology, various studies were carried out by various researchers such as Hamilton *et al.* (2014), Xu (2006), Erdős and Xirouchakis (2003), Suh *et al.* (2003), Storr *et al.* (2002), Weck *et al.* (2001) and Wolf (2001). While this implementation Zheng *et al.* (2005) states that, the Personal Computer (PC) has been one of the preferred hardware platform for open CNC systems because of its openness, low cost and high performance to price ratio. Aforementioned finding was further supported by Park *et al.* (2006) following statement “the implementation of PC based OAC technology on CNC systems can enable some hardware reconfiguration, communication and advanced numerical control programming technology in the CNC systems.” Later Ma *et al.* (2007) also supported these statements and highlighted that "the current trend of CNC system development must be towards the PC based Soft-CNC systems." Based on this approach various research work was carried out by various scholars to develop some CNC systems based on ISO 6983 and ISO 14649 with various modern functionalities by utilization different development technique such as; C, C++, JAVA, functional block etc (see Table 2.8 of Chapter 2).

Generally, a number of various approaches were presented but no such CNC control system is available based on ISO 14649 and ISO 6983 data interface model with modern functionalities (like monitoring, simulation, inspection etc) based on virtual component technology. Therefore, the philosophy of this research study is to introduce the virtual component technology for the development of modern (next generation) CNC controllers. This virtual component based technique has been utilized for the interpretation of ISO data interface model, its verification via graphical simulation and its implementation on a CNC system with some modern functionalities. Adopting the idea from the previous efforts, a new technique for the development of PC based open soft-CNC system based on ISO 14649 and 6983 data interface model with some modern functionalities is introduced in this study. Overall, the main idea of this research is to initialize the development of all-in-one CNC systems.

1.2 Problem Statement

Rapid growth in the manufacturing world demands more flexibility, adoptability, portability, interoperability and openness in CNC systems. In progression towards this development, some limitations of the current ISO 6983 data interface model were reported by (Suh & Cheon, 2002). In order to overcome these issues, a new ISO data interface model (ISO 14649) was introduced in 1999 (Suh *et al.*, 2002). The implementation of this new standard was initiated on commercial CNC units by utilizing "In-direct STEP-NC programming approach". While this implementation, the problem of being vender dependent in commercial CNC systems was found. In order to overcome that issue, OAC technology was introduced into the CNC systems (Xu & Newman, 2006). The combination of both of these aforementioned techniques was firstly implemented to increase openness in CNC domain. But, this approach failed to enable all the features of modern CNC systems because it translates the STEP-NC information into the GM codes (Rauch *et al.*, 2012). During this implication, it was suggested that there is a need of new CNC controller based on OAC technology, which directly interprets the STEP-NC information and enables modern functionalities into the CNC systems (Hamilton *et al.*, 2014).

1.3 Aim of the Study

The aspiration of this study is to develop a new breed of CNC controllers, which are able to work with both ISO (14649 and 6983) data interface models. It is also intended to enable new modern functionalities of; interpretation, simulation, monitoring, automatic document generations, tool path generation and shop floor editing into the CNC units. These functionalities provides flexible, portable, interoperable, adoptable and more open CNC environment at a single platform (all-in-one).

1.4 Scope of the Study

This study comprises of the development of new CNC controller based on OAC technology for 3-axis CNC milling machine with automatic tool changer facility (DENFORD NOVAMILL available at UTHM) designed for both ISO 14649 and ISO 6983 data interface models. This study includes the development of interpreter with bi-directional data flow (only between interpreter and machine motion control) for ISO14649-21 (only facing, drilling and pocketing processes) and ISO 6983 (linear motion only) data interface models, a Three Dimensional (3D) simulator for graphical verification of interpreted data, a closed loop control environment based machine motion controller with automatic tool changer for 3 axis, DENFORD NOVAMILL CNC, machine and live monitoring and automatic document generation systems for enabling a minute part of modern CNC functionalities into the CNC unit.

1.5 Limitations of the Study

The scope of this research study has the following limitations.

(i). The open cell controller is not completely open in terms of hardware and software, but in comparison to commercial CNC controller it provides more openness in both aspects.

(ii). The cell controller enables a bi-directional data flow only between interpreter and machine motion control for data modification.

(iii). The ISO 14649-21 interpretation technique is limited to facing, pocketing and drilling processes only.

(iv). The ISO 6983 interpretation technique is limited for linear motion control commands only.

(v). The machine motion control is limited to three axis, spindle and automatic tool changer control in closed loop control environment.

(vi). The cell controller enables only live monitoring and automatic document generation modern features into CNC core.

(vii). The cell controller only demonstrates the 3 axis CNC Denford NOVAMILL hardware configuration connection with PC.

(viii). In software communications, the cell controller demonstrate only MS word and PDF communication.

(ix). The experimental validation is limited only to check the performance of interpreter, machine motion control and modern features only. It does not concern with the surface roughness, accuracy etc issues.

1.6 Objectives of the Study

In order to achieve the aim of this study within defined scope and limitations, a following set of objectives has been defined for the development of open CNC cell controller.

(i). To introduce a new bi-directional data flow based technique for the interpretation of ISO 14649 - 21 and ISO 6983 data interface models with 3D graphical verification within offline or real machining environments.

(ii). To implement a new method of 3-axis CNC milling machine motion control with automatic tool changer based on closed loop control environment for real machining of interpreted information with some modern features.

(iii). To validate the developed open CNC cell controller (objective 1 and 2) through manufacturing of case study components.

1.7 Thesis Format

The further format of thesis includes, the brief introduction and discussion about the concerned technologies and the research gap was highlighted in Chapter 2. Chapter 3 presents the methodology adopted for addressing the found research gaps. The development of system as per research findings and adopted methodology is illustrated in Chapter 4. Chapter 5 highlights the experimental validation of the developed system. Lastly, the research contributions and conclusions with future suggestions are discussed in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents the review of basics of CNC, CAD/Computer Aided Process Planning (CAPP)/CAM, G codes, STEP, STEP-NC and CNC controller technologies. The review also addresses the complete road map for the development of next generation CNC systems. The conjunction of various technologies in the shape of several earlier studies has been discussed in details. The state of the art from NC to modern CNCs has also been presented herewith, which highlights the pervious approaches, methods and techniques that were utilized during this pursuit of development.

2.2 Computer Numerical Control

The term CNC means the control system which includes a computer. The first ever CNC machine was developed in 1970s, where the electronic hardware and punch card of the pervious NC systems were replaced by computers (Liana *et al.*, 2004). CNC system use minicomputers or microcomputers to generate, parse and execute the sequential control that describes the end effectors behaviour. This technology is often used in turning, milling, welding, metal cutting, sheet metal formating, cutting robots and various other applications (Groover, 2007).

In the further evolution towards modern systems, the need of producing wide range of parts arose during 1970s and 1980s. This wide range of part manufacturing created the requirement of Flexible Manufacturing System (FMS). In order to achieve flexible environment for manufacturing systems, the CNC machines play a critical role because of their ability to be reprogrammed for the manufacturing of different and complex parts in bulk quantities (Safaieh *et al.*, 2013). The development of these types of parts required sophisticated programs, therefore CAD and CAM systems were used to generate CNC part programs (Newman *et al.*, 2008; Yusof *et al.*, 2009).

The CAD system defines the geometry of a design created by using geometric primitives (e.g. points, lines and curves). The earliest CAD systems were essential only for Two-Dimensional (2D) drawings. In the 1980s, the solid modeling techniques described 3D CAD systems (Requicha, 1980). The current CAD systems generated file is stored in proprietary formats and all systems are capable to import and export these files in defined standards.

The development of CNC systems also sparked the research towards CAM technique. This technology uses computer systems to control, plan and manage manufacturing processes. The CAM system adds cutting strategies, tools and operation sequences information into CAD file. Around 1970s, the era of CAD and CAM integrated systems was initiated and the turnkey CAD/CAM system became popular in 1980s. The aim of integrated CAD/CAM system was to minimize the gap between design and manufacturing. In order to fill that gap CAPP systems was needed (Wang *et al.*, 2002).

CAPP system translates the CAD design specifications into manufacturing information (e.g. product geometry, selection of raw material, manufacturing operation and sequencing, selection of equipment and machine tool and machining operation condition) (Xu *et al.*, 2011). At this stage, the information is stored in CAM file and the post processor of CAM system generates the manufacturing instructions for machine tool from that CAM file (Xu & He, 2004). The output of the post processor is an NC file based on the specific language, which translates the job information from drawing to computer controlled machine unit (Mortenson, 1985). That specific language was initially known as Automatically Programmed Tool (APT) (Reintjes, 1991). Later in 1982, APT was adopted by ISO as an international standard ISO 6983 formally known as RS-274D and commonly known as G M codes (ISO 6983-1, 1982).

2.3 ISO 6983

ISO 6983 (GM code) is a part of computer aided engineering, mostly used in automation. It is a common name in NC programming, which remained unchanged since the development of first NC machine tool. In GM code programming the operator tells the computerized machine unit "how to make". The "how to make" defines the instructions of where, how and what path to move. The ISO 6983 CNC coding is based on five specifications (ISO 6983-1, 1982) as shown in Figure 2.1.

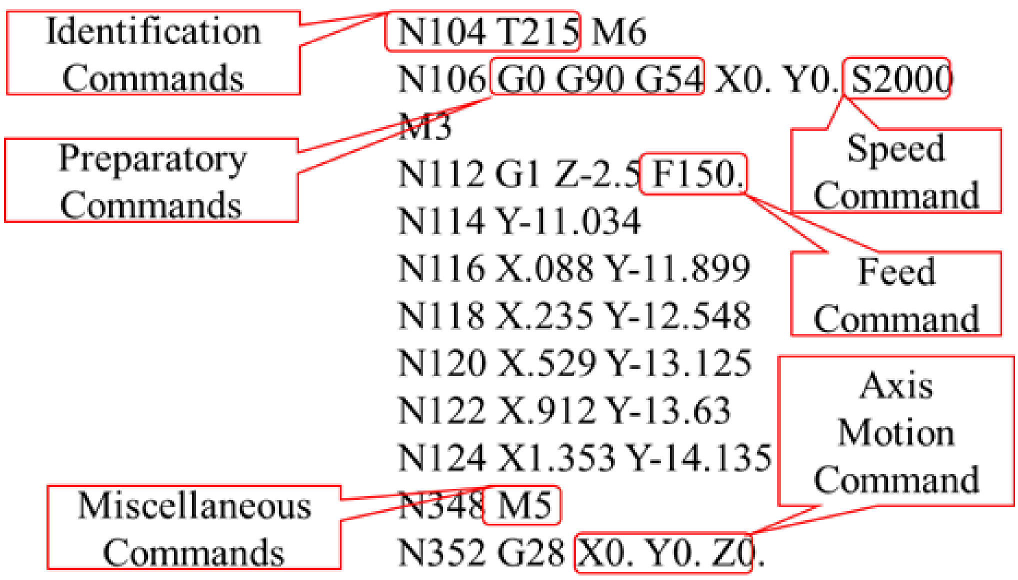


Figure 2.1 ISO 6983 CNC coding

(i). Preparatory Functions: - These commands are represented by "G", which conveys the controller regarding the kind of the motion (e.g. rapid positioning, linear or circular feed, fixed cycle). Up to date, there are around hundred commands in use from G0 to G99.

(ii). Miscellaneous Commands: - These commands are represented by "M" and are the auxiliary commands, in other words action codes, mostly used for machine functions.

(iii). Axis Motion Commands: - These commands define the absolute or incremental positions of machine tool axis represented by X, Y, Z, A, B, C.

(iv). Feed and Speed Commands: - These commands define the feed rate and spindle speed, represented by “F” and “S” respectively.

(v). Identification Commands: - These commands define the line number and cutting tool selection function, represented by “N” and “T” respectively.

Although with the introduction of minicomputers and microcomputers, a massive improvement was achieved in the capabilities of CNC machine tool such as; multi axis, multi tool and multi processes. However, with this development towards flexible manufacturing environment, the programming tasks became more complex and difficult (Newman *et al.*, 2008). The aim of flexible manufacturing was to make the CNC systems more interoperable, adaptable, open, intelligent and network portable (Mehrabi *et al.*, 2000; Mehrabi *et al.*, 2002). In order to fulfil these requirements, the current data interface model was found to have limited capabilities. There are number of problems that were found in ISO 6983 (Suh *et al.*, 2003; Xu & He, 2004), which are summarized below.

(i). The ISO 6983 language is focused on programming the path of the cutter centre location with respect to the machine axis, rather than the machining tasks with respect to the part (Suh *et al.*, 2002; Suh *et al.*, 2003; Xu & He, 2004; Yusof *et al.*, 2011).

(ii). The standard defines the syntax of program statements, but in most cases leaves the semantics unclear, together with low level limited control over program execution. These programs become machine dependent when processed in a CAM system by machine specific post processor (Xu & He, 2004; Xu & Newman, 2006; Yusof *et al.*, 2011).

(iii). Vendor usually enhances the language with further extension commands to provide new features, while these extensions are not covered by ISO 6983. Hence it becomes machine specific language and programs are not exchangeable between other machine tools (Calabrese & Celentano, 2007; Xu & He, 2004; Yusof *et al.*, 2011) as shown in Figure 2.2.

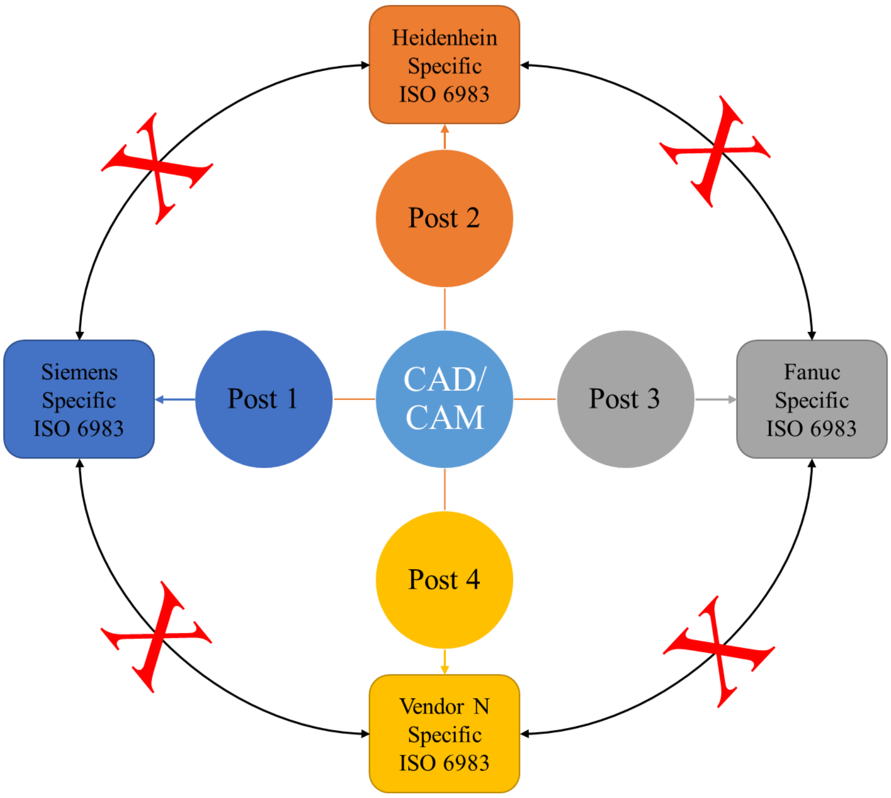


Figure 2.2 ISO 6983 vendor dependency environment

(iv). The flow of information from design to manufacturing is uni-directional. There is not any feedback of data in ISO 6983 as shown in Figure 2.3. Therefore the last minute changes and modifications of machining problems on shop floor are hardly possible (Sääski *et al.*, 2005; Xu & He, 2004).

Figure 2.3 Current manufacturing system information flow

(v). The control of program execution at the machine is limited. Therefore it is very difficult to make changes in program at workshop (Xu & He, 2004).

(vi). The CAD data is not directly used on the machine tool. It is processed by the means of a machine specific post processor in terms of low level data. This incomplete data set makes verification and simulations very difficult (Xu & He, 2004).

(vii). This standard does not support today's demand in the area of five axis milling or high speed machining, because it is incapable to process Spline data (Sääski *et al.*, 2005; Xu & He, 2004).

Apart from these limitations, some other advantages and disadvantages of ISO 6983 are highlighted by (Krzic *et al.*, 2009) as summarized in Table 2.1.

Table 2.1 ISO 6983 advantages and disadvantages

Advantages	**Disadvantages**
Language is very simple	Long NC programs, even for simple geometry
Easy to learn and understand	Code is unintuitive
Well accepted standard world wide	Almost impossible to run two different CNC machines on same NC program
	Spline interpretation is poor
	Poor support for kinematics features of 5 axis machines
	Almost impossible to feedback information from CNC to CAD/CAM
	Does not contain enough information about the part, material and stock

From the limitations of ISO 6983, it is clear that there are two major issues: interoperability and adaptability of CNC machines that need to be addressed for achieving the tasks of flexible manufacturing. Because of the fact that the current CNC machine tool follows the GM code program, which contains only "how-to-do" information, therefore, it is impossible to implement intelligent and optimization features on CNC (Xu & Newman, 2006). Due to these drawbacks, the need of new data interface model occurred. However in reality, these GM code programs are still very valuable because they integrate the micro-process plan with operator experience (Shin *et al.*, 2007). This is one of the reason to include GM code working environment in this research.

The initial challenge towards the development of new data model was the enabling of seamless geometrical data flow between CAD and CAM systems. During 1980s, different data formats were proposed but none of them was able to satisfy the needs of developers and users (Xu *et al.*, 2005). Then in the mid of 1980s, the international community decided to develop a better standard for geometrical data exchange between CAD and CAM systems. The result was the ISO 10303 standard commonly known as STEP (Krzic *et al.*, 2009).

2.4 ISO 10303

ISO 10303 standard is a mechanism to describe computer interpretable definitions of product characteristics (physical and functional) throughout its life cycle. According to the documentation of ISO 10303 standard, the objective of the STEP is “to provide a mean of describing the product data throughout the life cycle of a product, which is independent from any particular computer system”(ISO, 1994a; Sääski *et al.*, 2005). Moreover, according to Fowler, the main objectives of STEP also includes the creation of a single standard which covers all the aspects of CAD/CAM data exchange with the implementation and acceptance by industry (Fowler, 1995).

2.4.1 Antiquity of ISO 10303

The evolution towards STEP was started in 1979 with the development of Initial Graphics Exchange Specification (IGES). IGES was the first standard format for the CAD information exchange (Parks, 1984). The major drawback of IGES was the incapability of exchanging data among free form surfaces (Safaieh *et al.*, 2013). Later, VDA, a German company, developed Verband der Automobilindustri Flachenschnittstelle (VDAFS) to focus on free form surface information translation (Nassehi, 2007). During 1984, the initial development of ISO 10303 was started to overcome the drawbacks of IGES and VDA-FS. In 1988, the first major release of STEP was published, in which a large set of models had been assembled into a single model called Integrated Product Information Model (IPIM) (Wang, 2009). By the following year, STEP was diverted to use Application Protocol (AP) as a subset. The architecture of APs was developed in the following few years. Then finally, in 1994 the first version of STEP was adopted as an ISO standard (ISO, 1994a). In the following year, established companies like GE, General Motors and Boeing also committed to use STEP. During 1994/95, ISO published the initial release of STEP as an international standard. In that stage, STEP parts 1, 11, 21, 31, 42, 43, 44, 46, 101, AP201 and AP 203 were introduced (ISO, 1994c).

The next significant development in STEP occurred during year 2002. Where the capabilities of STEP was expanded in different industries (automotive, electronic manufacturing, aerospace and electrical etc) with the introduction of AP 202, AP 209, AP 210, AP 212, AP 214, AP 224, AP 225, AP 227 and AP 232. After that, the next development in the STEP was the introduction of STEP modular architecture. Modular architecture solved the problems emerging from large data structures. Currently, a new AP 242 is being developed for geometric dimensions and tolerance in combination with AP 203 and AP 214 (Safaieh *et al.*, 2013).

2.4.2 Building of STEP

This standard is separated into many parts namely: description method, information models, application protocols, implementation methods and conformance tools. These parts are represented by numbers, the total numbers are around 120 as described in Table 2.2.

Table 2.2 STEP standard parts

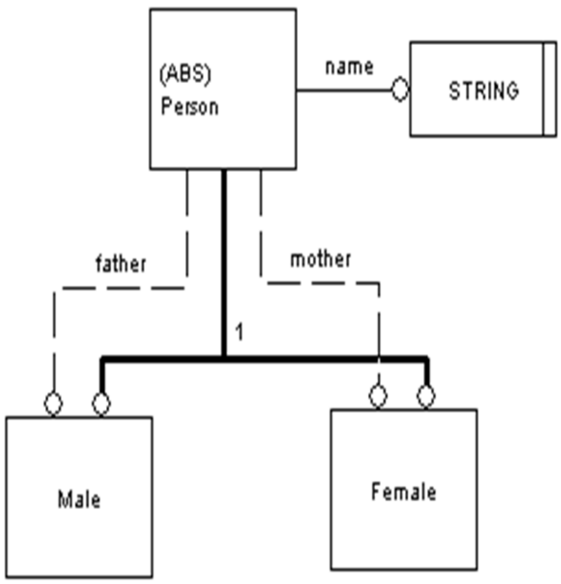
Part	Number	Description
Overview and fundamental principles	11-19	Gives STEP overview and explain its fundamental principles
Description methods	11-19	Covers EXPRESS and EXPRESS-G form
Implementation methods	21-29	Covers methods of EXPRESS modelled data representation
Conformance testing	31-39	Covers concepts of conformance testing with actual test methods and requirements
Integrated generic resources	41-59	Covers EXPRESS models used for geometry, topology and tolerance
Integrated application resources	101-199	Covers specific subject domain EXPRESS models
Application protocols	201-299	Covers parts intended for implementation in industries

2.4.2.1 Description Methods

These methods are defined by the data modelling language called EXPRESS (ISO, 1994c). This modelling language combines ideas from the entity-attribute-relationship family of modelling languages with object modelling concept (Xu & Newman, 2006). The EXPRESS information model is structured in schemas consisting of entities, which contains data type and object definitions. Within the entities, the attributes and constraints are encapsulated, which restricts the value of attributes (Zha, 2006). The EXPRESS language also have a graphical form called EXPRESS-G. EXPRESS-G shows all the features in form of graphics such as: entities in solid boxes, simple data in solid box with double line and data type in box with dashed borders. Figure 2.4 shows the example of a description method based on EXPRESS and EXPRESS-G.

```
SCHEMA Family;

ENTITY Person
  ABSTRACT SUPERTYPE OF (ONEOF (Male,
Female));
    name: STRING;
    mother: OPTIONAL Female;
    father: OPTIONAL Male;
END_ENTITY;

ENTITY Female
  SUBTYPE OF (Person);
END_ENTITY;

ENTITY Male
  SUBTYPE of (Person);
END_ENTITY;

END_SCHEMA;
```

EXPRESS



EXPRESS-G

Figure 2.4 Example of EXPRESS and EXPRESS-G schema

2.4.2.2 Implementation Methods

For the implementation of STEP, additional methods are need to be defined. Several technologies are introduced by ISO 10303 because EXPRESS language does not define any method of implementation.

(i). ISO 10303-21: - This method defines the rule of storing EXPRESS data in a character based physical file commonly known as STEP part 21 file (DIS, 1993). This physical file does not have any EXPRESS schema, it only defines the relationship of entities. Each entity of this method begins with ID “#” followed by integer “1, 2, 3…” and by equal sign “=”. After equal sign, the name of instance is defined, which is followed by the value of attributes listed between parentheses “()” and separated by commas “,” and finally ends with a semi colon “;” as shown in Figure 2.5. In addition, ISO 10303-21 physical file also contains special tokens “$” and “*”, which represent, object values not omitted and object value can be defined from other values, respectively.

Meta Data

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION((‘This is a sample person schema’),’1’);
FILE_NAME(‘Example P21 File’,’1999-08-08 T15:30:00’,(‘J.Doe’), (PDES, Inc.’),
‘Version 1’,’APPROVED BY P.H. Boss’);
FILE_SCHEMA;
ENDSEC;
```

Data

```
DATA;
#1=PERSON(‘Dilbert’,’Jones’,$,(30,5,1962),(),.WHITE.);
#2=PERSON(‘Wally’,’Smith’,$,(30,5,1960),(#11,#20),.BROWN.);
...
#10=MALE(‘Pointy’,’Boss’,$,(29,05,1961),(),.BLACK.,#21);
#11=MALE(‘Atos’,’Smith’,$,(16,03,1990),(),.BROWN.,$);
...
#20=FEMALE(‘Ellen’,’Smith’,$,(08,03,1992),().BLONDE.);
#21=FEMALE(‘Francis’,’Boss’,’Fran’,(18,6,1962),(),.BROWN.);
.
ENDSEC;
END-ISO-10303-21;
```

Figure 2.5 Example of ISO 10303-21 physical file

(ii). STEP Data Access Interface (SDAI): - This methods implements the STEP by means of binding the EXPRESS data with computer programming languages. In this method, the binding is classified into two approaches: early and late. In early binding approach, the entities of EXPRESS schemas are converted into C++ or JAVA classes. On other hand, late binding approach uses EXPRESS entity dictionaries for accessing data, but this approach is not suitable for large data systems. For such systems, a mixed binding approach is advantageous. Currently, there are four established standards available for SDAI.

a. SDAI (DIS, 1996)
b. C++ binding to SDAI (10303-23, 1998)
c. C language binding of SDAI (10303-24, 1998)
d. JAVA^{TM} binding to the SDAI (10303-27, 1998)

(iii). ISO 10303-28: - This method is implemented by means of two languages: configuration and existing STEP mapping. The combination of these two languages converts EXPRESS information into Extensible Markup Language

(XML) form (TC184, 2004). The implementation of XML in STEP is based on two levels: lower and upper. In lower level, CAD authorized systems can read and write data sets, whereas, in upper level, the modernization of STEP data sets are performed by means of inserting information from mapping tables into the XML data. Figure 2.6 shows the example of ISO 10303-28 file, also known as STEP part 28 file.

```
<?xml version="1.0" ?>
- <STEP-XML>
   - <PROJECT name="PROJECT" id="#1">
        <its_id name="identifier">'EXECUTE EXAMPLE1'</its_id>
      - <main_workplan name="WORKPLAN" id="#2">
        <its_id name="identifier">'MAIN WORKPLAN'</its_id>
            + <its_elements name="MACHINING_WORKINGSTEP" id="#10">
            + <its_elements name="MACHINING_WORKINGSTEP" id="#11">
            + <its_elements name="MACHINING_WORKINGSTEP" id="#12">
            - <its_elements name="MACHINING_WORKINGSTEP" id="#13">
              <its_id name="identifier">'WS ROUGH POCKET1'</its_id>
                  + <its_secplane name="ELEMENTARY_SURFACE" id="#62">
                  + <its_feature name="CLOSED_POCKET" id="#18">
                  + <its_operation name="BOTTOM_AND_SIDE_ROUGH_MILLING" id="#22">
                    <its_effect name="in_process_geometry" />
              </its_elements>
            + <its_elements name="MACHINING_WORKINGSTEP" id="#14">
              <its_channel name="channel" />
            + <its_setup name="SETUP" id="#8">
              <its_effect name="in_process_geometry" />
        </main_workplan>
      + <its_workpieces name="WORKPIECE" id="#4">
   </PROJECT>
  </STEP-XML>
```

Figure 2.6 Example of ISO 10303-28 physical file (Lee *et al.*, 2006)

Among all these methods, the most popular are STEP part 21 for offline manufacturing and STEP part 28 for online manufacturing or e-manufacturing.

2.4.2.3 Conformance Testing

Currently, there is no formal testing system in place for APs, whereas STEP provides these facilities in 30 parts and has been proposed for 300 parts (Kramer & Xu, 2009).

2.4.2.4 Integrated Resources

These are the collection of EXPRESS models, which provides fixed set of entities. These integrated resources include three type of models:

(i). The EXPRESS models for basic product data representation, which are called STEP integrated generic resources.

(ii). The EXPRESS models for widely applicable type of product data like drafting (Parks & Fox, 1991), kinematics (10303-105, 1996) and finite element analysis (10303-107, 1996). These models are commonly known as STEP integrated application resources.

(iii). These models are same as STEP integrated generic resources. Only difference in these models is of the data representation which was developed for other ISO standards but adopted by STEP. These are models known as generic resources from other ISO standards.

2.4.2.5 Application Protocols

APs are the part of ISO 10303 standard, which defines data models for a certain application domain. Each application protocol defines classes of objects and their relations (Batres *et al.*, 2007; Valilai & Houshmand, 2010). ISO 10303 had addressed many industrial data exchange requirements by means of APs (Garrido Campos & Hardwick, 2006). There are many protocols available for specific kind of products focused to product respective industries. Rather than that, the CAx manufacturing also utilizes APs such as; AP 203 is for configuration control design, AP 204 is for mechanical design using boundary representation, AP 214 is for core data for automotive mechanical design processes and AP 224 mechanical product definition for process planning (Ball *et al.*, 2008). According to the Sub Committee (SC) 4 website (http://www.iso.org/), there are currently 45 application protocols that have become international standards. Most of them are listed in Table 2.3.

Table 2.3 List of Application Protocols

AP	Description
201	Explicit Drafting
202	Associative Drafting
203	Configuration control design
204	Mechanical design using boundary representation
205	Mechanical design using surface representation
206	Mechanical design using wireframe representation
207	Sheet metal dies and blocks
208	Life cycle product change process
209	Design through analysis of composite and metallic structure
210	Electronic printed circuit assembly
211	Electronic test diagnostics and remanufacture
212	Electro technical plants
213	Numerical control process plans for machined parts
214	Core data for automotive mechanical design processes
215	Ship arrangements
216	Ship moulded forms
217	Ship piping
218	Ship structures
219	Dimensional inspection process planning for CMMs
220	Printed circuit assembly manufacturing planning
221	Functional data and schematic representations for process plans
222	Design engineering to manufacturing for composite structures
223	Exchange of design and manufacturing DPD for composites
224	Mechanical product definition for process planning
225	Structural building elements using explicit shape rep
226	Shipbuilding mechanical system
227	Plant spatial configuration
228	Building services
229	Design and manufacturing information for forged parts
230	Building structure frame steelwork
231	Process engineering data
232	Technical data packaging
233	Systems engineering data representation
234	Ship operational logos, records and messages
235	Materials information for products
236	Furniture product and project
237	Computational fluid dynamics
238	Integrated CNC machining
239	Product life cycle support
240	Process Planning

The concept of AP was introduced in STEP because AP enables the features of customizations to solve the needs of specific applications. The AP is composed of seven elements: Application Activity Model (AAM), Application Reference Model (ARM), Application Interpreted Model (AIM), Unit of Functionality (UOF), Application Interpreted Construct (AIC), Application Module (AM) and Conformance Classes (CC).

(i). AAM: - This model represents the activities and data flow information. This is a formal document which describes a portion of the product life cycle (what process do I want to support)(Feeney, 2002). These models are built by using Integrated Definition of functional modelling (IDEF) 0 approach. This approach is an integrated family of methods for business analysis between different collaborative works. With the completion of AAM, stage an ARM has been built.

(ii). ARM: - This model denotes the piece of product information (what are the information requirements of the activity in industry terminology) (Feeney, 2002), which are needed for the particular application. The information of ARM is described by the information model via library of pre-existing definitions. The building of ARM is usually done by the experts where they decide what entities and their attributes should be defined. This model can be written in EXPRESS, EXPRESS-G or IDEF1, but mostly EXPRESS and EXPRESS-G are used.

(iii). AIM: - This is an EXPRESS model which contain exactly same information as ARM. Only difference is of information encoding in terms of the STEP integrated resources (how do I model the required information using STEP and EXPRESS) (Feeney, 2002; Wang & Xu, 2004). The encoding is done by using mapping tables, the format of which is formally defined and uniform across STEP.

(iv). UOF: - It is a subset of ARM of an AP containing entities and related constructs that support some specific functionality. A number of APs were produced containing UOFs (Kramer & Xu, 2009) such as: AP 219 contains UOFs of administrative_data, dimensional_measurement_analysis, feature_profile, functional_limitations and part_properties (10303-219, 2007).

(v). AIC: - It is an interpreted UOF in terms of the STEP integrated resources. The idea is that, an AIC developed for use in the AIM of one AP can be reused in other APs. Currently, over 20 AICs have become international standards (Kramer & Xu, 2009).

(vi). AM: - It is a tiny module with small functionality like AP. AM replaced AP because AP was found to be insufficient to support reuse environment. Like an AP, an AM has an ARM written in terms of the domain being modelled

(Feeney, 2002). In AM of an AP the Module Integrated Model (MIM) is called an AIM. The MIM is a reinterpretation of the ARM using STEP integrated resources. The AMs are able to refer each other to build a complex functionality (Kramer & Xu, 2009).

(vii). CC: - It is the subset of an AP, which enables the implementation of very large and multi domain APs in STEP architecture (Kramer & Xu, 2009) such as: AP214 has 20 CCs (10303-214, 1997; Nielsen & Kjellberg, 2000) and AP 238 has 4 CCs (10303-238, 2007).

2.4.3 Architecture of STEP

ISO 10303 is the most successful product data exchange standard. Its structure is recognized by two approaches: classic and modular as shown in Figure 2.7. As STEP is composed of APs, which contains activity model and conformance class. In the classic approach of STEP architecture, the AP is composed of AAM, CC, ARM, mapping and AIM. In this approach, there is a separate module for each of the components of AP. The information of APs is processed by the AICs to exchange common product data to two or more APs. While implementing classic approach in product data integration, some limitations had been found such as: high cost, document duplication and repetition and less interoperability in APs (Batres *et al.*, 2007; Kramer & Xu, 2009; Le Duigou *et al.*, 2009; Mehta *et al.*, 2009). In order to overcome these drawbacks, some provisions were proposed in a classic approach (Feeney, 2002; Gielingh, 2008). The result of these provisions was the introduction of modular architecture of STEP.

In this approach, the common information requirements are divided, organized and mapped into smaller packages known as AMs. These AMs can be used with other AMs of APs. The AP of this approach is composed of AAM and CC definitions (Kramer & Xu, 2009). In this approach, an AIC is replaced by AM, however the objects of both are similar. The main objectives of modularization is “to enable the more efficient technical development, standardization, implementation and deployment of STEP standard without changing the fundamentals of the current technical architecture” (Feeney, 2002) and to meet the high level industry requirements which are (Feeney, 2002; Houshmand & Valilai, 2012):

(i). Reduce the high cost and lengthy time to develop an AP.

(ii). Enabling the implementation of a combination of multiple APs.

(iii). Enabling application software reuse.

(iv). Eliminate duplication and repeated documentation of the same requirements in different APs.

(v). Reuse data generated by an implementation of one or more APs.

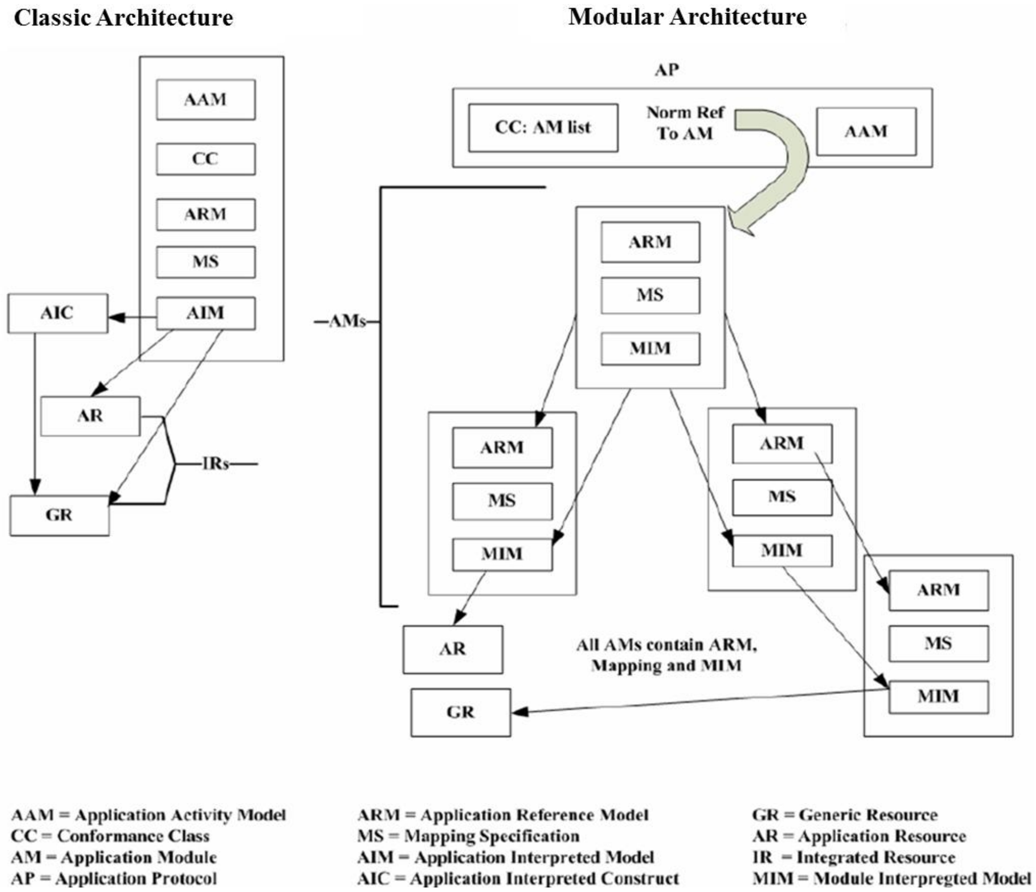


Figure 2.7 STEP architecture approaches (Fowler, 1995)

STEP significantly improves the interoperability between CAD systems but in the meantime, it also created the requirement of new standard to exchange the information between CNC machines as well as CAM systems. Accordingly, in 1999, an international project was started to bring the benefits of STEP to CAM and CNC known as STEP-NC (ISO 14649) (Suh *et al.*, 2002).

2.5 STEP-NC

As ISO 10303 standard resolves the problems relating to the product data exchange between CAD, CAPP and CAM systems. Therefore for establishing a seamless data flow between CAM and CNC, a new standard, ISO 14649, was introduced commonly known as STEP-Compliant Numerical Control or STEP-NC in short. This standard offers the possibility of seamless data integration of application throughout design to manufacturing cycle (Kramer & Xu, 2009). Currently, the attention of ISO is on the development of STEP manufacturing environment, which includes STEP in, STEP out and STEP throughout (Shin *et al.*, 2007). The aim of STEP-NC is to provide remedies for the shortcomings of ISO 6983 by specifying machining processes rather than tool motion. It is done by using object and feature oriented concept of working steps which provides a seamless link in CAx to make CNC more open, interoperable, portable, adoptable, flexible and intelligent. The major benefit of STEP-NC is that, it uses existing data models of ISO 10303 for enabling of smooth and seamless information exchange in CAx (Cai *et al.*, 2005). ISO 14649 contains high degree of information sets, which includes "What-to-make" (geometry) and "How-to-make" (process plan) (Shin *et al.*, 2007).

2.5.1 Versions of STEP-NC

Currently, there are two versions of STEP-NC (ISO 14649 and ISO 10303-238) that are under development by two different sub committees of Technical Committee (TC) 184 under ISO.

2.5.1.1 ISO 14649

It is being developed by SC1 of TC 184 under ISO, whose preliminary focus is on machine control (ISO, 2002a). The models of this version were written in EXPRESS language and are of ARM type (Hardwick *et al.*, 2013). In this version of STEP-NC, a CAM software has total access to all of the production data (Krzic *et al.*, 2009). The ISO 14649 is made of several parts such as:

REFERENCES

10303-23, I. (1998). ISO Committee Draft 10303-23: Industrial automation systems and integration–Product data representation and exchange–Part23: Implementation methods: C++ language binding to the standard data access interface *ISO TC184/SC4 N*.

10303-24, I. (1998). ISO Committee Draft 10303-24: Industrial automation systems and integration–Product data representation and exchange–Part24: Implementation methods: C language binding of standard data access interface *ISO TC184/SC4 N*.

10303-27, I. (1998). ISO Committee Draft 10303-27: Industrial automation systems and integration–Product data representation and exchange–Part27: Implementation methods: JAVA™ programming language binding to the standard data access interface with internet/intranet extensions *ISO TC184/SC4 N*.

10303-105, I. (1996). ISO Committee Draft 10303-105: Industrial automation systems and integration–Product data representation and exchange–Part105: Integrated application resource: Kinematics *ISO TC184/SC4 N*.

10303-107, I. (1996). ISO Committee Draft 10303-107: Industrial automation systems and integration–Product data representation and exchange–Part107: Integrated application resource: Finite element analysis definition relationships *ISO TC184/SC4 N*.

10303-214, I. (1997). ISO Committee Draft 10303-214: Industrial automation systems and integration–Product data representation and exchange–Part214: Application Protocol: Core data for automotive mechanical design process *ISO TC184/SC4 N* (Vol. 577).

10303-219, I. (2007). ISO Committee Draft 10303-219: Industrial automation systems and integration–Product data representation and exchange–Part219: Application Protocol: Dimensional inspection information exchange *ISO TC184/SC4 N*.

10303-238, I. (2007). ISO Committee Draft 10303-238: Industrial automation systems and integration–Product data representation and exchange–Part238: Application Protocol: Application interpreted model for computerized numerical controllers *ISO TC184/SC4 N*.

Albert, M. (2000). FEATURES-EMPHASIS: CNC and CAM-STEP NC-The end of G-Codes?-Cover story. One day soon, the only input the CNC will need is a digital part model obtained directly from the Web. *Modern Machine Shop, 73*(2), 70-85.

Asato, O., Kato, E., Inamasu, R., & Porto, A. (2002). Analysis of open CNC architecture for machine tools. *Journal of the Brazilian Society of Mechanical Sciences, 24*(3), 208-212.

Association, O. (2001). *OSACA Handbook, Version 2.0* (Vol. 16).

Balic, J., Klancnik, S., & Brezovnik, S. (2008). Feature extraction from CAD model for milling strategy prediction. *Strojniški vestnik, 54*(5), 301-307.

Ball, A., Ding, L., & Patel, M. (2008). An approach to accessing product data across system and software revisions. *Advanced Engineering Informatics, 22*(2), 222-235.

Batres, R., West, M., Leal, D., Price, D., Masaki, K., Shimada, Y., Fuchino, T., & Naka, Y. (2007). An upper ontology based on ISO 15926. *Computers & Chemical Engineering, 31*(5), 519-534.

Benavente, J. C. T., Ferreira, J. C. E., Goulart, C. M., & Oliveira, V. G. d. (2013). A STEP-NC compliant system for the remote design and manufacture of mechanical components through the Internet. *International Journal of Computer Integrated Manufacturing, 26*(5), 412-428.

Bin, L., Yunfei, Z., & Xiaoqi, T. (2004). A research on open CNC system based on architecture/component software reuse technology. *Computers in Industry, 55*(1), 73-85.

Bishop, R. H. (2009). *LabVIEW 2009 Student Edition*. Upper Saddle River, NJ, USA: Prentice Hall Press.

Brecher, C., Verl, A., Lechler, A., & Servos, M. (2010). Open control systems: state of the art. *Production Engineering, 4*(2-3), 247-254.

Brecher, C., & Voss, M. (2005). Potenziale komponentenbasierter offener NCSteuerungssysteme. *Fortschritt-Berichte VDI—Fertigungs-und Medizintechnik: Gemeinsame Lösunganssätze. VDI Verlag, Düsseldorf,* S121-S134.

Cai, J., Weyrich, M., & Berger, U. (2005). Ontological machining process data modelling for powertrain production in extended enterprise. *Journal of Advanced Manufacturing Systems, 4*(01), 69-82.

Calabrese, F., & Celentano, G. (2007). Design and realization of a STEP-NC compliant CNC embedded controller. *Emerging Technologies and Factory Automation ETFA.*, Patras. IEEE. 1010-1017

Cha, J. M., Suh, S. H., Hascoet, J. Y., & Stroud, I. (2014). A roadmap for implementing new manufacturing technology based on STEP-NC. *Journal of intelligent manufacturing*, 1-15.

Chen, L., Yu, D., Zhang, H., Geng, C., & Dong, L. (2012). Design and implement of a modularized CNC interpreter based on the integration of tool path planning module. *Computer Science and Automation Engineering (CSAE)*. IEEE. 613-616.

Chunhao, L., Lijin, G., & Jingdong, L. (2012). Research of motion control system based on PCI-1243. *Digital Manufacturing and Automation (ICDMA)*. IEEE. 662-665.

Consortium, I. S.-N. (2003). Technical Report 3 of IMS Project (97006) STEP-compliant data interface for numerical controls (STEP-NC) *Report Period* (Vol. 1).

Da Rocha, P., Diogne de Silva e Souza, R., & De Lima Tostes, M. E. (2010). Prototype CNC machine design. *Industry Applications (INDUSCON)*, Sao Paulo. IEEE. 1-5.

Denkena, H., Tönshoff, J., Selle, A., Storr, S., Heusinger, S., & Rogers, G. (2002). Offline-Berechnung der Zerspankräfte in der NC-Programmierung. *Vorhersage der Zerspankräfte beim HSC-Schlichtfräsen*.

DIS, I. (1993). 10303-21,“Industrial automation systems-product data representation and exchange-part 21: Implementation methods: Clear text encoding of the exchange structure," *International Organization for Standardization, Geneva, Switzerland*.

DIS, I. (1996). 10303-22, "Product data representation and exchange-part 22: Standard data access interface" *TC184/SC4*.

Dong, Y., Hu, L., Ruifeng, G., Jiangang, Y., & Pengfei, X. (2005). The research on real-time middleware for open architecture controller. *Embedded and Real-Time Computing Systems and Applications*. IEEE. 80-83.

Ekkachai, K., Komin, U., Chaopramualkul, W., Tantaworrasilp, A., Kwansud, P., Seekhao, P., Leelasawassuk, T., Tanta-Ngai, K., & Tungpimolrut, K. (2009). Design and development of an open architecture CNC controller for milling machine retrofitting. *ICCAS-SICE*, Fukuoka. IEEE. 5629-5632.

Elias, D., Yusof, Y., & Minhat, M. (2013). CNC machine system via STEP-NC data model and LabVIEW platform for milling operation. *Open Systems (ICOS)*. IEEE. 27-31.

Elias, D., Yusof, Y., & Minhat, M. (2014). An open STEP-NC controller via labview platform. *Applied Mechanics and Materials, 660*, 873-877.

Elliott, C., Vijayakumar, V., Zink, W., & Hansen, R. (2007). National instruments LabVIEW: a programming environment for laboratory automation and measurement. *Journal of the Association for Laboratory Automation, 12*(1), 17-24.

Erdős, G., & Xirouchakis, P. (2003). STEP-NC data model developement for wire-EDM manufacturing. IFAC.

Ertell, G. G. (1969). *Numerical control*. New York, NY Wiley.

ESPRIT III, E. OSACA public document: Open system architecture for controls within automation systems EP 6379 & EP 9115 (OS2FIN4. DOC) *Final Rep., Version* (Vol. 1).

Feeney, A. B. (2002). The STEP modular architecture. *Journal of Computing and Information Science in Engineering, 2*(2), 132-135.

Fowler, J. (1995). STEP for data management, exchange and sharing.

Garrido Campos, J., & Hardwick, M. (2006). A traceability information model for CNC manufacturing. *Computer-Aided Design, 38*(5), 540-551.

Gielingh, W. (2008). An assessment of the current state of product data technologies. *Computer-Aided Design, 40*(7), 750-759.

Groover, M. P. (2007). *Automation, production systems, and computer-integrated manufacturing*. Upper Saddle River, NJ, USA: Prentice Hall Press.

Guo, X., Liu, Y., Du, D., Yamazaki, K., & Fujishima, M. (2012). A universal NC program processor design and prototype implementation for CNC systems. *The International Journal of Advanced Manufacturing Technology, 60*(5-8), 561-575.

Gutierrez, M. E., & Álvares, A. J. (2013). Development of a cnc router adherent to standard STEP-NC based on the controller advanced machine (EMC2). *22nd International Congress of Mechanical Engineering (COBEM)*. 8200-8213.

Hamilton, K., Hascoet, J. Y., & Rauch, M. (2014). Implementing STEP-NC: Exploring possibilities for the future of advanced manufacturing *Modern Mechanical Engineering* (pp. 199-239). Berlin Heidelberg: Springer.

Han, J., Pratt, M., & Regli, W. C. (2000). Manufacturing feature recognition from solid models: a status report. *Robotics and Automation, IEEE Transactions, 16*(6), 782-796.

Han, J., Regli, W. C., & Brooks, S. (1998). Hint-based reasoning for feature recognition: status report. *Computer-Aided Design, 30*(13), 1003-1007.

Hardwick, M. (2001). *STEP into Automatic Machining*: STEP Tools, Inc.
Hardwick, M. (2004). On STEP-NC and the complexities of product data integration. *Journal of Computing and Information Science in Engineering, 4*(1), 60-67.
Hardwick, M., Zhao, Y. F., Proctor, F. M., Nassehi, A., Xu, X., Venkatesh, S., Odendahl, D., Xu, L., Hedlind, M., & Lundgren, M. (2013). A roadmap for STEP-NC-enabled interoperable manufacturing. *The International Journal of Advanced Manufacturing Technology, 68*(5-8), 1023-1037.
Houshmand, M., & Valilai, O. F. (2012). LAYMOD: a layered and modular platform for CAx product data integration based on the modular architecture of the standard for exchange of product data. *International Journal of Computer Integrated Manufacturing, 25*(6), 473-487.
ISO 6983-1. (1982). ISO 6983/1 Numerical control of machines-program format and definition of address words-part 1: data format for positioning, line and contouring control systems *International Organization of Standard*. Vernier, Geneva, Switzerland: ISO.
ISO. (1994a). 10303-1 TC184/SC4: Product data representation and exchange—part 1: overview and fundamental principles *International Standard*. Vernier, Geneva, Switzerland: ISO.
ISO. (2002a). 14649-1. Industrial automation systems and integration physical device control-data model for computerized numerical controllers-Part 1: Overview and fundamental principles draft international standard *USA: ISO TC184/SC4*.
ISO. (2002b). 14649-10. Industrial automation systems and integration physical device control-data model for computerized numerical controllers-Part 10: General process data. *USA: ISO TC184/SC4*.
ISO. (2002c). 14649-11. Industrial automation systems and integration physical device control-data model for computerized numerical controllers-Part 11: Process data for milling. *USA: ISO TC184/SC4*.
ISO. (2002d). 14649-12. Industrial automation systems and integration physical device control-data model for computerized numerical controllers-Part 12: Process data for turning. *USA: ISO TC184/SC4*.
ISO. (2002e). 14649-111. Industrial automation systems and integration physical device control-data model for computerized numerical controllers-Part 111: Tools for milling. *USA: ISO TC184/SC4*.
ISO. (2002f). 14649-121. Industrial automation systems and integration physical device control-data model for computerized numerical controllers-Part 121: Tools for turning. *USA: ISO TC184/SC4*.
ISO, C. (1991). 10303-1:" Product Data Representation and Exchange-Part 1: Overview and Fundamental Principles.". *TC, 184*.
ISO, I. (1994b). 10303-1. *Industrial automation systems and integration—Product data representation and exchange—Part, 1*.
ISO, T. (1994c). 184/SC 4, ISO 10303-11: 1994 Industrial automation systems and integration-Product data representation and exchange-Part 11: Description methods: The EXPRESS language reference manual *International Organization for Standardization*. Vernier, Geneva, Switzerland: ISO.
Khanna, A., Kumar, A., Bhatnagar, A., Tyagi, R., & Srivastava, S. (2013). Low-cost production CNC system. *Intelligent Systems and Control (ISCO)*, Coimbatore, Tamil Nadu, India. IEEE. 523-528.
Kramer, T., & Xu, X. (2009). STEP in a Nutshell *Advanced design and manufacturing based on STEP* (pp. 1-22): Springer.

Kramer, T. R., Proctor, F., Xu, X., & Michaloski, J. (2006). Run-time interpretation of STEP-NC: implementation and performance. *International Journal of Computer Integrated Manufacturing, 19*(6), 495-507.

Krzic, P., Stoic, A., & Kopac, J. (2009). STEP-NC: A new programming code for the CNC machines. *Strojniški vestnik, 55*(6), 406-417.

LabVIEW, F. (2009). National Instruments (pp. 78730-75039). Texas, USA: Austin.

Laguionie, R., Rauch, M., & Hascoët, J. Y. (2009). Toolpaths programming in an intelligent STEP-NC manufacturing context. *Journal of Machine Engineering, 8*(1), 33-43.

Laguionie, R., Rauch, M., Hascoët, J. Y., & Suh, S. H. (2011). An extended manufacturing integrated system for feature-based manufacturing with STEP-NC. *International Journal of Computer Integrated Manufacturing, 24*(9), 785-799.

Lan, H., Liu, R., & Zhang, C. (2008). A multi-agent-based intelligent STEP-NC controller for CNC machine tools. *International Journal of Production Research, 46*(14), 3887-3907.

Lan, H., Zhang, C., & Liu, R. (2006). A Framework for Intelligent STEP-NC Controller Based on Multi-agent.

Le Duigou, J., Bernard, A., Perry, N., & Delplace, J. C. (2009). Global approach for technical data management. Application to ship equipment part families. *CIRP Journal of Manufacturing Science and Technology, 1*(3), 185-190.

Lee, W., Bang, Y., Ryou, M., Kwon, W., & Jee, H. (2006). Development of a PC-based milling machine operated by STEP-NC in XML format. *International Journal of Computer Integrated Manufacturing, 19*(6), 593-602.

Li, P., Gao, T., Wang, J., & Liu, H. (2010). Open architecture of CNC system research based on CAD graph-driven technology. *Robotics and Computer-Integrated Manufacturing, 26*(6), 720-724.

Li, P., Hu, T., & Zhang, C. (2011). A unified communication framework for intelligent integrated CNC on the shop floor. *Procedia Engineering, 15*, 840-847.

Liana, S. Y., Hecker, R. L., & Landers, R. G. (2004). Machining process monitoring and control: the state-of-the-art. *Journal of manufacturing science and engineering, 126*(2), 297-310.

Ma, X. B., Han, Z. Y., Wang, Y. Z., & Fu, H. Y. (2007). Development of a PC-based open architecture software-CNC system. *Chinese Journal of Aeronautics, 20*(3), 272-281.

Maoyue, L., Hongya, F., Yuan, L., & Zhenyu, H. (2009a). An intelligent controller based on constant cutting force for 5-axis milling. *Information Technology and Computer Science*. IEEE. 237-241.

Maoyue, L., Hongya, F., Yuan, L., & Zhenyu, H. (2009b). Research on reusable and configurable intelligent machining system. *Industrial Electronics and Applications*. IEEE. 3130-3133.

Mehrabi, M. G., Ulsoy, A. G., & Koren, Y. (2000). Reconfigurable manufacturing systems: key to future manufacturing. *Journal of intelligent manufacturing, 11*(4), 403-419.

Mehrabi, M. G., Ulsoy, A. G., Koren, Y., & Heytler, P. (2002). Trends and perspectives in flexible and reconfigurable manufacturing systems. *Journal of intelligent manufacturing, 13*(2), 135-146.

Mehta, C., Patil, L., & Dutta, D. (2009). STEP in the Context of PLM *Advanced Design and Manufacturing Based on STEP* (pp. 383-397): Springer.

Mekid, S., Pruschek, P., & Hernandez, J. (2009). Beyond intelligent manufacturing: A new generation of flexible intelligent NC machines. *Mechanism and Machine Theory, 44*(2), 466-476.

Minhat, M., Vyatkin, V., Xu, X., Wong, S., & Al Bayaa, Z. (2009). A novel open CNC architecture based on STEP-NC data model and IEC 61499 function blocks. *Robotics and Computer-Integrated Manufacturing, 25*(3), 560-569.

Morales Velazquez, L., Romero Troncoso, R. d. J., Osornio Rios, R. A., Herrera Ruiz, G., & Cabal Yepez, E. (2010). Open architecture system based on a reconfigurable hardware software multi agent platform for CNC machines. *Journal of Systems Architecture, 56*(9), 407-418.

Mori, M., Yamazaki, K., Fujishima, M., Liu, J., & Furukawa, N. (2001). A study on development of an open servo system for intelligent control of a CNC machine tool. *CIRP Annals-Manufacturing Technology, 50*(1), 247-250.

Mortenson, M. E. (1985). *Geometric modeling*.

Müller, P., & Hyun, Y. (2001). ESPRIT Projekt EP29708 STEP-Compliant data interface of numerical controls (STEPNC) *Final report, STEP-NC Consorcium* (pp. 1-28).

Nacsa, J. (2001). Comparison of three different open architecture controllers. *IFAC MIM, Prague*. 2-4.

Nassehi, A. (2007). The realisation of CAD/CAM/CNC interoperability in prismatic part manufacturing. *Dissertation Abstracts International, 68*(4).

Nassehi, A., Liu, R., & Newman, S. (2007). A new software platform to support feature-based process planning for interoperable STEP-NC manufacture. *International Journal of Computer Integrated Manufacturing, 20*(7), 669-683.

Nassehi, A., Newman, S., & Allen, R. (2006). The application of multi-agent systems for STEP-NC computer aided process planning of prismatic components. *International Journal of Machine Tools and Manufacture, 46*(5), 559-574.

Newman, S., Allen, R., & Rosso Jr, R. (2003). CAD/CAM solutions for STEP-compliant CNC manufacture. *International Journal of Computer Integrated Manufacturing, 16*(7-8), 590-597.

Newman, S., Nassehi, A., Xu, X., Rosso, R., Wang, L., Yusof, Y., Ali, L., Liu, R., Zheng, L., & Kumar, S. (2008). Strategic advantages of interoperability for global manufacturing using CNC technology. *Robotics and Computer-Integrated Manufacturing, 24*(6), 699-708.

Nielsen, J., & Kjellberg, T. (2000). The ISO 10303-214 process model as a core for a process planning tool. *International CIRP Design Seminar*.

Pabolu, V. K., & Srinivas, S. (2010). Design and implementation of a three dimensional CNC machine. *International Journal on Computer Science and Engineering, 2*(8), 2567-2570.

Pacheco, N. d. O., Harbs, E., Rosso Jr, R. S., Hounsell, M. d. S., & Ferreira, J. C. E. (2012). Application of the step-nc standard in a computer numerical controlled machining device. *ABCM Symposium Series in Mechatronics, 5*, 713-723.

Park, S., Kim, S. H., & Cho, H. (2006). Kernel software for efficiently building, re-configuring, and distributing an open CNC controller. *The International Journal of Advanced Manufacturing Technology, 27*(7), 788-796.

Parks, C. H. (1984). IGES as an interchange format for integrated circuit design. *Design Automation*. IEEE. 273-274.

Parks, R., & Fox, M. (1991). STEP Part 101-Draughting Resources *ISO TC184/SC4 Dokument Nr. N-97, ISO CD* (pp. 10303-10101).

Po, H., Hongya, F., Zhenyu, H., & Dedong, H. (2014). A closed-loop and self-learning STEP-NC machining system. *Advanced Intelligent Mechatronics (AIM)*. IEEE. 1598-1603.

Pritschow, G., Altintas, Y., Jovane, F., Koren, Y., Mitsuishi, M., Takata, S., Van Brussel, H., Weck, M., & Yamazaki, K. (2001). Open controller architecture–past, present and future. *CIRP Annals-Manufacturing Technology, 50*(2), 463-470.

Pritschow, G., Daniel, C., Junghans, G., & Sperling, W. (1993). Open system controllers–a challenge for the future of the machine tool industry. *CIRP Annals-Manufacturing Technology, 42*(1), 449-452.

Proctor, F. M., & Michaloski, J. (1993). *Enhanced machine controller architecture overview*: US Department of Commerce, National Institute of Standards and Technology.

Qiang, R. (2007). Research of Software Open-CNC System. http://www.paper.edu.cn

Ramesh, R., Jyothirmai, S., & Lavanya, K. (2013). Intelligent automation of design and manufacturing in machine tools using an open architecture motion controller. *Journal of Manufacturing Systems, 32*(1), 248-259.

Ramesh, R., & Poo, A. (2009). Intelligent Ethernet based open architecture control system for machine tools. *Intelligent Computing and Intelligent Systems ICIS*, Shanghai. IEEE. 612-616.

Rauch, M., Laguionie, R., & Hascoet, J. Y. (2009). Achieving a STEP-NC enabled advanced NC programming environment *Advanced Design And Manufacturing Based On STEP* (pp. 197-214): Springer.

Rauch, M., Laguionie, R., Hascoet, J. Y., & Suh, S. H. (2012). An advanced STEP-NC controller for intelligent machining processes. *Robotics and Computer Integrated Manufacturing, 28*(3), 375-384.

Rauch, M., Laguionie, R., Hascoët, J. Y., & Xu, X. (2009). Enhancing CNC manufacturing interoperability with STEP-NC. *Journal of Machine Engineering, 9*(4), 26-37.

Reintjes, J. F. (1991). *Numerical control: making a new technology*: Oxford University Press, Inc.

Requicha, A. G. (1980). Representations for rigid solids: Theory, methods, and systems. *ACM Computing Surveys (CSUR), 12*(4), 437-464.

Richard, J., & Stark, J. (2002). Standardisation of the manufacturing process: the STEP-NC project. *IPLnet Workshop, Saas-Fee, I-tech, EIG, HES-SO*. 10-11.

Ridwan, F., Xu, X., & Liu, G. (2012). A framework for machining optimisation based on STEP-NC. *Journal of intelligent manufacturing, 23*(3), 423-441.

Sääski, J., Salonen, T., & Paro, J. (2005). Integration of CAD, CAM and NC with STEP-NC *Espoo, VTT*.

Safaieh, M., Nassehi, A., & Newman, S. T. (2013). A novel methodology for cross-technology interoperability in CNC machining. *Robotics and Computer Integrated Manufacturing, 29*(3), 79-87.

Sarhan, H. (2014). A novel technique for controlling CNC systems. *Control Theory and Informatics, 4*(5), 82-92.

Schofield, S., & Wright, P. (1998). Open architecture controllers for machine tools, part 1: design principles. *Journal of manufacturing science and engineering, 120*(2), 417-424.

Shin, S. J., Suh, S. H., & Stroud, I. (2007). Reincarnation of G-code based part programs into STEP-NC for turning applications. *Computer-Aided Design, 39*(1), 1-16.

Sivakumar, S., & Dhanalakshmi, V. (2013). A feature-based system for CAD/CAM integration through STEP file for cylindrical parts. *Indian Journal of Engineering & Materials Sciences, 20*(1), 21-26.

Sperling, W., & Lutz, P. (1997). Designing applications for an OSACA control. *International Mechanical Engineering Congress and Exposition*. Citeseer. 16-21.

Storr, A., Pritschow, G., Heusinger, S., & Azotov, A. (2002). Workingstep planning for turning with STEP-NC: planning methods for user support. *IWF Zeitschrift fur Wirtschaftlichen Fabrikbetrieb, 97*(7-8), 390.

Suh, S. H., & Cheon, S. U. (2002). A framework for an intelligent CNC and data model. *The International Journal of Advanced Manufacturing Technology, 19*(10), 727-735.

Suh, S. H., Cho, J. H., & Hong, H. D. (2002). On the architecture of intelligent STEP-compliant CNC. *International Journal of Computer Integrated Manufacturing, 15*(2), 168-177.

Suh, S. H., Kang, S. K., Chung, D. H., & Stroud, I. (2008). *Theory and design of CNC systems*: Springer.

Suh, S. H., Lee, B., Chung, D., & Cheon, S. (2003). Architecture and implementation of a shop-floor programming system for STEP-compliant CNC. *Computer-Aided Design, 35*(12), 1069-1083.

TC184, I. (2004). Product data representation and exchange: Implementation methods: XML Schema governed representation of EXPRESS schema governed data. *SC4/WG11 N223, ISO/WD 10303-28* (pp. 02-17).

Ueno, S., Chino, S., Hoshino, Y., & Uneme, M. (2000). Development of the standard Application Program Interface (API) for Open FA controller in Japan. *15th Annual Meeting, ASPE*. 296-299.

Ueno, S., Mitsuishi, M., Muto, K., & Takata, S. (2002). Standard API for open-architecture CNC and it's application to HMI and operation monitoring *Initiatives of Precision Engineering at the Beginning of a Millennium* (pp. 789-793): Springer.

Uri, Y. K. J. B. (1971). Digital control of multiaxial-motion system. *IFAC 5th world congress*, Paris, France. The Federation]; Pittsburgh, Pa.: distributed by the Instrument Society of America.

Valilai, O. F., & Houshmand, M. (2010). INFELT STEP: An integrated and interoperable platform for collaborative CAD/CAPP/CAM/CNC machining systems based on STEP standard. *International Journal of Computer Integrated Manufacturing, 23*(12), 1095-1117.

Wang, H. (2009). *New control strategy for CNC machines via STEP-NC.* (PhD), ResearchSpace@ Auckland.

Wang, H., & Xu, X. (2004). A STEP-Compliant "Adaptor" for linking CAPP with CNC. *34th International MATADOR Conference*. Springer. 45-50.

Wang, H., Xu, X., & Des Tedford, J. (2007). An adaptable CNC system based on STEP-NC and function blocks. *International Journal of Production Research, 45*(17), 3809-3829.

Wang, K., Tang, M., Wang, Y., Estensen, L., Sollie, P. A., & Pourjavad, M. (2002). Knowledge-based CAD/CAPP/CAM integration system for manufacturing *Digital Enterprise Challenges* (pp. 406-415): Springer.

Wang, T., Liu, Q., & Wang, L. (2010). An RTOS-based embedded CNC system. *Computer, Mechatronics, Control and Electronic Engineering (CMCE)*, TBD, Changchun, China. IEEE. 33-36.

Weck, M. (2003). STEP-NC–A new interface closing the gap between planning and shop-floor. *WZL RWTH Aachen, STEP-NC Workshop*, Aachen, Germany.

Weck, M., & Bruhl, J. (1999). Originalaufsatze-OSACA produktreif-Einheitliche Schnittstelle zu allen Steuerungen. *Werkstattstechnik-Forschung und Entwicklung fur die Produktion, 89*(5), 263-264.

Weck, M., Kohring, A., & Klein, F. (1993). Offene NC-Systeme, grundlage herstellerunabhängiger flexibilität. *VDI-Z, 135*(5), 51-55.

Weck, M., & Wolf, J. (2002). ISO 14649 provides information for sophisticated and flexible numerically controlled production. *Prod Eng [WGP-Annals]*.

Weck, M., Wolf, J., & Kiritsis, D. (2001). STEP-NC–The STEP compliant NC programming interface. *International Intelligent Manufacturing System Forum*.

Weidong, Y., & Zhanbiao, G. (2010). An open CNC controller based on LabVIEW software. *Computer Application and System Modeling (ICCASM)*, North University of China, Taiyuan, China. IEEE. V4-476-V474-479.

Wolf, J. (2001). STEP-NC—integrating shop floor into industrial data flow for the enabling of intelligent near to process functions. *Korea–Germany Workshop on STEP-NC*.

Wu, H., Zhang, C., Li, G., & Wang, B. (2006). Windows XP embedded based open architecture computer numerical control system. *Mechatronic and Embedded Systems and Applications*. IEEE. 1-6.

Xiao, S. (2010). An open-architecture embedded manufacturing control system. *Measuring Technology and Mechatronics Automation (ICMTMA)*. IEEE. 517-520.

Xiao, S., Li, D., Lai, Y., Wan, J., & Feng, S. (2007). An open architecture numerical control system based on Windows CE. *Control and Automation ICCA*, Guangzhou. IEEE. 1237-1240.

Xiao, W., Zheng, L., Huan, J., & Lei, P. (2015). A complete CAD/CAM/CNC solution for STEP-compliant manufacturing. *Robotics and Computer Integrated Manufacturing, 31*, 1-10.

Xu, X. (2006). Realization of STEP-NC enabled machining. *Robotics and Computer Integrated Manufacturing, 22*(2), 144-153.

Xu, X., & He, Q. (2004). Striving for a total integration of CAD, CAPP, CAM and CNC. *Robotics and Computer Integrated Manufacturing, 20*(2), 101-109.

Xu, X., & Newman, S. (2006). Making CNC machine tools more open, interoperable and intelligent—a review of the technologies. *Computers in Industry, 57*(2), 141-152.

Xu, X., Wang, H., Mao, J., Newman, S., Kramer, T., Proctor, F., & Michaloski, J. (2005). STEP-compliant NC research: the search for intelligent CAD/CAPP/CAM/CNC integration. *International Journal of Production Research, 43*(17), 3703-3743.

Xu, X., & Wang, J. (2004). Development of a G-code free, STEP-compliant CNC lathe. *ASME International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers. 75-82.

Xu, X., Wang, L., & Newman, S. (2011). Computer-aided process planning–a critical review of recent developments and future trends. *International Journal of Computer Integrated Manufacturing, 24*(1), 1-31.

Xu, X. M., Li, Y., Sun, J. H., & Wang, S. G. (2012). Research and development of open cnc system based on pc and motion controller. *Procedia Engineering, 29*, 1845-1850.

Yu, D., Hu, Y., Xu, X., Huang, Y., & Du, S. (2009). An open CNC system based on component technology. *Automation Science and Engineering, IEEE Transactions, 6*(2), 302-310.

Yuan, L., Yong Zhang, W., & Hong Ya, F. (2008). An open architecture motion controller for CNC machine tools. *Systems and Control in Aerospace and Astronautics ISSCAA*. IEEE. 1-4.

Yuhan, W., Jun, H., & Ye, L. (2003). Study on a reconfigurable model of an open CNC kernel. *Journal of materials processing technology, 138*(1), 472-474.

Yusof, Y., Kassim, N. D., & Zamri Tan, N. Z. (2011). The development of a new STEP-NC code generator (GEN-MILL). *International Journal of Computer Integrated Manufacturing, 24*(2), 126-134.

Yusof, Y., Newman, S., Nassehi, A., & Case, K. (2009). Interoperable CNC system for turning operations. *World Academy of Science, Engineering and Technology*. Citeseer. 941-947.

Zha, X. F. (2006). Integration of the STEP-based assembly model and XML schema with the fuzzy analytic hierarchy process (FAHP) for muti-agent based assembly evaluation. *Journal of intelligent manufacturing, 17*(5), 527-544.

Zhanbiao, G. (2010). An open CNC controller based on LabVIEW software. *International Conference on Computer Application and System Modeling (ICCASM)*, North University of China, Taiyuan, China. IEEE.

Zhang, C., Wang, H., & Wang, J. (2003). An USB-based software CNC system. *Journal of materials processing technology, 139*(1), 286-290.

Zhang, X., Nassehi, A., Safaieh, M., & Newman, S. (2013). Process comprehension for shopfloor manufacturing knowledge reuse. *International Journal of Production Research, 51*((23-24)), 1-15.

Zhang, Y., Xu, X., Bai, X., & Liu, Y. (2010). Understanding the STEP-NC data model for computer numerical control. *Advanced Computer Control (ICACC)*, Shenyand, China. IEEE. 300-304.

Zhao, Y. F., Habeeb, S., & Xu, X. (2009). Research into integrated design and manufacturing based on STEP. *The International Journal of Advanced Manufacturing Technology, 44*(5-6), 606-624.

Zheng, J., Zhao, W., & Li, Z. (2005). Open EDM CNC system based on RT Linux. *Computer Integrated Manufacturing Systems, 11*(8), 1179.

Zhou, Z., Xie, J., Chen, Y., Chen, B., Qiu, Z., Wong, Y., & Zhang, Y. (2004). The development of a fieldbus-based open-CNC system. *The International Journal of Advanced Manufacturing Technology, 23*(7-8), 507-513.

Živanović, S., & Glavonjić, M. (2014). Methodology for implementation scenarios for applying protocol STEP-NC. *Journal of Production Engineering, 17*(1), 71-74.