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A Novel Methodology for Cross-Technology Interoperability in CNC Machining

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ABSTRACT

In CNC part programmes, the lack of standardisation for representing part geometry and semantics of manufacturing operations leads to the necessity for existence of a unique part programme for each machine. Generating multiple programmes for producing the same part is not a value adding activity and is very time consuming. This wasteful activity can be eliminated if users are given the ability to write an NC program for a specific machine and robustly convert the program to syntax suitable for another CNC machine with a different structure. This, cross-technology interoperability, would enable for parts manufactured on old CNC machines using legacy code to be manufactured on new CNC machines by automatically converting the programmes. Every NC programme is written based on various categories of information such as: cutting tool specifications, process planning knowledge and machine tool information. This paper presents an approach for cross-technology interoperability by refining high-level process information (i.e. geometric features on the part and embedded manufacturing resource data) from NC programmes. These refined items of information stored in compliance with the ISO14649 (STEP-NC) standard may then be combined with new manufacturing resource information to generate NC code in a format that is compatible with machines based on different technologies. The authors provide a framework for this process of identification, semantic interpretation and re-integration of information. The focus of this paper is on asymmetric rotational components as the initial application area. To demonstrate the proposed cross-technology interoperability approach, a C-axis CNC turn-mill machine and a 4 axis CNC machining centre have been used with a simple test component.

KEYWORDS

CNC; interoperability; STEP-NC; Turn-Mill machining.

1. INTRODUCTION

Mass production has been the paradigm of choice for production since the 1800s, and ever since, the most prominent configuration of manufacturing system has been the transfer machine lines. Such lines enabled mass production at high efficiency and low cost. In the evolution towards more modern systems, flexible manufacturing became prevalent between the 1970s and 1980s to enable low batch production of a wide range of parts. In order to realise flexible manufacturing, Computer Numerical Controlled (CNC) machines became a critical manufacturing resource due to their capability for being reprogrammed to produce different parts [1]. Consequently, CNC machines with multi axes and multi-process workstation configurations were developed to support high-speed manufacturing of precision parts such as complex aerospace components [2]. The advances in computing allowed more complex calculations to be carried out on the machines and as such newer generations of controllers with significantly higher capabilities were developed. Utilising these capabilities required complex programmes and therefore Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) systems were used to generate the CNC programmes [2, 3].

Today, many CNC machines with different controllers and multiple capabilities are employed in a range of industries to meet customer demands. The rapid advances have caused hardware and software incompatibilities

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amongst the various computer based systems in manufacturing enterprises. With the growing global need for agile manufacturing, these systems need to interoperate with each other to enable flexibility within the enterprise to allow it to maintain market share. This paper provides an overall review of the research in CNC manufacturing data exchange standards followed by a brief review of interoperability in CNC manufacturing.

A theoretical framework for transferring information between various types of CNC machines through the use of high-level process information refinement is then presented as an approach to alleviate some of the identified problems resulting from the lack of interoperability. Finally, a system based on the process of identification, semantic interpretation and re-integration of information for interoperability between different types of CNC machines is specified. The technological focus of the paper is on asymmetric rotational components which can be machined with both technologies; the interoperability have thus been presented through a demonstration of the approach using a CNC C-axis turn-mill machine and a 4 axis vertical machining centre. It is noteworthy that the focus of this paper is on the semantic feasibility of cross-technology interoperability and thus two fundamental assumptions have been made: both the source machine and the destination machine are physically capable of producing the part for which the programme is translated within the required tolerances and surface quality specifications; and if several alternative operations are available in translation the one with the higher accuracy is chosen. The assessment of the machine tool capability and the choice of most efficient operations are complex manufacturing engineering problems and topics of research in process planning and are considered to be outside the scope of this paper.

2. A REVIEW OF DATA EXCHANGE STANDARDS AND INTEROPERABILITY IN CNC MANUFACTURING

CNC machines were developed in the 1970s with the introduction of minicomputers and CAD drawing software to support the development of on-machine programs to enable machining of different parts [4]. These CNC machines can be classified by a range of different categories including machining process, number of axes, spindle arrangement, number of spindles, and kinematics configuration [5, 6]. The development of various CAD/CAPP/CAM/CNC systems in the Cax process chain created a requirement for data exchange standards to enable data integration between machines and systems from different vendors. The Initial Graphics Exchange Specification (IGES) was among the first standards for exchanging CAD information; this standard was developed in 1979 by a group of CAD users and vendors [7]. This standard was not capable of exchanging data about free-form surfaces and this limitation was a disadvantage. Verband der Automobilindustrie - Flächenschnittstelle (VDA-FS) was developed in 1999 by the VDA German company to focus on free-form surface data transformation [8]. Various shortcomings of IGES and VDA-FS resulted in the international drive to develop a better standard for data exchange; the result was the ISO standard for exchange of product data (STEP).

STEP is an international product data standard (ISO 10303) to provide a computer-interpretable definition of the physical and functional characteristics of a product throughout its life cycle. STEP has been developed through three release phases: the first phase started in 1984 with the initial development of the standard as the successor of IGES and VDA-FS. In 1994/95 ISO published the initial release of STEP as an international standard. In this stage parts 1, 11, 21, 31, 42, 43, 44, 46, 101, Application Protocols (AP) 201 and AP 203 were introduced [9]. The second phase started in 2002 with more capability in different industries such as aerospace, automotive, electrical and electronics with parts such as AP 202, AP 209 and AP 214. etc being introduced. The third phase solved the problem emerging from the large data structures of first and second phases with the introduction of the STEP modular architecture. Currently a new phase of development has started where the new AP 242 is being developed based on geometric dimensioning and tolerancing in combination with STEP AP 203 and 214.

STEP significantly improved interoperability between CAD systems. This highlighted the necessity for the development of a similar standard for exchange of information between CNC machines as well as CAM systems. Consequently, in 1999 an international project started to specify a new standard entitled STEP-NC to bring the benefits of STEP to CAM and CNC [10]. The first models for CNC milling and turning were presented in 2005 with draft models for EDM and contour cutting developed in parallel [11, 12]. STEP-NC is mainly focused on exchange of data with the machine tool controller and is formalised as ISO14649 and ISO10303-AP238 [8, 13].

The CNC interoperability research started with developments in manufacturing technology and processes by Suh and Sheon in terms of a proposing a framework for intelligent CNC systems [15], this framework was followed by Hardwick as the first outlook for implementation of STEP-NC [16]. Consequently, a five-axis milling machine that accepted STEP-NC input was designed by Lee and Bang [17] and another prototype was proposed by Newman et al with a STEP-Compliant CAD/CAM system using ISO 14649 [18]. These systems were tested by Feeney and Frechette for numerical controllers [19]. Xu et al then focused on STEP-Compliant process planning for

manufacturing [20]. Kumar et al introduced an intelligent and self-learning framework that could get feedback from measurement errors within the STEP-NC framework to close the manufacturing loop [21]. In 2007, Amaitik and Kilic created a STEP compliant feature based process planning system entitled ST-FeatCAPP that supported prismatic parts [22]. This was followed by the research carried out by Liu et al on prismatic parts to realise a complex feature recognition process that produces the corresponding machining operations [23].

In the first decade of the 21st century, researchers started to investigate and design a universal platform for supporting CNC manufacturing by using software and hardware standards to support a variety of CAx applications by enabling them to exchange standardised information through a communication system without knowing the particulars of the destination application [24]. This was followed by designing frameworks for interoperability in CNC turning machines such as the G-Code free StepTurn system, which is independent of CAD/CAM, and reads geometry data from STEP AP-203 part 21 and displays the part geometry and performs normal process planning tasks such as feature recognition to generate a STEP-NC file. Other STEP-NC based systems from this era include: TurnStep which is the earliest systems to support the STEP-NC XML schema (which is suitable for e-manufacturing); G2STEP which generates a STEP-NC part program from a G-Code program with additional information related to real machining that is easily compiled by skilled operators; SCSTO which proposes a STEP compliant CAD/CAPP/CAM System for the manufacture of rotational parts on CNC turning centres; and PPS which demonstrated the feasibility of interoperable CNC manufacturing using of STEP standards [25, 26]. These systems managed to demonstrate the applicability of STEP-NC for realising interoperability between machines with similar structures and technologies albeit with different controllers. The authors have found no references to research on realising interoperability between machines with completely dissimilar architectures and technologies; a gap which this paper addresses.

3. A FRAMEWORK FOR CNC MANUFACTURING INTEROPERABILITY FOR ASYMMETRIC COMPONENTS

To fully enable interoperability, it is necessary to have a system, which is not dependent on a machining process. Such a system, would be able to generate NC codes for different CNC machines based on a holistic view of manufacturing information not just the machine process. In the current CAx machining chain, in order to machine a part, a CAD system is used to generate a file containing geometry, dimensions and tolerances information. This information - often contained in a STEP file - is imported into a CAM system where machining information is added. Manufacturing process selection forms the first step for inserting machining information; the operator chooses the process, e.g. milling or turning and then the information for that operation is linked to the geometrical features. Finally a post processor is used by the CAM system to generate CNC machine codes. This system is shown in figure 1.

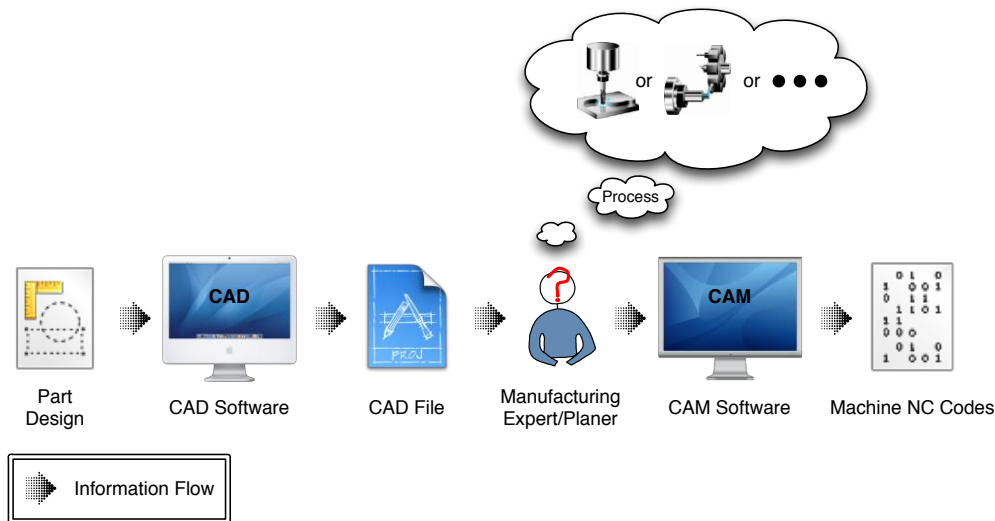


Figure 1: Current flow of information in the CNC machining chain

The aim of this research is to find an efficient way of realising interoperability between CNC machine tools with different technologies such as milling, turning and mill-turn that can produce the same part to the required specifications. A system entitled Cross-Technology CNC Interoperability System (XTSys) based on the use of resource independent data for realising this aim is proposed in figure 2 where NC code from one machine is imported to an adapter, and new NC codes for a different type of machine are automatically generated.

XTSys has the capability to recognize tools, operations and features in the NC code and store this information in a standardised database. Three main elements form the system: the manufacturing dictionary that supports the comprehension of the semantics associated with the above items of information by providing the syntax information; the adapter that carries out the information transformation function; and the manufacturing database which stores the standardised manufacturing process data derived from the input.

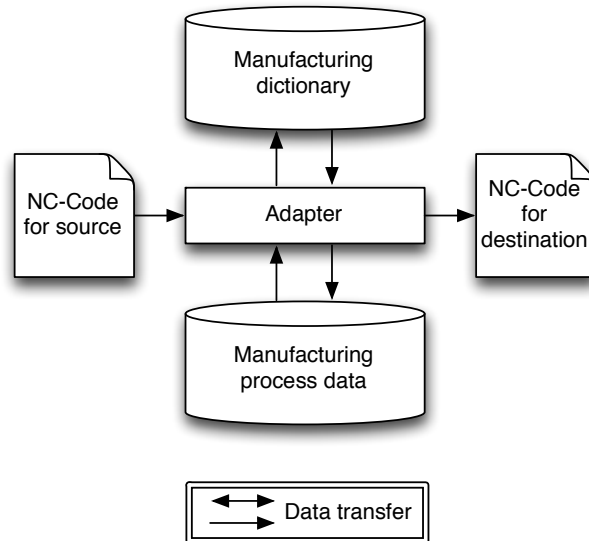


Figure 2: Cross-Technology CNC interoperability system (XTSys) overview

Figure 3 shows the structural overview of XTSys. The machining programme is read by the system either as G&M codes or STEP-NC data structures by the reader component of the XTSys adapter. The information is then translated into standardised syntax and passed on to the analyser where it is refined to high level manufacturing process data. When required, the data is passed on to the writer component in the XTSys adapter to be fused with the resource information for the destination machine obtained from the manufacturing dictionary.

3.1 STRUCTURAL OVERVIEW OF XTSYS

The manufacturing dictionary is a highly flexible database that contains five types of information: machine reference information including the kinematic structure of the machine and its supporting data; cutting tool reference information including assemblies; operation meta-data that describes various manufacturing operations and their effects; feature meta-data that provide a template for all manufacturing features and their associated operations; and CNC G&M code meta-data that provides the lexicon for various syntaxes of machine tool programming languages.

The XTSys adapter is comprised of three components. The first is a reader that parses through STEP-NC or G&M code from source and utilises the manufacturing dictionary to identify items of information pertaining to the various aspects of the process such as workpiece, manufacturing features, machining operations, working steps, strategies, etc. and store this manufacturing process data in the XTSys manufacturing database. As the manufacturing dictionary is extensible, with the addition of the necessary meta-data it is possible to adapt XTSys to read machine code written in any language (e.g. G&M Codes, STEP-NC, Heidenhain language, etc.) for input and output.

The second component of the XTSys adapter is the semantic analyser that interprets the manufacturing process data and finds semantically equivalent constructs for generating new STEP-NC codes that are technologically compatible with the destination machine. These are stored in the XTSys manufacturing database and linked to the original data items. The third XTSys adapter component, the writer, combines this generated information with machine information from the manufacturing dictionary to generate appropriate NC code for destination machine.

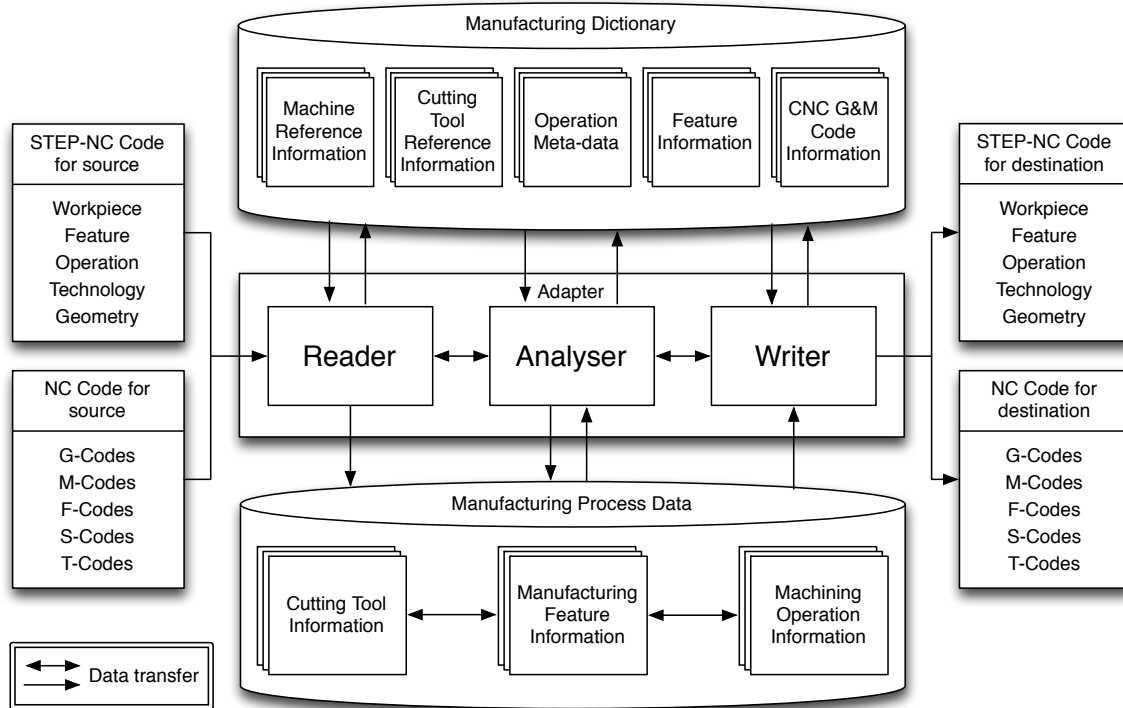


Figure 3: The structure of the Cross-Technology CNC interoperability system (XTSys)

The manufacturing process database contains the high level manufacturing process data as refined by the analyser as well as basic manufacturing data such as the cutting tool selection within a CNC machining programme that is read by XTSys. The high level information is comprised of manufacturing feature information with the details about the manufacturing operations linked to each feature.

3.2 A FUNCTIONAL OVERVIEW OF THE XTSYS ADAPTER

The XTSys reader parses the input code line-by-line and uses additional information such as cutting tool geometry and selection and machine tool information to refine high level manufacturing process data. To generate output, XTSys writer uses the high level manufacturing process data in conjunction with manufacturing information about the destination machine and creates low-level instructions that can drive the destination machine to produce the desired part.

Figure 4 illustrates an overview of the information flow within the reader and writer components of the XTSys adapter. As shown in figure 4a, the XTSys reader, considers the first line of source NC code and checks whether it is a movement instruction or an auxiliary instruction; in the case of an auxiliary instruction, the reader will process the machine code and in case of a movement instruction, it will assess the interpolation path. In a linear interpolation, the reader uses the last tool changing code parsed and determines the cutting tool specifics such as length, diameter and type of tool from the information in the manufacturing dictionary. Having access to the cutting tool information, the reader analyses the type of tool that is being used (milling, turning, drilling), and then read the next line in the NC code to determine the manufacturing operation and store it in the manufacturing process database. With access to cutting tool information, operations and the configuration of the axes, the manufacturing feature can be determined and stored in the manufacturing process database as well.

The same overall methodology is used for the XTSys writer in reverse; the writer reads the first operation and its corresponding feature from the manufacturing process database and generates the necessary NC code for performing the operation on the destination machine based on the standard information in the manufacturing dictionary. The XTSys writer will then write the NC code for the operation to the output file and move to the next operation.

After gathering the information from the source code by the reader, the XTSys analyser's role is to convert machining operation and machining features information from source to destination based on the availability of tools and operations in the destination machine. To realise such a system, the analyser should categorise the machining operations and features to different sublevels and then start to find the operations and features from the manufacturing process database that are suitable for the destination CNC machine based on the machine information. These transformations should only be made if they are semantically equivalent. The analyser uses a set of pre-defined rules to assess the equivalence of various operations in each case. Figure 5 shows a simple instance of these rule sets; the rule sets are entitled "semantic transformation templates" to denote the fact that replacement of operations do not modify the results achieved by running the programme and, in essence, the operations carried out on their respective machines yield the same result. In the shown semantic transformation template, the **facing** operation in the turning context is the equivalent of **plane_milling** in the milling context and similarly the **bottom_and_side_milling** or **side_milling** operations are the equivalent of **contouring** in the turning context.

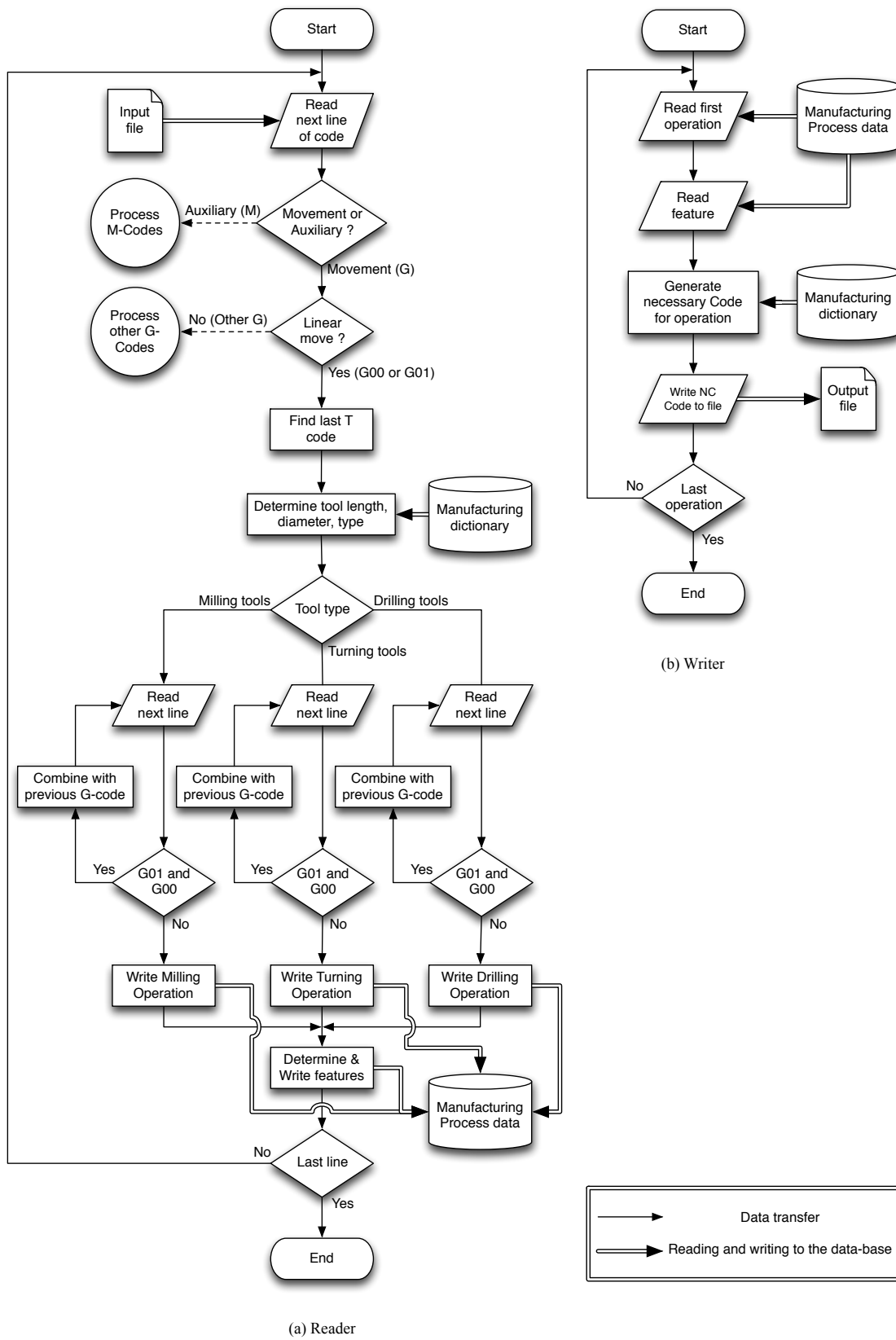


Figure 4 : (a) Reader and (b) Writer process flowchart

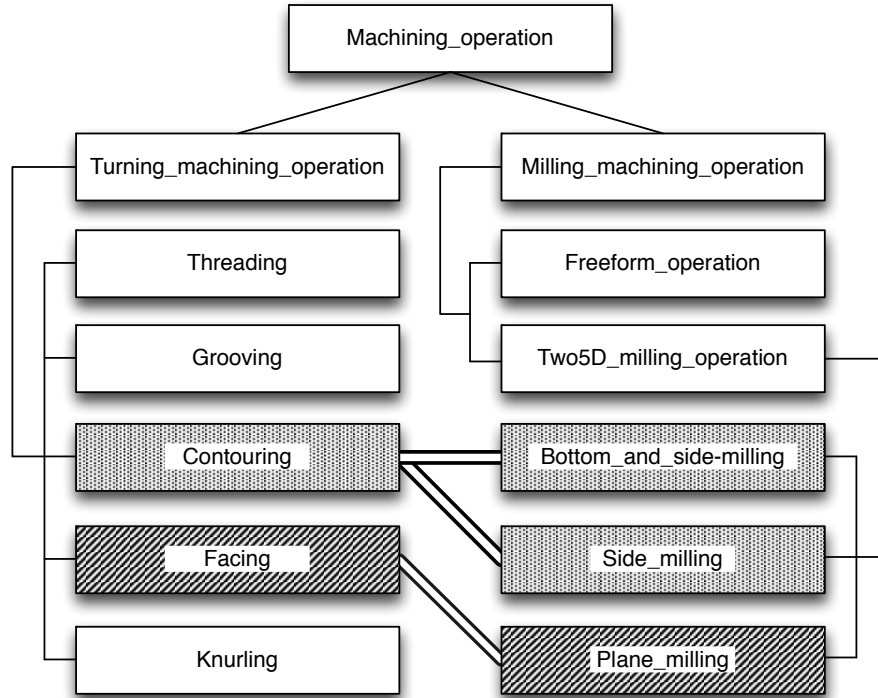


Figure 5 : A simple semantic transformation template in the XTSys analyser

After the semantic transformation, another rule set in the XTSys analyser is activated to determine the choice of operations based on availability of cutting tools and the method of setup the workpiece in the machine. Figure 6 illustrates an excerpt of this rule set in the XTSys analyser.

As illustrated in figure 6, the XTSys analyser reads the destination machine information from the manufacturing dictionary and then by considering each manufacturing feature assesses the best manufacturing option based on the the capability of the destination machine for performing various operations. For example, for manufacturing a pocket on a turning centre, if the destination machine has milling capability in the appropriate axes, the XTSys analyser will simply use the milling operation whereas if the destination machine does not have this capability, then the analyser will check the pocket to assess whether it is machineable using an alternative approach. In the given scenario, there is no viable machining method for an open pocket but for a closed pocket the XTSys analyser will check to assess if the pocket is located at the centre of the workpiece. Should the pocket have a circular boundary and be located at the centre of the workpiece, the analyser will choose the appropriate turning operation to manufacture pocket. It is also conceivable that a non-centric pocket would be manufacturing using special non-concentric tooling and therefore the availability of such resources is also checked in the XTSys analyser.

With determination of all appropriate semantic transformation templates and the rule sets for all features as defined within the STEP-NC standard, it should be possible to convert programmes among capable machines for which the manufacturing dictionary has been established. The various sequences of features and the numerous possible logical relationship between the features could, however, have an implication for the feasibility of the destination programme. Enumerating such relationships and their implications will be considered in future research.

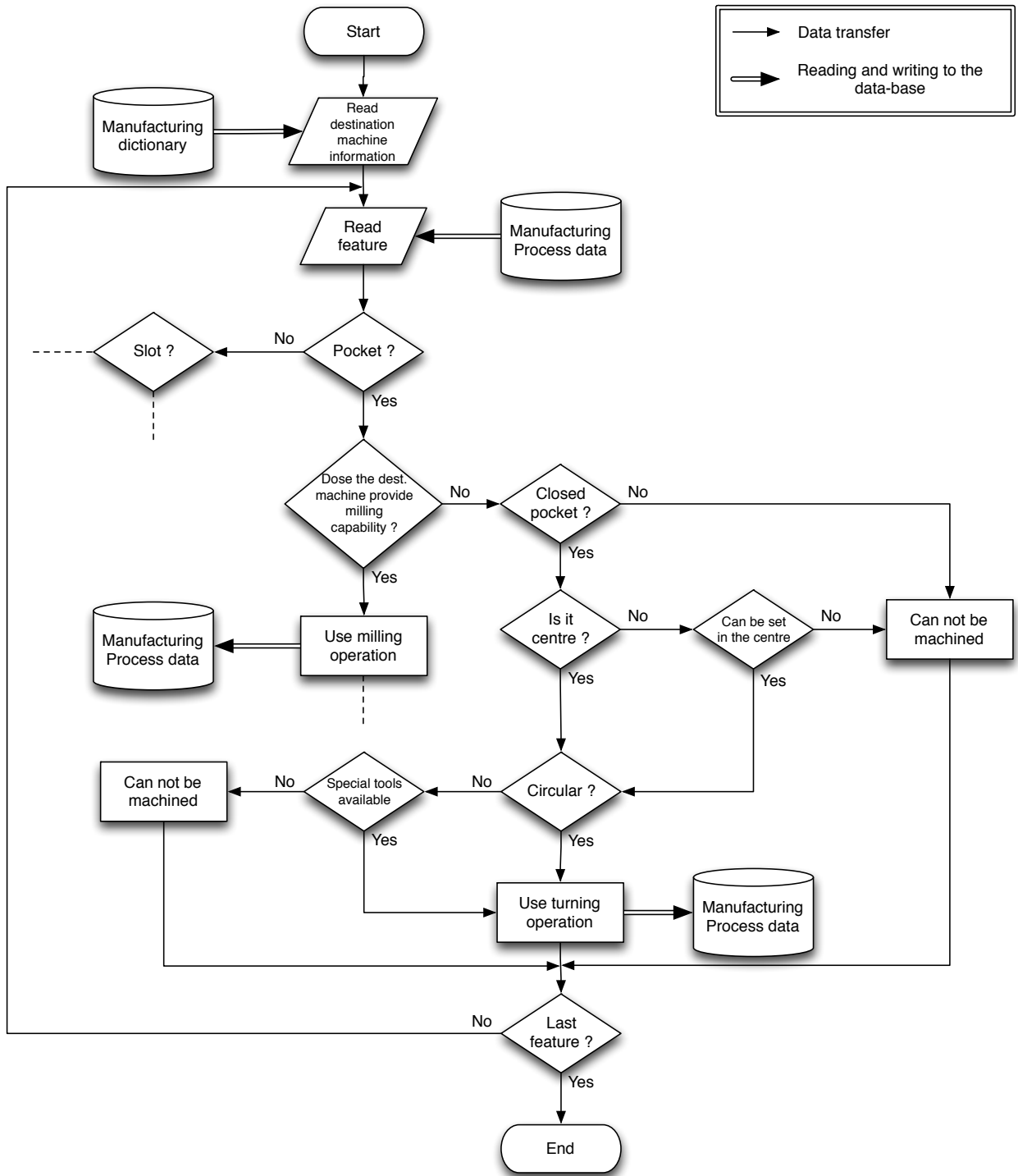
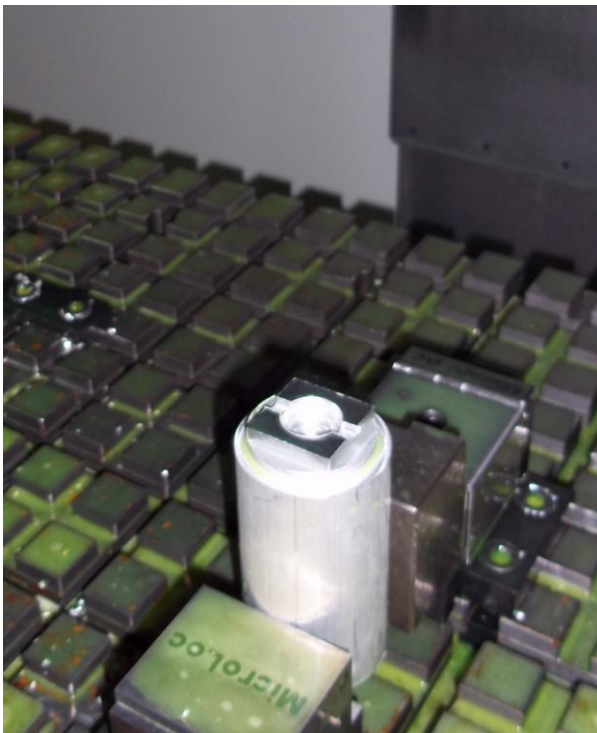


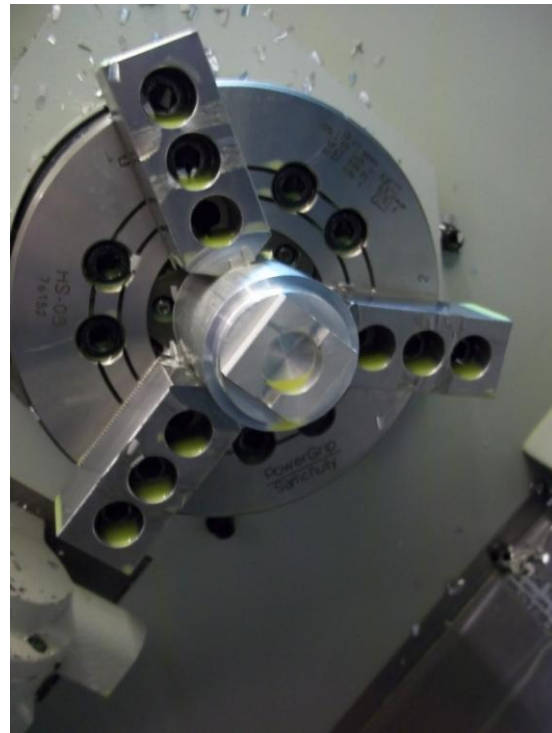
Figure 6 : An excerpt of operation determination rule set in the XTSys Analyser.

4. CASE STUDY TESTING

In order to verify the proposed methodology, a prototype implementation of XTSys has been tested by attempting to convert the NC programme for a part with milling and turning features from a 4-axis vertical CNC machining centre to one usable on a CNC turn-mill machine. To test the NC programmes, a Dugard Eagle 850 4-axis CNC milling machine with a FANUC21M controller and a Hyundai-Kia SKT 15 LM turn/mill CNC machine with a FANUC18T controller were chosen. Both controllers have the capability to carry out milling and turning type manufacturing operations. The chosen part has five manufacturing features and as shown in figure 7 can be manufactured on both machines.



(a) Case study part machined on a vertical milling centre



(b) Case study part machined on a turn-mill machine

Figure 7 : Case study Part with five features

The component is formed by machining a planar face; a profile; four steps; a closed pocket; and a slot on the source machine (the Dugard milling machine). These features all are machined with milling operations. In the generated programme for the destination machine (the Hyundai Kia), the analyser chose turning for the facing the part together with contouring to manufacture the profile. The four steps, the slot and the circular pocket were formed using milling operations.

The results from XTSys are shown in figure 8 where the transformation of cutting tools, operations and features from the source machine to the destination machine is shown.

5. CONCLUSIONS

This paper reviewed interoperability in CNC manufacturing and the appropriate NC standards used in interoperability to identify cross technology interoperability as an important research gap. The major contribution of the paper is a new approach for the design and verification of a framework for cross technology interoperability in CNC machining. This framework entitled XTSys should enable a part to be manufactured without dependency on a specific process or resources.


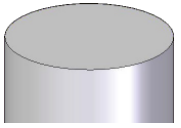
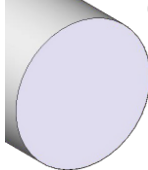



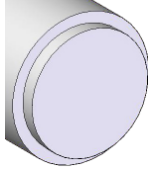


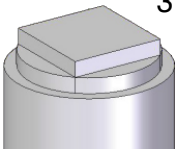
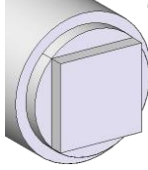


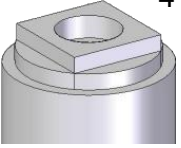
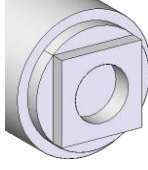


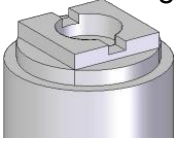
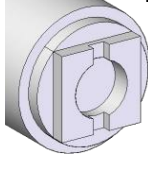

The XTSys approach is based on using a semantic adapter for refining and transforming high level manufacturing data. The internal structure of the data is compliant with the STEP-NC standard as the standard provides the necessary entities to capture manufacturing process information in a resource independent manner.

The feasibility of the proposed approach has been tested by transforming the milling programme used to manufacturing a cylindrical part to a turn mill programme to manufacture the same component and executing both programmes to compare the results. The future work will focus on extending the intelligence that is embedded in the decisions made in the XTSys analyser by identifying relevant process planning sequences and feature interactions.


6. ACKNOWLEDGMENTS

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ADAPTER

Source (Milling machine)			Destination (Turn-mill machine)			
Tools	Features	Operations		Operations	Features	Tools
	Planar_Face	 1	▶	 6	Revolved_Flat	
	Profile_Feature	 2	▶	 7	General_Revolution	
	4x Step	 3	▶	 8	4x Step	
	Closed_Pocket	 4	▶	 9	Closed_Pocket	
	Slot	 5	▶	 10	Slot	

1 :
Plane_rough_milling & Plane_finish_milling
2, 3, 4, 5 :
Bottom_and_side_rough_milling
Bottom_and_side_finish_milling

 Convertor

1 :
Facing_rough & Facing_finish
2 :
Contouring_rough & Contouring_finish
3, 4, 5 :
Bottom_and_side_rough_milling
Bottom_and_side_finish_milling

Figure 8: Feature and operation in the XTSys analyser for the case study

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