STEP-NC CONTROLLER FOR 3-AXIS CNC MILLING MACHINE

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ABSTRACT

In contemporary Computerised Numerical Controlled (CNC) machine tools, Computer-Aided Manufacturing (CAM) and CNC conduct a number of inter-related operations and parameters using G/M-codes, set as RS274 or ISO 6983 standard. However, both standards do not explicitly relate to each other to have control of arbitrary locations other than the motion of the block-by-block sequence. STEP-NC is an alternative standard to replace the current standards. It contains the information on how CNC machine tools can be represented in STEP product data model. STEP-NC is an extension of STEP which is the standard for exchange product model data. This determines the neutral data format for digital information from a product. The controller based on STEP-NC neutral data via LabVIEW platform has been developed in this research. Through this development, it was successfully used to create an open CNC controller based on ISO 14649 and ISO 10303. This system offers interoperability, portability, and adaptability. The system consists of three main modules; (1) Data Input Generator Module, (2) STEP/LabVIEW Module (STEP-NC Controller), and (3) Software-Hardware Integration Module, these three modules called LVSTEPNC system. The two case studies in ISO 14649-11 were carried out through this system. The LVSTEPNC was successfully tested and implemented in actual 3-axis CNC milling machine. It shows the bi-directional data flow between STEP-NC controller and CNC hardware tools. The system simplifies the design of CNC machine controller with the architecture structures through G-programming (LabVIEW platform) which responsible for data processing, data storage, and execution. Furthermore, this research also suggests the requirements for global interoperable manufacturing for intelligent machining system in future.

ABSTRAK

Dalam Kawalan Berkomputer Berangka (CNC) terkini bagi peralatan mesin, Pembuatan Berbantukan Komputer (CAM) dan CNC menjalankan beberapa operasi yang saling berkaitan dan parameter menggunakan kod G berdasarkan kepada piawaian RS274 atau ISO 6983. Walau bagaimanapun, kedua-dua piawaian ini tidak mempunyai perkaitan yang jelas antara satu sama lain untuk mempunyai kawalan lokasi sembarangan selain daripada gerakannya berdasarkan kepada urutan blok-demi-blok. STEP-NC adalah sebagai piawaian alternatif untuk menggantikan piawaian semasa. Ia mengandungi maklumat tentang bagaimana sesuatu alatan mesin CNC boleh diproses daripada produk model data STEP. STEP-NC adalah merupakan lanjutan daripada piawaian STEP untuk melakukan pertukaran produk model data. Ia menentukan maklumat secara digital bagi format neutral data daripada produk. Pengawal STEP-NC berdasarkan kepada data neutral telah dibangunkan melalui perisian LabVIEW dalam kajian ini. Melalui pembangunan system ini, ia berjaya menghasilkan satu sistem terbuka bagi pengawal CNC berdasarkan kepada piawaian ISO 14649 dan ISO 10303. Sistem ini menawarkan operasi secara; "interoperability", "portability" dan "adaptability". Sistem ini terdiri daripada tiga modul utama; (1) "Data Input Generator Module", (2) "STEP/LabVIEW Module (STEP-NC Controller)", dan (3) "Software-Hardware Integration Module", ketiga-tiga modul ini dinamakan sebagai sistem "LVSTEPNC". Dua kajian kes seperti dalam ISO 14649-11 telah dijalankan. LVSTEPNC telah berjaya diuji dan dilaksanakan dalam mesin CNC peraut 3-paksi yang sebenar. Ia menunjukkan aliran data berlaku dalam dua arah diantara pengawal STEP-NC dan CNC. Sistem ini memudahkan reka bentuk pengawal mesin CNC dengan struktur seni bina melalui pengaturcaraan-G (platform LabVIEW) yang bertanggungjawab untuk memproses data, penyimpanan data, dan pelaksanaan proses pemesinan. Seterusnya, kajian ini juga mencadangkan beberapa keperluan untuk pembuatan secara global bagi sistem pemesinan secara pintar di masa hadapan.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Background of study

Machining plays an important role in the growth of manufacturing industries. The machining revolution marked a change from conventional machining to Numerical Control (NC) machining for accuracy and consistency, enabling production of components for the automotive industry, aerospace, and other manufacturing industries. In 1800, the first metalworking lathe was created by Henry Maudslay (Arthur R. Meyers &Slattery, 2001). The machine held a piece of the rotating workpiece to produce the desired shape and the machining work was fully controlled by the operator. The first milling machine by Eli Whitney in 1818 (Rao, 2013), placed the cutting tool in a rotating spindle and the machining process was either vertical or horizontal. Modern machines called Numerical Control (NC) were first introduced by John T. Parsons in the 1950s (Olexa, 2001). By utilizing a computer card reader and accurate servomotor control, the resulting machine has the high degree of accuracy required by the manufacturing, automotive and aircraft industry.

Since Computer Numerical Control (CNC) was introduced in the 1950s the industrial sector has developed CNC machines that have been widely used in manufacturing industries around the world because of their efficiency in processing, accuracy of the machines and facilities for operation. So far, most of the CNC machines use G code and M code, also known as ISO 6983 or RS274D. G and M codes are the current programming language used in CNC. The RS274D was developed by Electronic Industry Association in the 1960s and became the international standard ISO 6983 (ISO6983-1, 1982) after approval in February 1980. Over the 60 years that CNC has been used in manufacturing industries, the way of programming using low level G-Code language has remained unchanged for most of the CNC machines. In the future, CNC technology will be more developed, bi-directional data flow, and open system. There is no need for skilled operators to operate the machines. Modification of the data between the Computer-Aided Manufacturing (CAM) and CNC, involving geometry, tooling, features, tolerances, and machine parameters will utilise bi-directional data flow as well as an intelligent system.

At the CAD level containing geometrical data needs to add information typically includes tool definitions, feeds, speeds and machining strategies, it can be relies through CAM. This data is stored with a proprietary format in a CAM file and a postprocessor is utilised to transform the information from the 'product space' in CAM to the 'machine space' in the CNC (Newman &Nassehi, 2007b). This method of data conversion becomes loss of information due to the need of conversion. For example, the information about the workpiece geometry is lost by the conversion to ISO 6983 as its sole description is that of the tool paths (Heusinger, 2006). Through this proprietary format, vendors have tried to protect their market share by using proprietary standards (Newman *et al.*, 2007b). This issues continuing today at shop floor level and to eliminate the problems resulting from multiple standards for information exchange along the manufacturing chain from design to production, new standards have been developed (Nassehi, 2008). These two standard are STEP (ISO 10303) and STEP-NC (ISO 14649), it will be described in detail in chapter 2 and chapter 4.

In this chapter, a brief explanation related to current CNC language, CAx chains, Standard for the Exchange of Product (STEP) and STEP-compliant Numerical Control (STEP-NC). STEP and STEP-NC is a motivation towards a new standard for manufacturing integration and data exchange between CAx. It is also highlight some research issues in CAx chains. Finally, the aim of research, objectives and scope of research is also given.

1.2 CAx chains

CNC manufacturing has evolved in the manufacturing industries with the use of computer and communication technologies. The methods mentioned are towards intelligent control in concurrent CNC systems. The G-code language was designed in the decade when paper tape was used for moving data between computers and CNC systems. Parallel to the technology change and market demand, more than 70% of manufacturing businesses in the UK and the US now rely on CNC machines as a part of their production capacity (Newman, 2007a). Widespread CAx chain systems will reduce human interaction, and this should result in increased production quantity, reduced costs and improvements in the quality of product.

Within the machining process, there is information that can be categorized into relevant information, product design, process planning, materials, cutting tools, machining control conditions, machining execution and programming. Traditionally, this process is done in sequence for CAx chain for machining process of their complete integration from design stage up to shop floor. The vendors and users have been seeking a common language for CAD, CAPP, CAM, and CNC, which integrates and translates the knowledge of each stage (Xu, 2005). The designer will start the drafting and planning process through CAD and CAPP. The tool path of the machine tool, CAM is more narrowly connected to the CNC post processor.

The technologies are varied and change from time to time. Significant change can occur in the system for a machine in accordance with its functionality. The system must be more open and intelligent. The development of STEP-based intelligent CAPP systems will be very useful to manufacturing engineering (Amaitik &Kiliç, 2007). In additional, the CNC system architecture should incorporate data products and processes to offer bi-directional data flow with more CAx chain at high-level and may consist of geometric and manufacturing information. As CNC moves forward through the various stages, the entire manufacturing process must be kept moving forward.

Delivery of data products is a key issue in the manufacturing industry and manufacturing has a long history of reducing communications problems through standards (Hardwick, 1996). It involves various sources as well as technology from a single source or technology. Data translation process is a process in which a data format is converted to other formats and they interpret data according to their respective software. In CNC systems, data transfer starts with the design in CAD, followed by CAPP, CAM and sent to the CNC. In future, data system integration will result in much more seamless data integration, intelligent and more open architecture systems for the CAx chain (Suh, 2002b).

Figure 1.1 shows a current CAx chains data flow. The G/M codes of the tool path are generated through CAD/CAM. However, the CNCs of different vendors implement different versions of G-codes, which lack any portability and lead to proprietary CAx chains (Xu, 2006a). The CAM software is needed in order to generate G/M code from the CAD data, and it depends on the different brand of the machine, from different manufacturers. The resulting machine code will differ in terms of cutting tools and other auxiliary components depending on the type of CNC machine. The Post-Processor found in a CAM will serve to produce G/M code, machine tools and data for a CNC machine. The machining process will be realised as a result of CAM and modifications of the program that can be done manually but only in uni-direction and it does not change the original CAD data.

The G-code is essentially based on the tool-path and machine status description implemented by industry as a way to move three-dimensional (3D) geometry between CAD and CAM systems and CNC machine tools, by exchanging manufacturing process information and product data between the systems (Hardwick &Loffredo, 2006).

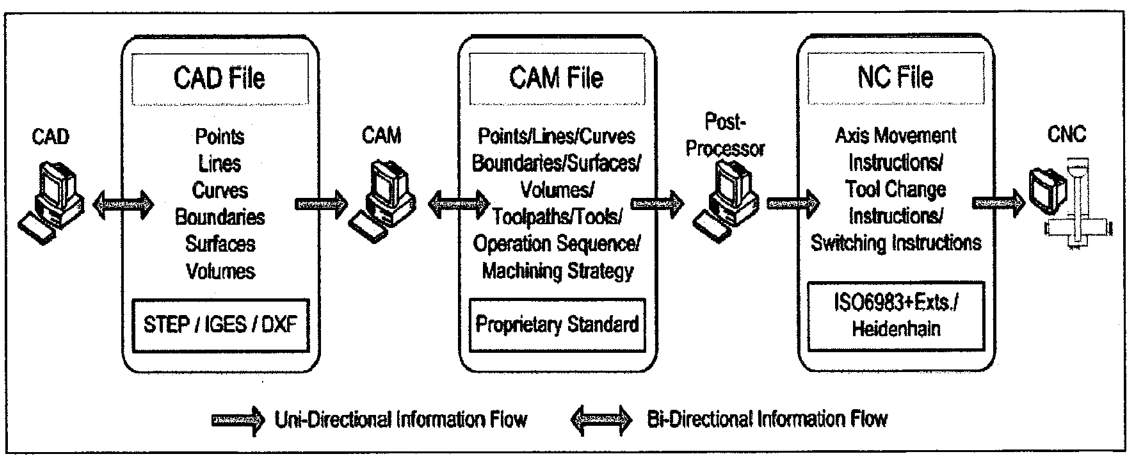

Figure 1.1: The CAx Chain Data Flow (Nassehi *et al.*, 2008)

In the development of NC to CNC, most CNC machines were programmed using the G-code language, which was designed to sequentially document and pass instructions to the controls of single machine tools (Lee, 2006).

1.3 Current CNC language

The G-code is commonly known as a preparatory code that is based on the tool-path or cutter location and on the machine status descriptions. It is defined by just numerical codes such as G, T, M, F, S indicating the movement of a machine and an axis to the controller (Shin,Suh &Stroud, 2007). The data interpretation involved geometrical data and machining strategy for CNC machines. Based on ISO 6983 standard, G-code can be classified the following terms (ISO6983-1, 1982) as in Figure 1.2:

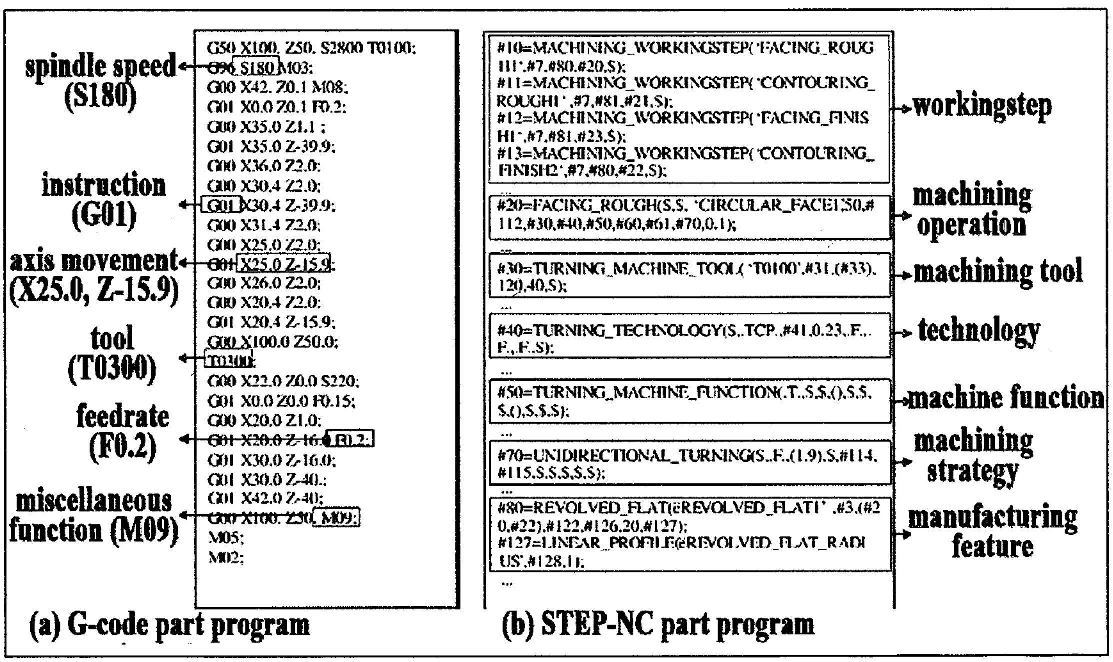

Figure 1.2: Comparison of G-code and STEP-NC formats (Shin *et al.*, 2007)

(i) G00 to G99 codes - Preparatory functions

(ii) M codes - Miscellaneous commands (also called Machine functions)

(iii) X,Y, and Z - Axis motion commands (X,Y and Z direction for 3-axis)

(iv) A, B, and C - Axis motion commands (for absolute or incremental position for X,Y and Z direction for 3-axis)

(v) F (Feed-rate), S (Spindle Speed) commands

(vi) N (Block number) - Identification commands/sequence number

(vii) T - Cutting Tool

It shows a low-level language and only supports one-way information flow from design to manufacturing and the changes in the shop-floor cannot be directly feedback to the designer. Hence, invaluable experiences on the shop-floor can hardly be preserved (Xu &He, 2004). Vendors usually supplement the language with extensions that are not covered in the limited scope of ISO 6983, hence the CNC programs are not exchangeable(Xu *et al.*, 2004). This become necessary to perform so called post-processing in order to convert the neutral part program for each controller (Shin *et al.*, 2007). In term of program execution at shop-floor as noted by Xu (2004) was difficult to change the program in the workshop, means that the bi-directional data flow between CAx chains (CAD/CAM/CNC).

1.4 Research issues

NC or Numerical Control means a control device that machines a target part by activating the servo motor according to commands. The NC combined with computer technology is called computerized NC or CNC (Computer Numerical Control). Now, NC and CNC mean Numerical Controller and there is no difference between them. Therefore, NC machine means a machine tool with a CNC system (Suh, 2008b). Another definition from the Electronics Industries Association 1965 defines the NC system as 'a system in which actions are controlled by the direct insertion of numerical data at some point' (Childs, 1982). Figure 1.2 shows the current CNC system from designing stage up to machine controller.

Before CNC (Computer Numerical Control) control systems had been applied on machines, NC (Numerical Control) was used as a medium for machining control systems of the machining process. NC is the first technology in machines which combines the numerical control using several electronic technologies to run machines. It contains a number, letters and alphabet called programs and the operation of the machine tool. NC programs convert the program into an electrical signal as an input to the motor to operate the machine. The program can be loaded manually. NC has a number of important components, namely i) Tape punch, ii) Tape reader, iii) controller and, iv) NC Machine (Makely, 2005).

Revolutionary changes in the manufacturing industry have forced the development of computer use in analogue and digital control of CNC machines in the machining process. In CNC, the computer is used as a medium for controlling a

CNC machine such as for data input and output. In the contemporary CNC systems, drafting to machine programs for component design is highly automated using computer-aided design (CAD) and computer-aided manufacturing (CAM) programs. The machine programs are generated in a specific format such as text format to be interpreted to extract the commands needed. For an example the AP 203 is converted into AP 224 in the form of manufacturing features, which is used by a feature-based CAPP/CAM system for the manufacturing of the part (Kumar, 2007). It will be used to operate a particular machine through postprocessor (for specific machine controllers), and then loaded into the CNC machines for machining. The machine controller will receive data in specific machine code and interpret it, then the signal will be sent to the motor controller in the form of electrical signals in either pulse or I/O. The generated machine code does not represent a machine features in program; it shows a code or cutter location (CL) according to ISO 6983 in programming language. This is a one of the disadvantages of the current CNC language.

Currently, the CNC tool-path was generated by the CAM tools and the information obtained from the CAD system. However, there are several problems (Xu *et al.*, 2004) in the implementation of ISO 6983 and Xu (2004) has summarised a problem which are underneath.

(i) The language focuses on programming the path of the cutter centre location (CL) with respect to the machine axes, rather than the machining tasks with respect to the part.

(ii) The standard defines the syntax of program statements, but in most cases leaves the semantics ambiguous.

(iii) Vendors usually supplement the language with extensions that are not covered in the limited scope of ISO 6983, hence the CNC programs are not exchangeable.

(iv) It only supports one-way information flow from design to manufacturing, the changes in the shop-floor cannot be directly fed back to the designer. Hence, invaluable experiences on the shop-floor can hardly be preserved.

(v) There is limited control of program execution and it is difficult to change the program in the workshop or shop-floor.

(vi) The CAD data are not used directly on the machine, instead, they have to be processed by a machine-specific post-processor, only to obtain a set of low-level, incomplete data that makes verification and simulation difficult, if not impossible.

(vii) ISO 6983 does not support the spline data, which makes it incapable of controlling five or more axis milling.

The problems that occur on CNC machines are more magnified because of the role CNC machines play in the manufacturing world. ISO 6983 is a low-level language mainly specifying the cutter motion position and feed rate (Xiaoming,Yongzhang &Hongya, 2006) and (Suh, 2008a). Figure 1.3 shows a uni-directional data flow in the current CNC system of CAx chains. Each workstation is making off-line software tools and generating the machine code for various post-processors generated by CAM which are specified by the manufacturer. CNCs of different vendors implement different versions of G-code which lacks any portability and leads to proprietary CAD–CAM–CNC chains (Xu, 2006a, Wang,Xu &Tedford, 2007). That means, each machine controller needs a specific CAM tool in order to generate a different G-Code for CNC machines based on a specific controller.

In term of data editing for NC program at shop-floor level, it is impossible to capture the knowledge from the shop-floor and pass it back through the chain (Newman, 2008). The modification on the shop floor does not rely on CAM software and this makes the CNC system unintelligent or reduces interoperability. According to Newman (2008) the flow of process data is uni-directional and there is no feedback to the CNC system controller. These capabilities of current technology have made the programming task increasingly more difficult and needs more effort on development of the open controller.

In Figure 1.3 also shows the problem highlighted in current standards and represents a problem to be solved. It has become necessary to perform so called post-processing in order to convert the neutral part program for each controller (Shin *et al.*, 2007). Furthermore, with machine tool and process developments, CNC vendors have built their own proprietary versions and specific controllers based on programmable logic controllers (PLCs) and PC hardware and software designs. This is limited to particular machines by controllers or system post-processors (Newman *et al.*, 2008).

Since G-code programs describe only plain machining commands, a richer programming language is required to cater for other automated operations. Such a language needs to be open and rich to handle CNC machines of different vendors (Minhat, 2009). For these reasons it is necessary for CNC system to have a more open system, bi-directional data flow at shop-floor level, data feedback from or to HMI (Human Machine Interface), plug-and-play system and no post-processor in real situations. Minhat (2009) also mentioned the portability and interoperability issues in CAD/CAM tools for supporting CNC manufacturing, that one of the key issues in limiting wider use of these tools (Minhat.M, 2009). Hence, a new standard, that is, STEP (ISO 10303) and STEP-NC (ISO 14649) will offer better data exchange and intelligent. According to Xu (2004) there are some benefits of using STEP-NC; i) Post-processors will be eliminated, ii) STEP-NC is independent from the machine tool vendor, iii) STEP-NC provides a complete and structured data model, and iv) Modification at the shop-floor can be saved and feedback to the design department hence bi-directional information flow from CAD/CAM to NC is achieved.

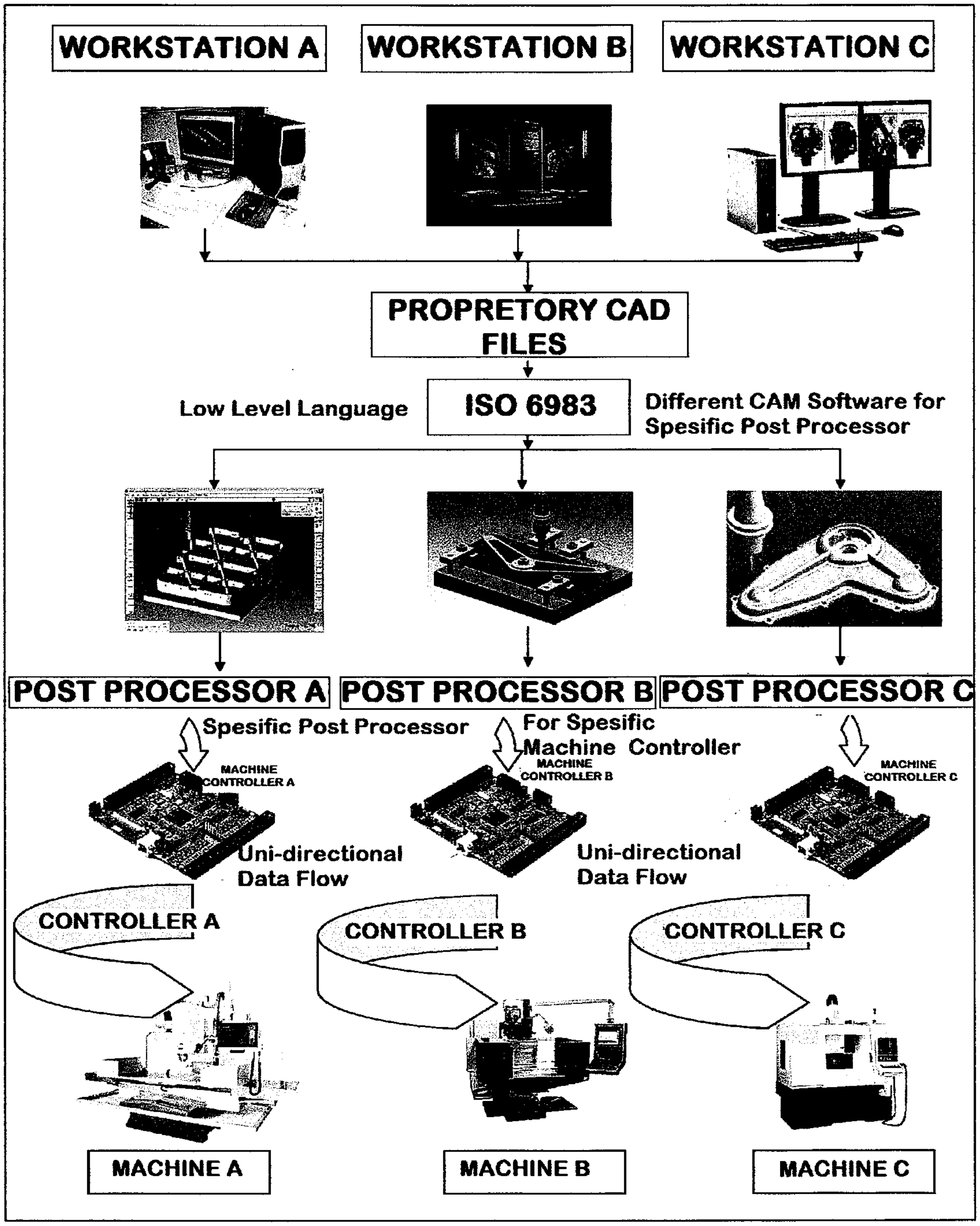

Figure 1.3: The current CAx Chains

1.5 The aim of research

This research aims to meet the requirement of open architecture to develop a CNC system controller based on new ISO standards of ISO 14649 and ISO 10303. The development of this controller involved a new hardware and software design for the 3-axis CNC mill machine that offers interoperability, portability, adaptability.

1.6 Research objectives

The overall goal of the research is to develop a STEP-Compliant manufacturing system of the 3-axis milling machine. To be more specific, the research has three main objectives:

(i) To implement the concept of STEP-NC data model and data exchange for a 3-axis CNC milling machine.

(ii) To develop a controller based on computational and hardware platforms on fundamental technologies of a STEP-NC controller.

(iii) To demonstrate the design framework and implement real machining through two case studies of ISO 14649 (example 1 and example 2) for asymmetric parts on CNC controller machines (open controller).

1.7 Research scope

This research focuses on several aspects:

Related to CAx chain, Standard for the Exchange of Product (STEP) and STEP-compliant Numerical Control (STEP-NC). Currently, the two standard in STEP-NC, which is ARM (ISO 14649) and AIM (ISO 10303-238). The ARM standard focused on ISO 14649-10, IS0 14649-11 and ISO 14649-111 will be employed.

(ii) Interpreted data model using Mastercam, Pro/ENGINEER, ST-Developer V14, Java base and LabVIEW 2011 platform are applied for this research.

(iii) The use of table top Denford 3-Axis milling machine.

(iv) For the machining application, an example 1 and example in ISO 14649-11 are implemented as a case study.

1.8 The benefit of research

STEP/STEP-NC together with LabVIEW provides a global data-exchange format and technology that cover the whole product manufacturing cycle. Through this rich data model, user will be able to generate tool-path data for milling operation. This generated data can be modify and expand according to their requirements for the STEP-NC applications.

(ii) The Manufacturing sector in Malaysia, it will be important contribution in extending STEP and STEP-NC in the development of STEP-NC controller by applying knowledge and application. This research will provide an approach outlining how STEP-NC data models can be interpreted and applied in real CNC machine.

(iii) The use of LabVIEW is a graphical language without writing any code or text for application, especially in CNC machine system. LabVIEW offers virtual instruments for test and measurement, automation, instrument control, data acquisition, and data analysis applications, which can increase efficiency and productivity in various situations.

1.9 The new standard

Now, the CNC multi-workstation configuration process has been changed to support the manufacturing industry, particularly in automotive manufacturing from low-volume to high-volume of volatile production components. This configuration provides for more flexible production of larger quantities involving more complex geometries, from the smallest to the biggest parts, from various combinations of materials that would be difficult to achieve through former standards. In the future, manufacturing should more flexible and intelligent and with the concept having found expression in DA-BA-SA (Design-Anywhere, Build-Anywhere, Support-Anywhere), which has become the catch phrase of e-Manufacturing (Suh *et al.*, 2008a). STEP-NC as a new language has provided solutions to replace the G and M codes that have been used since the 1950s in CNC. To overcome this problem from a variety of standards, two different ISO subcommittees developed new standards known as ISO 10303 (STEP) and ISO 14649 (STEP-NC). ISO TC 184/SC4 subcommittees termed the Application Interpreted Model (AIM) are developing STEP-238 and ISO TC 184/SC1 subcommittees termed the Application Reference Model (ARM) or ISO14649. These two models represent the data model information to program intelligent CNC controllers, but the AIM is fully STEP compliant, whereas the ARM contains the information required to program a CNC machine. These two standards can be are realise in STEP-NC controller development system.

1.10 Thesis structure organization

This thesis is presented in seven chapters and the first chapter is a brief background of the research study including the issues in the CAx machining chains and CNC systems. It also provides the aim of research, objectives, and research scope. Finally, the thesis structure is described for each chapter.

Chapter 2 covers the topics of CNC systems, the STEP-NC data model, STEP-NC controller and LabVIEW. This chapter also describes studies that have been conducted around the world and provides a comprehensive review of the CNC and its development, scientific research related to the STEP-NC and use of LabVIEW as an open architecture for CNC.

Chapter 3 focused on the important issues of the STEP-NC data model, such as STEP, application protocol, STEP-NC controller and LabVIEW. The end of this chapter will describe the research methodology and analyzes the concept of the study.

Chapter 4 deals with the system framework. It first briefly reviews relevant conceptual system frameworks and continues with the preparation of data input for a system that exploits STEP/LabVIEW translator and details the design system in LabVIEW, organisation of systems and execution of software and hardware technologies in LabVIEW.

Chapter 5 presented the issues associated with the development of NC controller integration and testing.

While chapter 6 focused on results and discussions for commissioning of the complete system based on example 1 and 2 in ISO 14649.

Chapter 7 concludes this thesis with the issues that arise and makes recommendations on the nature and direction of future research. It opens the way for further research works and describes novel contributions to the CNC group.

This thesis also contains appendices that summarize the STEP-NC part program, LabVIEW, Wiring Diagrams for hard-wire, G-code, and lists of attended conferences and publications as an outcome of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter explores a research work of the STEP (ISO 10303) and STEP-NC (ISO 14649, ISO 10303 AP-238) compliant, research around the world. The first part of this chapter focuses on the introduction and application of STEP and STEP-NC projects. Followed by research and development in this area based on current standard, open CNC system, process planning and features recognition of the machining operations. Furthermore, this is followed by reviews of STEP-NC-Compliant systems for the manufacturing environment, focused on milling operations. The chapter summarises with discussion of the applications in this particular area.

This chapter consists of a review on four areas of research: i) STEP and STEP-NC, ii) current CNC standard, iii) STEP-compliant CNC systems and, iv) STEP-NC controller.

2.2 Standard for the Exchange of Product Data (STEP)

In today's environment, the data for a product are managed in many different systems, often with little integration and with a great deal of data redundancy. The ISO is addressing the data exchange problem by offering a unified standard to describe all the aspects of a product during its life-cycle. This endeavour led to the establishment of STEP (ISO10303-1, 1994). The unique feature of STEP is that it integrates product data by providing a single product data standard. STEP does this through establishing various Application Protocols (APs) targeted at different application domains, for designing, manufacturing, or maintenance. STEP provides both broadly useful data modelling methods and data models focused on specific industrial uses.

The different parts of common STEP standards are used today as shown in Figure 2.1. AP-203 defines an interface for design (ISO10303-203, 2005), whereas AP-238 defines an interface for manufacturing. AP-224 (part features) and AP-240 is a process planning data model that can be used to assist manufacturing activities (ISO 10303-224, 2000) and (ISO 10303-240, 2005). In the long term, a CAD system will write AP-203 edition 2 or AP-224. Which, in AP-203 edition 2 the information contains tolerance data. A process planning system will read AP-224 and write AP-240. A CAM system will then read AP-240 and write AP-238 executed by a CNC controller system.

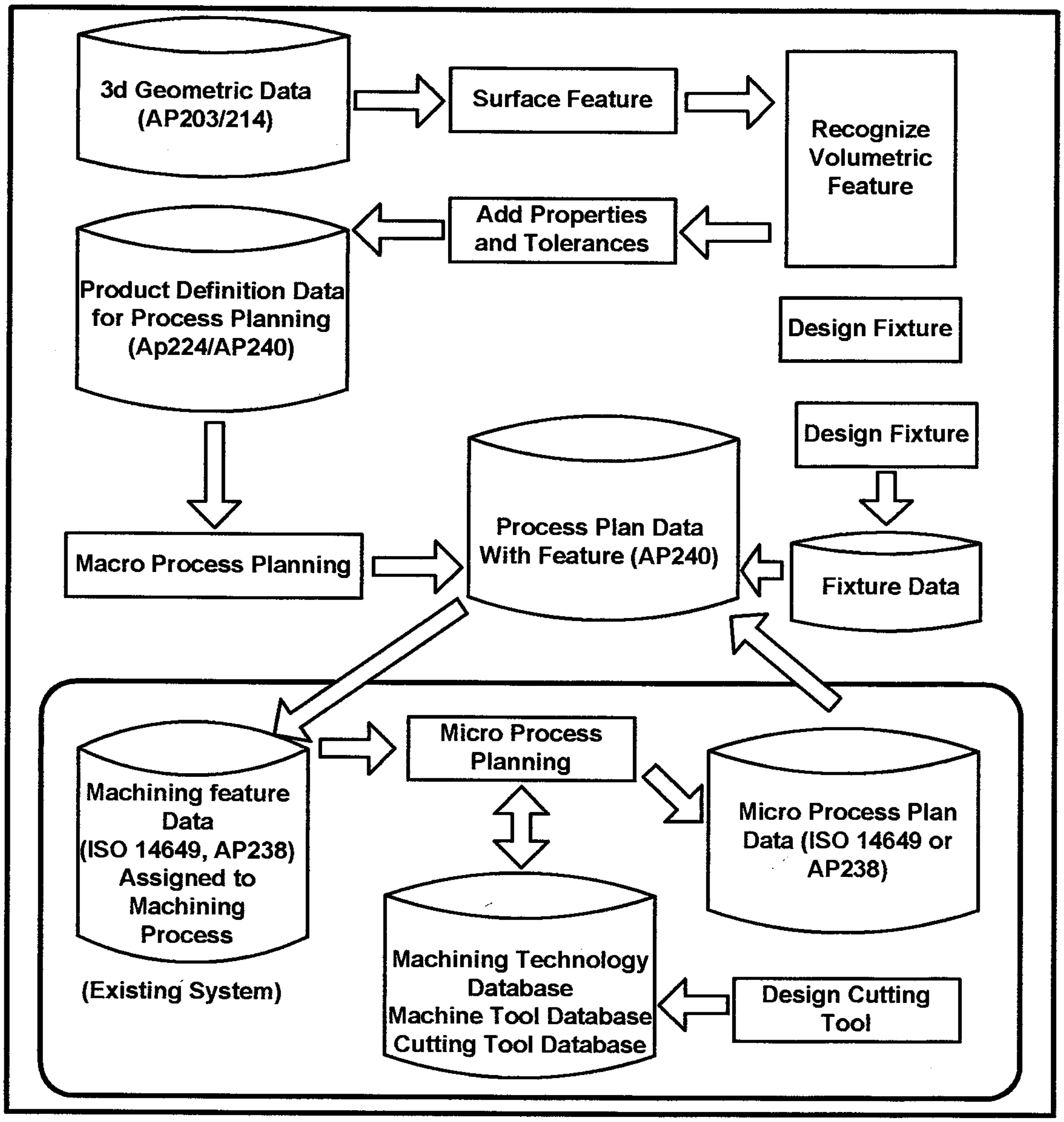

Figure 2.1: Design – Manufacturing data exchange enabled by STEP
(Wang, H., 2009)

2.2.1 History of STEP

The evolution of STEP is divided into two release phases. The first major release of proposed STEP documents occurred in 1988, when a large set of models were assembled into a single Integrated Product Information Model (IPIM). The documents from the IPIM were adopted as initial drafts of ISO standards at a Sub-Committee 4 (SC4) meeting in Tokyo in late 1988. By 1989, STEP had focused on the concept of AP as a sub-set of STEP that would be intended for a specific industrial use and could be implemented and subjected to conformance testing (Ridwan, 2011). The architecture for APs were developed in the following few years.

It was apparent from the beginning of the use of application protocols that developing and using them was difficult. In addition, it frequently occurred that different application protocols would use the same type of information, particularly geometry and topology. This led to the development of methods of modularizing APs. The first version of STEP to become an ISO standard was adopted in 1994 and companies such as GE, Boeing, and General Motors began announcing commitments to using STEP in 1995. In 1994/95 the ISO published the initial release of STEP as International Standards (IS) with ISO 10303 Parts 1, 11, 21, 31, 41, 42, 43, 44, 46, 101, AP-201, and AP-203.

In the second phase, the capabilities of STEP became widely extended, primarily for the design of products in the aerospace, automotive, electrical, electronic, and other industries. This phase ended in the year 2002 with a second major release, including ISO 10303 APs such as AP-202, AP-209, AP-210, AP-212, AP-214, AP-224, AP-225, AP-227, and AP-232. As of June 2008, the SC4 web site (TC184/SC4, 2008) lists 23 application protocols that have become international standards.

2.2.2 Objectives of STEP

The ISO 10303 document states the purpose of the adoption STEP as, "the purpose of ISO 10303 is to specify a form for the unambiguous representation and exchange of computer-interpretable product data throughout the life of a product". STEP permits different implementation methods to be used for storing, accessing, transferring, and archiving product data (ISO10303-1, 1994). At the beginning of STEP, most STEP developers agreed to support and argue for the implementation in order to support the partnership. Although the partnership is not among the objectives set out in the document of basic principles, and the introduction of the document will say that STEP is suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases. In addition, the objectives of the original developers of STEP included the creation of a single international standard covering all aspects of CAD/CAM data exchange and the implementation and acceptance of this standard by industry in lieu of other methods (Fowler, 1995).

2.2.3 Structure of STEP

The STEP standard is separated into several parts, and consists of implementation architectures, conformance testing, resource information models and application protocols. They are also called Description Methods, Information Models, Application Protocols, Implementation Methods and Conformance Tools. Figure 2.2 illustrates the structure of the STEP standard.

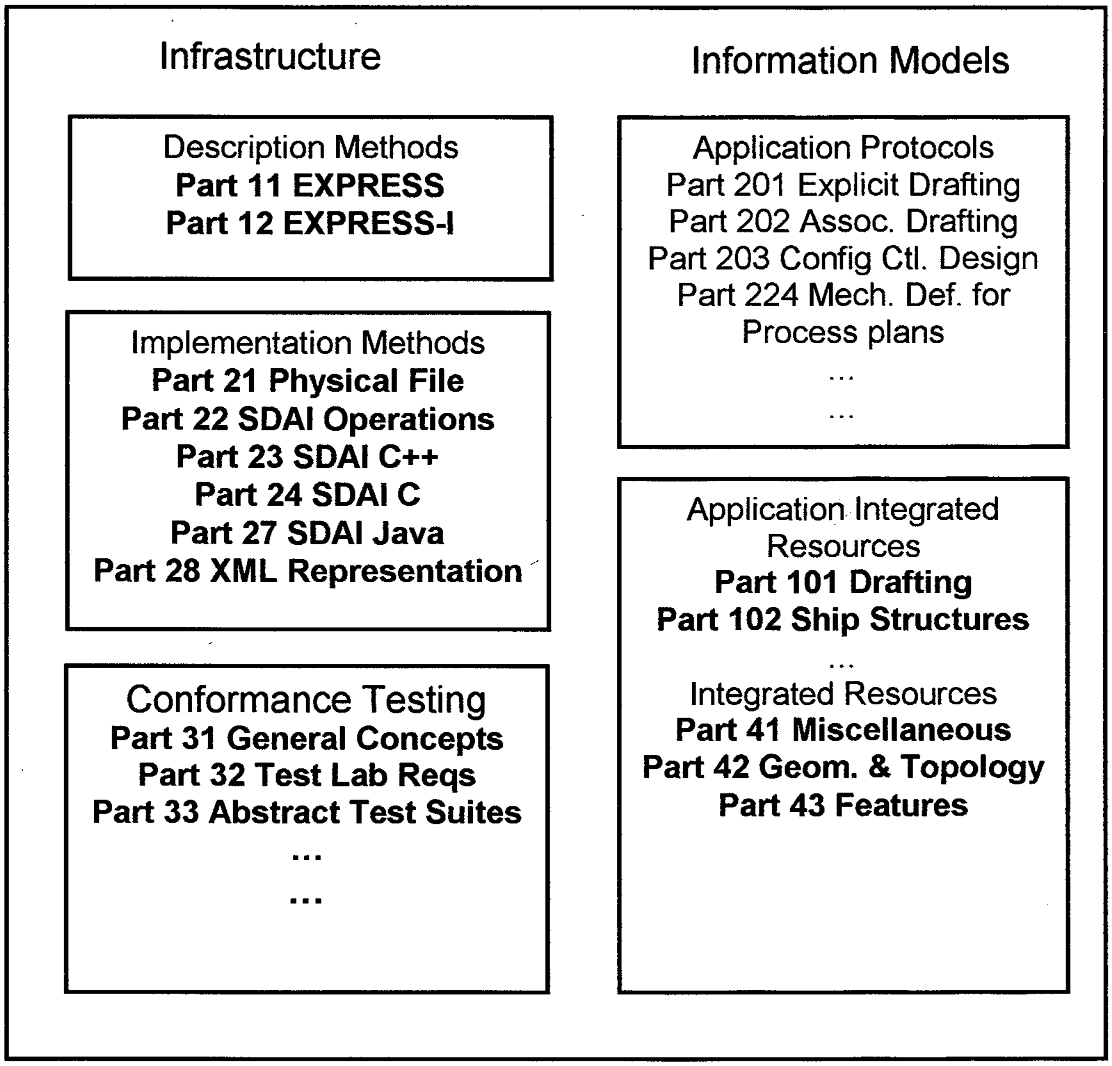

Figure 2.2: Structure of STEP standard (ISO10303-1, 1994)

The Parts of STEP may be grouped by type as follows: the Parts are numbered so that all Parts of the same type fall in the same number range. The range is given below after the type. Not all numbers are used. There are several hundred application modules in STEP or ISO10303 and they can be divided into six series (not including number one). The total number of parts of the other types which are listed in Figure 2.3 is about 120 (Xu &Nee, 2009).

An Application Protocol (AP) can be built and may have a large number of application modules. Using application modules is a more recent architectural approach than using Application Interpreted Constructs (AIC) and they can be replaced.

ISO Number	Descriptions
Overview and fundamental principles - (1)	This is a single document giving an overview of STEP and an exposition of its fundamental principles.
Description methods - (11-19)	These cover the information modelling language EXPRESS and its graphical form, EXPRESS-G.
Implementation methods - (21-29)	These cover methods of representing data that have been modelled in EXPRESS.
Conformance testing methodology and framework – (31-39)	These give the general concepts of conformance testing as well as actual test methods and requirements on testing labs and clients.
Application protocols - (201-299)	These are the Parts intended for implementation in industry. As described in more detail below, each application protocol includes several documents.
Integrated generic resources – (41-59)	These are EXPRESS information models of widely useful specific subject domains, such as geometry, topology, and tolerances.
Integrated application resources – (101-199)	These are EXPRESS information models of more narrowly focused specific subject domains.

Figure 2.3: Six series of parts of in STEP standard and number (1) is excluded (adopted from ISO 10303)

2.2.4 Description Methods

The EXPRESS language is the fundamental Description method of STEP (Loffredo, 1999). EXPRESS is a completely generic modelling language and is used to model data objects. Figure 2.4 shows the function for supporting complex rules. EXPRESS is a language for the definition of the entity-attribute data models. The 3D physical graphical object, for example, 3D CAD drawings, which are drawn into commercial

CAD software are used as an initial definition of standard data models.

The EXPRESS language is completely declarative, implementation independent, and well suited for the definition of standardized data models. EXPRESS, as a data modelling language, it only defines entities and their properties, but does not define methods that might be applied to those entities in an application context. The information of data model in EXPRESS is organized into schemas. It contains the mode definitions and serve as a scoping mechanism for subdividing large information models.

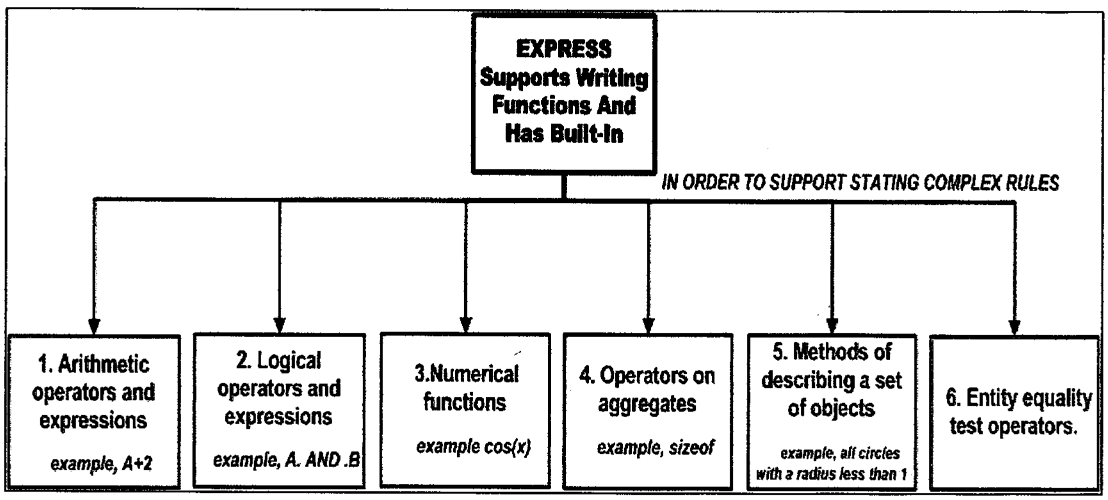

Figure 2.4: The Express functions

The EXPRESS function can also be used for computing values of the acquired properties. Figure 2.5 shows a sample of schema that can be implemented and defines some basic entity for pictures consisting of straight lines, circles, and text.

```
SCHEMA example;

TYPE data =ARRAY [1:3] OF INTEGER;
END_TYPE;

TYPE jobPosition =ENUMERATION OF (manager, clerk, technician, operator, office) ;

END_TYPE;

ENTITY person
        ABSTRACT SUPERTYPE OF (ONE OF (female, male)) ;
        firstName           : STRING ;
        familyName          : STRING ;
        nickName            : OPTIONAL STRING ;
        jointDate           : date ;
        jobPosition         : position ;
DERIVE
        workinghours : INTEGER  := hours (permonth) ;
END_ENTITY

ENTITY female SUBTYPE OF (person) ;
INVERSE
        maleWorkers : SET [0:1] OF male FOR femaleworkers;
END_ENTITY;

ENTITY male SUBTYPE OF (person) ;
        femaleWorkers : OPTIONAL female ;
END_ENTITY;

FUNCTION hours (past : date) : INTEGER;
        (* This function calculates the number of hours between the past date and the current date *)
END_FUNCTION;

END_SCHEMA;
```

Figure 2.5: An example of EXPRESS entity

In the other part of the EXPRESS language, there is another description method called EXPRESS-G as shown in Figure 2.6 and a notation (from A to G) also describes in detail.

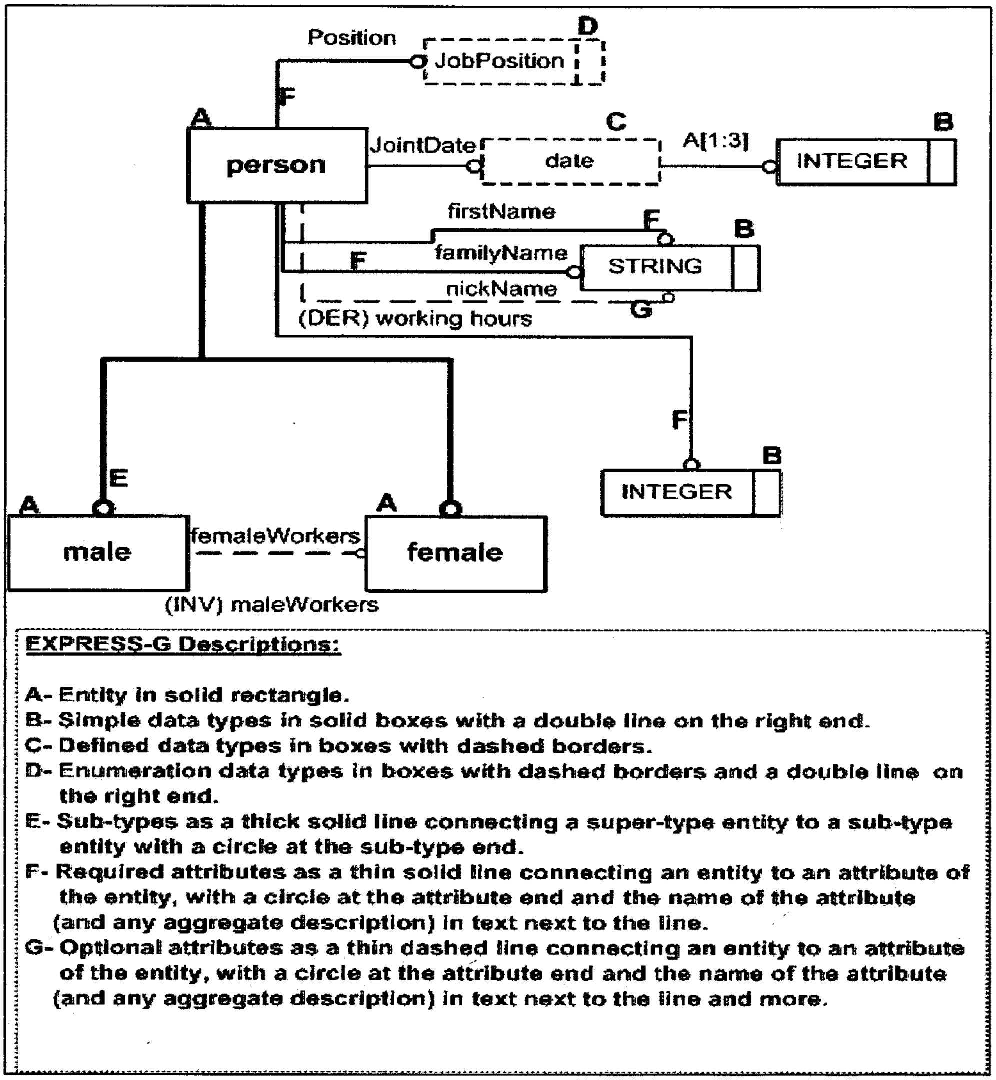

Figure 2.6: The Express-G definitions (Kramer &Xu, 2009b)

2.2.5 STEP Implementation Methods

The EXPRESS language does not specify any implementation method. Therefore, an additional implementation method can be used to define and build a model, for example, ISO 10303 AP-238. There are a number of technology implementations in STEP as shown in Figure 2.7.

PART	STANDARD	DESCRIPTION
Part 21	[ISO 10303-21, 2002]	A product model specific file format called physical file.
Bindings Set, developed for C, C++ and Java	[ISO 10303-22, 1998, ISO 10303-23, 2000, ISO 10303-24, 2001, ISO/TS 10303-27, 2000]	A variety of programming language bindings that allow an application programmer to open a data set and access values in its entity instances.
Part 28 Edition 1	[ISO 10303-28 (E1),2002]	The three methods for mapping the EXPRESS defined data into eXtensible Markup Language (XML).
Part 28 Edition 2	[ISO 10303-28 (E2), 2004].	The XML Schema-governed representation of EXPRESS.

Figure 2.7: The description of ISO 10303, adopted from (ISO14649-1, 2003)

2.2.6 ISO 10303 Part 21 (Physical File)

The first implementation method was STEP Part 21, and it defines the basic rules of storing EXPRESS/STEP data in a character-based physical file. The main purpose of this physical file is to provide a method so that it is possible to write EXPRESS or STEP entities and transmit those entities using normal networking and communication protocols for an example; File Transfer Protocol (FTP), e-mail and Hyper Text Transfer Protocol (HTTP). There is no EXPRESS schema included in Part 21. It only defines the relationships between entities that are defined by external EXPRESS schemas. Figure 2.8 shows the example of a Part 21 file and its descriptions. Figure 2.9 describe the entity and the symbols containing in physical file.

2.3 Application Protocols

An application protocol is focused on a particular application domain. There were three parts of AP when the concept was first introduced in STEP; i) Application Activity Model (AAM), ii) Application Reference Model (ARM), and iii)

Application Interpreted Model (AIM). These three APs have different rules and certain advantages.

PART 21 PHYSICAL FILE

Entity/symbols	**Description**
HEADER; FILE_DESCRIPTION(/* description */ ('ISO 14649-11 EXAMPLE 1, SOMEWHAT MODIFIED', 'ISO14649 EQUIVALENT OF test238.stp', 'SIMPLE PROGRAM WITH 5 WORKINGSTEPS', '1 PLANAR_FACE, 1 POCKET, AND 1 ROUND_HOLE'),	- Comments in the header indicate what each header item means.
#23=BOTTOM_AND_SIDE_FINISH_MILLING ($,$,'FINISH POCKET1',15.000,$,#39,#52, #41,$,$,$,#53,2.000,10.000,$,$);	
#23=	- Each entity instance in a Part 21 file begins with a unique Entity ID - Entity ID is a hash symbol "#" - followed by an integer and has to be unique within the data exchange file. - The Entity ID is followed by an equal symbol ("=")
BOTTOM_AND_SIDE_FINISH_MILLING	- The name of the entity that defines the instance. - The names are always capitalized because EXPRESS is case Insensitive.
(15.000,$,#39,#52,)	- The name of the instance is then followed by the values of the attributes listed between parentheses and separated by commas.
";"-	- terminates with a semicolon ";"
("$")	- The special token is used to represent an object whose value is not omitted.
("*")	- The special token is similar to ("$") except that the value can be derived from other values according to rules given in the EXPRESS schema.

Figure 2.8: The Application Protocol Part 21 adopted from (ISO10301-21, 2002)

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