CNC Machine Tool Information Reusability within Virtual Machining Systems

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Abstract

Virtual Machining (VM) allows simulation of the machining process by realistically representing kinematic, static and dynamic behaviour of the intended machine tools. Using this method, manufacturing related issues can be brought to light and corrected before the product is physically manufactured. Machining systems utilised in the manufacturing processes are represented in the VM environment and there is a plethora of commercial VM software used in the industry. Each software system has a different focus and approach towards virtual machining; more than one system may be needed to complete machining verification. Thus, the significant increase in the use of virtual machining systems in industry has increased the need for information reusability. Substantial time and money has been put into the research of virtual machining systems. However, very little of this research has been deployed within industrial best practice and its acceptance by the end user remains unclear. This paper reviews current research trends in the domain of VM and also discusses how much of this research has been taken on board by software venders in order to facilitate machine tool information reusability. The authors present a use cases which utilises the novel concept of Machining Capability Profile (MCP) and the emerging STEP-NC compliant process planning framework for resource allocation. The use cases clearly demonstrate the benefits of using a neutral file format for representing MCPs, as opposed to remodelling and or reconfiguring of this information multiple times for different scenarios. The paper has shown through the use cases that MCPs are critical for representing recourse information from a kinematic, static and dynamic perspective that commercial software vendors can subsequently use. The impact of this on mainstream manufacturing industry is potentially significant as it will enable a true realisation of interoperability.

Keywords

Virtual Machining, Digital Manufacturing, CNC, CAD/CAM, STEP-NC, Interoperability

1. Introduction

A typical CNC machining system consists of physical machine tools and material handling devices, CAx environments, control systems, cutting tools and fixture inventory. Computer interpretable representations of these manufacturing resources are employed within a variety of CAx applications. Software systems utilise these representations for taking various manufacturing decisions, and to perform manufacturing activities such as process planning, tool path verification, cost estimation, process simulation and CNC part programming. Data in manufacturing applications has typically been managed using dedicated information management mechanisms embedded in CAx systems. Currently, in the manufacturing environment the information regarding a single manufacturing resource is generated and stored multiple times and in different formats. This is due to variety of dedicated manufacturing applications used in the production process. A typical use case scenario has been presented in Figure 1. This depicts a machining cell composed of various units, namely machine tool, rotary table and robotic arm, manufactured by different equipment manufacturers. A machine tool itself is a complex mechactronical system [1], which has its own integrated design and development phase with the machine tool manufacturer and then the service phase with end users. VM systems are utilised in the development phase in order to simulate kinematic, static and dynamic behaviour of the machine tools. This also involves modelling the control behaviour, as motion characteristics may vary from one NC control to another. This analysis is important to define the capability of the machine tool and to revise the machine tool structure if required. Similarly, VM systems are exploited in the service phase for many manufacturing applications such as generating machine dependent process plans and to realistically simulate machining tool paths etc.

Four clusters of information are identified in the virtual model of the machine tool namely; Geometric information, Kinematic information, Technological information and Health information [2]. The objective of this paper is to investigate reusability of these information clusters involved in modelling machine tools in the VM environments, and highlight research gaps associated with manufacturing resource information utilisation in current manufacturing best practice. First, a brief overview of current state of the art in modelling above information clusters is presented. Various application scenarios, (as oppose to single application oriented user case in most publications) where manufacturing resource information is required for various manufacturing applications are discussed. This followed by the state of the commercial tools and associated

International Standards available for modelling machine tools. Various application scenarios are rendered where available manufacturing resource information cannot be used ubiquitously. This is followed by a data model to represent CNC control data as a part of machining capability profile, with specific use case scenarios. Finally, it discusses why CAD/CAM/CNC control vendors and solution providers are apprehensive in supporting international standards and research work for enhancing reusability of manufacturing resources in VM environment.

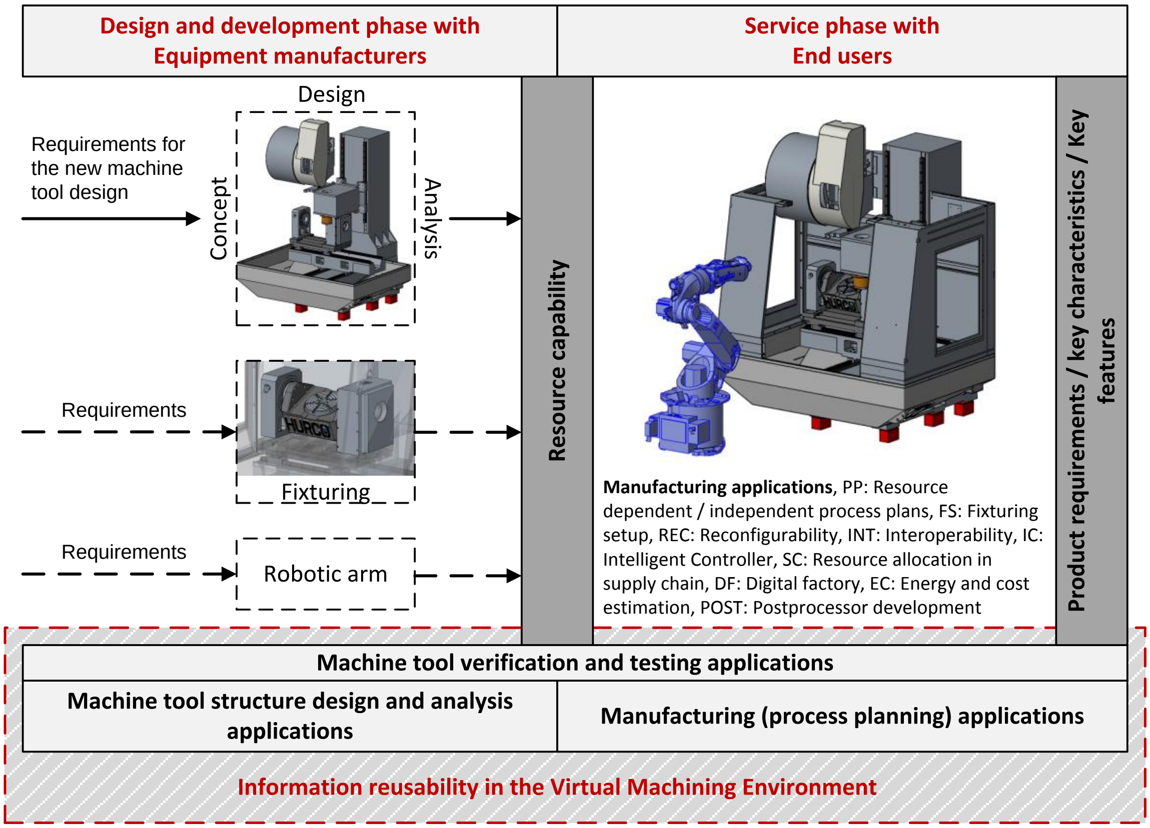

Figure 1: Digital models of the machine tool and other manufacturing resources are utilised in the VM environment from the design and development phase through the service phase by various supply chain key players

2. CNC machine tool information clusters and associated standards

Process planning is a highly-skilled and time intensive job, conventionally performed by experienced human experts [3]. Today, it is still considered as a laborious job due to the complex nature of manufacturing resource configurations but comparatively less time consuming due to advancement of computer applications in the industry. Literature [4, 5] reveals application levels of process planning activities in the manufacturing decision making. These application levels start from machine level process plans where machine tool elements such as machine tools, cutting tools, fixtures are involved and can be extended towards enterprise level process plans where various manufacturing cells, production shops and material handling systems are involved. Furthermore, the process planning activity in collaborative manufacturing becomes an even more challenging task due to the complex nature of manufacturing resources involved [6]. That is why VM concepts are considered to be of paramount importance for verifying complex manufacturing operations before actual production takes place. Owing to the fact that manufacturing resources govern process plans, investigating virtual manufacturing approaches for supporting manufacturing decisions is of importance.

2.1 Geometric information

Computer interpretable representations (geometric model) of manufacturing resources are employed within a variety of CAx applications. Software systems utilise these representations for making various manufacturing decisions, and to perform manufacturing activities such as process planning, tool path verification, cost estimation, process simulation, CNC part programming etc. These software systems (manufacturing applications) generate proprietary resource information; resulting in same resource modelled in different formats and causing redundancy of manufacturing resource data generation [7]. As a consequence, neutral format standards such as IGES, SET and VDA/FS were developed by academics and end users. These standards achieved relative success in representing geometric information; however, their failure to represent technological and contextual aspects of the product (or manufacturing resource element) forced practitioners and developers to unpack the scope of developed standards [8]. Xu and He [5] commented that integrated CAD/CAM environments consist of two types of data exchange interfaces namely, CAD to CAM and CAM to CNC, the former of which is now available and generally considered sufficient [9] for exchanging geometric information of the single machine tool as shown in Figure 2.

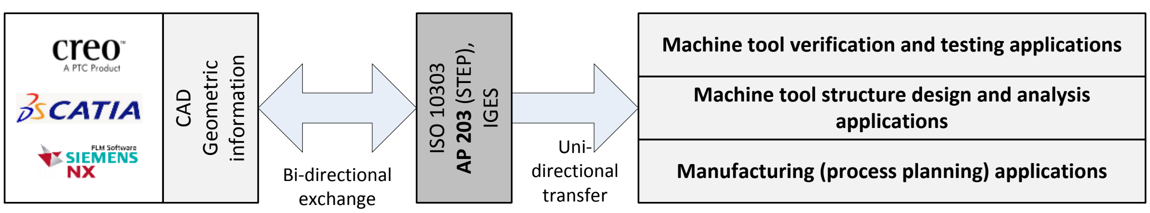

Figure 2: Geometric model of the machine tool can be transferred to any CAM system (or any manufacturing application) using neutral file format

However, this situation deteriorates with the addition of more resources (machine tools, material handling systems, fixtures and tooling, factory layout etc) and associated geometry for simulating manufacturing process of the whole production line. A typical case scenario has been presented in Figure 3, where a work cell consists of a machine tool with a rotary table, supplied by two different manufacturers. In addition, a robot arm is part of the work cell, supplied by a third party manufacturer. It it highly unlikely that all these manufacturers are using the same CAD systems, thus the digital representative models supplied to the end user are likely to be in different CAD formats. The end user will have to transfer these models in the implemented VM (or CAD/CAM) environment using neutral file format as shown in Figure 3. Today, lightweight CAD modelling concepts (such as JT, 3DXML etc.) are accepted as standard practice in industry with the primary objective to visualise geometric data.

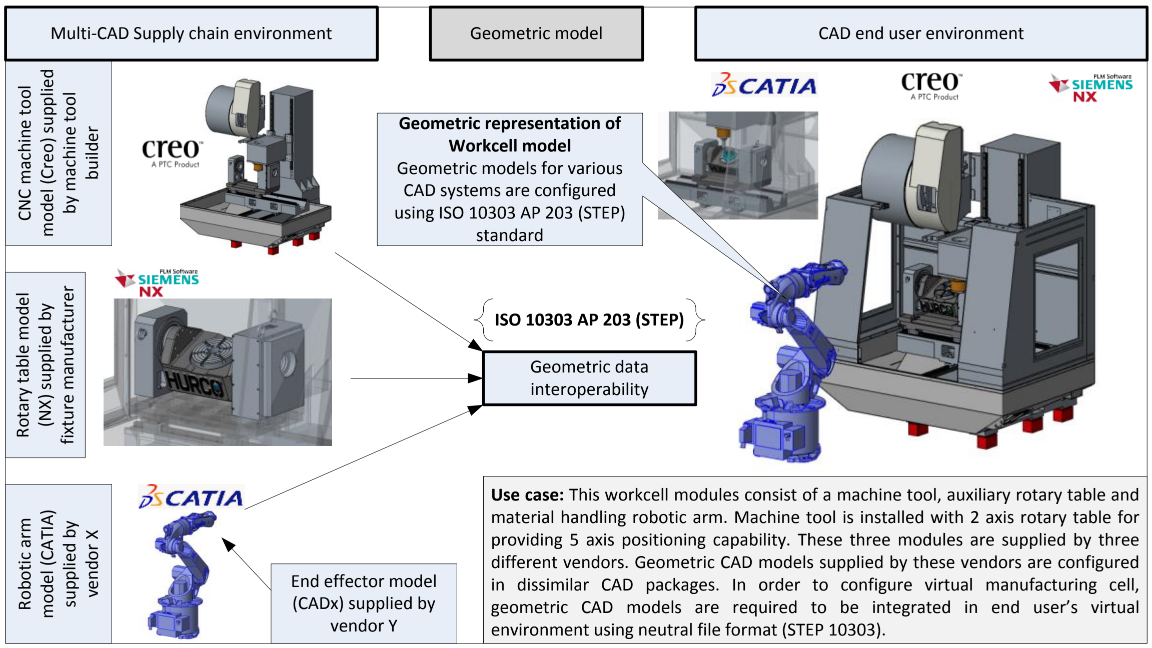

Figure 3: Geometric data exchange in Multi-CAD supply chain environment

2.2 Kinematic information

A wide variety of kinematic joints such as slides, pin joints, ball joints etc. are used in manufacturing resources. The capability of a manufacturing resource, such as axes travel limits, speed, degrees of freedom etc. is by virtue of such kinematic joint configurations. This capability information plays a pivotal role in manufacturing decision making such as, tool path generation, multi-route process planning and resource allocation. Machine tool kinematics is based on the coordinates that describe the various positions and orientation of the end effector i.e. workpiece and cutting tool. For any machine tool, the prerequisite of positioning and orienting the end effector is the information regarding displacement of linear axes and joint angles with the machine tool elements geometry. Today, most CAD system are capable of exchanging geometry of the machine tools using neutral file formats such as STEP, IGES etc. However, kinematic information cannot be easily exchanged as this information is configured in most proprietary format. Thus the cost and time required for compiling the kinematic model the machine tool is significant. A typical scenario would be a workcell simulation which consists of a machine tool connected with the material handling system. In order to simulate accurate production process, a kinematic model of the machine tool as well as material handling system has to be compiled and synchronised. The fact that these two resources are delivered by two different vendors may require geometric data exchange using neutral CAD formats as shown in Figure 4. However, kinematic information associated with the geometric model is lost in the process.

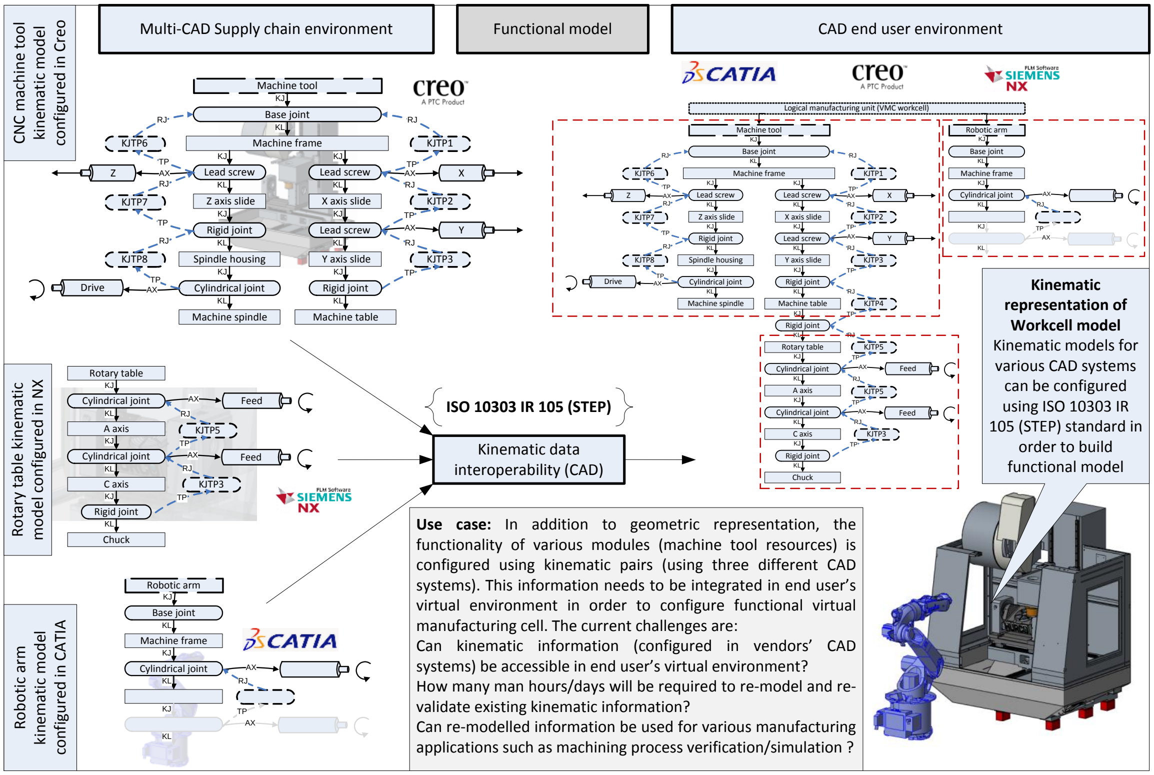

Figure 4: Kinematic information associated with geometric model has to be preserved / translated in VM environment in order to build functional model

The possible linkage between the two machine elements could be a combination of kinematic pairs such as a slides, rotary head, rotary table etc. STEP's integrated application resources (IR) 105 [10] specifies an information model for the kinematic aspects of the mechanical product. It describes a variety of kinematic joints and associated information constructs which are utilised in this framework. A range of kinematic joints and associated constraints (such as travel limits) can be represented with STEP's IR [10]. This IR specifies an information model for the kinematic aspects of the mechanical product. It also describes a methodology for representing kinematic structures. A fundamental procedure of this methodology to represent a mechanism that associates all kinematic joints to the mechanism's coordinate system as shown in Figure 4. The coordinate systems are called frames in this part of STEP. For the purpose of representing the kinematic aspect of a mechanism, a machine element is placed by the location and orientation of the associated kinematic pairs with respect to mechanism's coordinate system [10, 11]. This methodology is capable of representing serial as well as parallel kinematic structures [12, 13]. The objective of developing this STEP's IR was to establish a neutral file format for exchanging kinematic configuration information between CAx systems.

2.3 Technological information modelling and processing

In addition to Geometric and Kinematic information, it is important to specify technology specific machine tool information in order to represent the machine tool structural elements. The geometry of structural elements can be modelled using CAD tools. However, the geometry can be seen as an isolated information cluster, unless contextualised for its purpose in the VM environment. When machine tools are modelled in any VM systems, all structural elements are contextualised using bespoke taxonomy. For example, tool path simulation applications compiles technology specific information such as “tool holder” can only be held in the “spindle” while cutting; otherwise it will be placed in the “tool magazine”. Tool holder placement point (can be referred as tool change point) and orientation in the spindle has to be referenced with respect to “Machine coordinate system”. Machine coordinate system (machine zero) should be specified in the machine tool assembly. “Maximum tool length” and “Maximum tool diameter” that can be placed in the tool magazine is 200 mm and 50 mm respectively. All “linear axes” of the machine tool can be “simultaneously interpolated” with “rotary axes”. These aspects regarding specific machine tools are required in order to simulate toolpaths realistically.

Another application domain which requires such technological information is automated fixture planning. Such applications compile technology specific information such as “Workpiece” can be mounted on the “table” using an auxiliary “fixture”. The fixture will be attached to table using “T slot” configuration and “strap clamps”. “4 jaw chuck” can be utilised for holding “box” shaped components. Such application specific technological taxonomy is always associated with virtual machine tool models. The purpose of using such taxonomies is to represent the application oriented machine tool technological information. Corresponding application scenario has been depicted in Figure 5.

ISO 14649 is a new model of data transfer between CAD/CAM systems and CNC machines, which replaces ISO 6983. It remedies the shortcomings of ISO 6983 by specifying machining processes rather than machine tool motion, using the object-oriented concept of Workingsteps. The information form in ISO 14649 already allows major improvements [14, 15] over existing methods but in order to support even more efficient production it is necessary to have a description of the manufacturing environment in addition to the manufacturing information. Part 201 [16], therefore, is a first step to allow the description of machine tools as a manufacturing resource. The description allows process planners to describe their machine needs for a micro-process plan (an ISO 14649 file), a so-called requirements model. The model also allows existing machine tools to be described as an assembly of various machine tool elements as shown in Figure 5. The standard is intended to provide a basis for process planning and simulation applications, for controller developers to describe machine tool capability, for machine tool developers to describe their products as well as for cloud manufacturing [17] research.

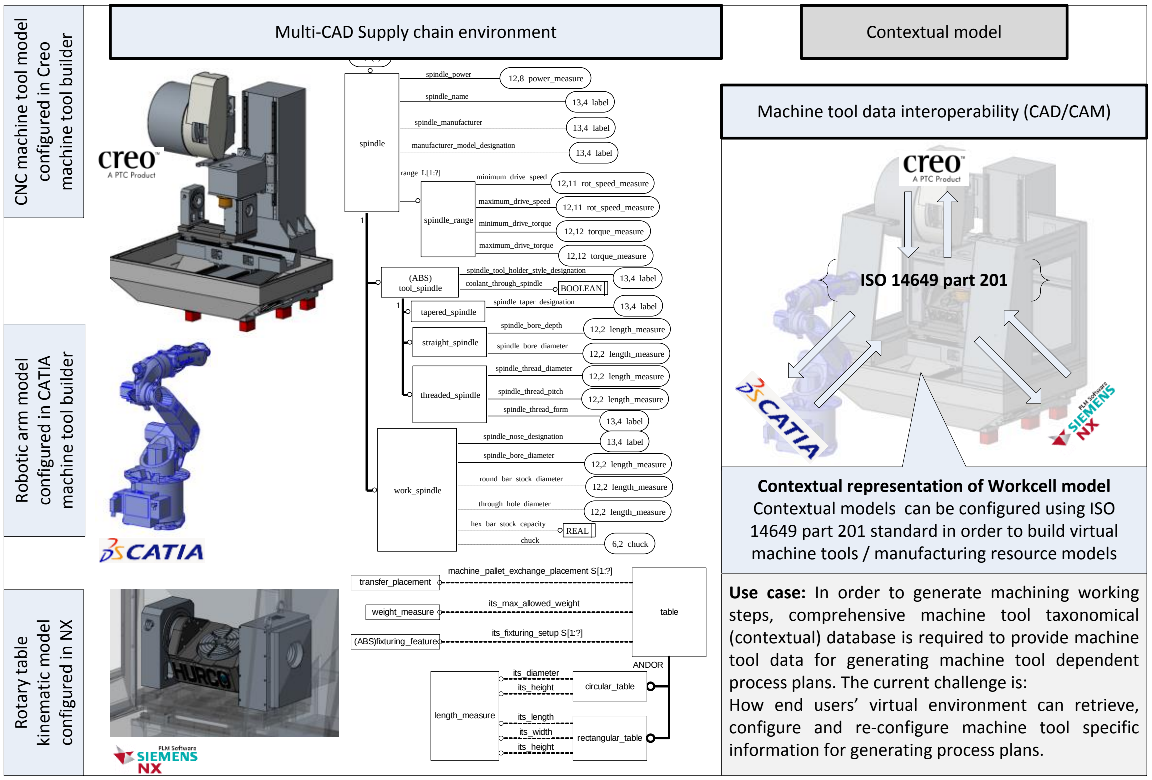

Figure 5: New merging standard, ISO 14649 Part 201 can be utilised for exchanging contextual information of machine tool resources over the Multi-CAD supply chain environment

2.4 Health information

In order to select an appropriate machine tool, a decision maker needs to evaluate a large quantity of capability information regarding available machine tools. The state-of-the art machine tool testing and verification standards provide valuable guidelines for making such decisions. They define various machine tool verification techniques to express machine tool's health. These standards also provides different health attributes along with statistical control charts as health monitoring measures. However, they do not provide any guidelines on the structure of these informative attributes to store, use and exchange this machine tool health information digitally within the supply chain to make informed decisions [18]. Thus, the absence of standard format or procedure to store this capability information complicates the selection process. Although standards specify test procedures along with graphical representation methods, the information structure beneath has vendor specific formats which escalate non-interoperability in the supply chain [2]. Furthermore, the information stored is often limited to the data required to produce the graphs and reports specified in the various machine tool testing and verification standards (ISO 230 Series). Thus, this information does not carry any other resource information to represent any kinematic or technological aspect of the machine tool.

3. Information reusability within International Standards

High levels of cost and time savings have been reported as a result of developing and implementing international standards for exchanging manufacturing information throughout the supply chain [19]. These initiatives have progressively managed to standardise various facets of manufacturing information to resolve information exchange challenges. Consequently, today the STEP format is the preferred choice to exchange geometric data across the supply chain. Longview Advisors, Inc. found fewer companies now use service providers for CAD/PDM data migration due to wide acceptance of STEP standards [20]. Figure 6 illustrates various elements of the manufacturing resource information and associated standards for exchanging this information. For example, the STEP's IR Part 105 [10] of the STEP defines kinematic aspects of mechanisms. The objective of developing this STEP's IR was to establish a neutral file format for exchanging kinematic configuration information between CAx systems. This information can be linked with other STEP based standards such as ISO 10303-203 for representing product geometry. Similarly, some initiatives are in progress for connecting this information to ISO 14649-201 for representing technological information of the manufacturing resources. Thus, it will be possible to connect geometric, kinematic and technological information of the manufacturing resources using STEP compliant standards. It is important to recognise that these initiatives were launched as a result of industry's needs for more intensive standards that can cover a wider scope of the manufacturing resource elements listed in Figure 6.

Resource information element & Standards		Description	Information extensibility										
			A	B	C	D	E	F	G	H	I	J	K
Geometry		Geometric features: points, lines, curves, surfaces, solids etc.											
A	ASME Y14.26M	The Initial Graphics Exchange Specification (IGES) a vendor neutral data format	/	N	N	N	N	N	N	N	N	N	N
B	ISO 10303-203	STEP: Configuration controlled 3D designs of mechanical parts and assemblies		/	Y	N	Y	Y	N	N	N	N	N
Kinematics		Kinematic configurations, kinematic pairs and links, mechanisms etc.											
C	ISO 10303-IR 105	Information model for the kinematic aspects of a mechanical product			/	N	Y	Y	N	N	N	N	N
D	ANSI/ASME B5.54	Machine kinematic arrangements (axis stacking) have been defined				/	N	N	N	N	N	N	N
Technology		Resource elements: machining head, turret, tool and workpiece holder, etc.											
E	ISO 14649-200	Description of machine tool as a manufacturing resource information					/	Y	N	N	N	N	N
F	ISO 13399	Representation and exchange of cutting tool assembly data.						/	N	N	N	N	N
G	ASME B5.59-2	Machine Classes have been defined: Turning machines, Milling centres etc.							/	N	N	N	Y
H	I++	Interface standards for dimensional metrology interoperability								/	N	N	N
Health		Machine tool parametric errors: Linear Axes Motion, Angular Axes Motion etc.											
I	ISO 230	Specifies methods for testing the accuracy of machine tools									/	Y	Y
J	ISO 13041	Test conditions for numerically controlled turning machines and turning centres										/	N
K	ASME B5.59-1	Data specification for machine tool performance tests											/

Standards for representing resource information elements are not compatible with each other

Legend: Y Resource information elements can be linked; N Resource information elements can not be linked due to scope of the standards

Figure 6: Manufacturing resource information extensibility among standards

Previously, domain specific standards such as ASME Y14.26M (IGES), ANSI/ASME B5.54 (machine tool kinematic arrangement representation) were lacking information extensibility, targeting very specific application domains. For example, ASME Y14.26M (IGES) can be utilised for representing geometry of the manufacturing resource (eg. Machining centre) and ANSI/ASME B5.54 can be utilised for representing machine tool configurations. However, integration of this information is not covered in the scope of these standards. Today, this situation has resulted in a variety of non-compatible standards for representing various aspects of the manufacturing resource. For instance, control charts at present are used to provide statistical representation of machine tool health. These charts are based on machine tool testing standards, for example ISO 230 and VDI 3441. However, these standards do not specify any mechanism to exchange and use the information within these control charts to integrate it with other important elements of the resource information shown in Figure 6. Thus this information remains isolated and largely un-retrievable while assessing whether the machine is performing to the desired level of capability and whether the machine is healthy or not.

With the high volume of research in modelling virtual machine tools, VM and Product Lifecycle Management (PLM) vendors are constantly required to adapt to attempt to meet the end user's needs. Abdul Kadir et al. [4] states that even though many VM systems are now capable of producing similar outputs, the technology and methods used are varied. The research is still mainly devoted to improving system competencies rather than expanding on the systems current functionalities to support emerging standards. In fact, development of standards for sharing and exchanging resource information is regarded as a commercial suicide by the VM developers, as they see no business value stream for supporting International Standards.

4. Commercial approaches and trends for modelling virtual machine tools

Various VM systems are available on the market for simulating component manufacture in the virtual environment. Abdul Kadir et al. [4] states that between 1996 and 2009, material removal simulation, tool-path generation, NC code interpretation functions as well as methods for modelling machine tools behaviour were the main research streams. Typical examples of those are shown in the Figure 1 as manufacturing applications. These are used in evaluating component manufacturability by executing part program on the virtual machines. The majority of VM systems can model CNC machining system resources such as machine tools, material handling systems, fixtures and relevant kinematics. In addition, they can emulate CNC controller logic for observing controller specific performance. Thus, a VM system can be used for simulating the manufacturing process and interaction of corresponding resources to anticipate a range of manufacturing problems [21]. However, only nominal process simulation is possible where processes are designed by a manufacturing engineer; thus, applications such as automatic process plan generation, resource allocation, compensating process variations, incorporating inspection results for corrective measures are still regarded as manufacturing challenges. Another disadvantage of the above commercially available systems is that their information regarding the machine tool resource functionality is not exchangeable.

Today, many VM vendors have introduced software specific user interfaces to allow the transfer of information between VM environments and PLM systems and this has improved the reusability of information to some extent. However this trend has only been adopted for major CAD interfaces such as Cero, CATIA and Siemens NX. Primarily, these interfaces can reuse geometry of the workpiece and the component to be machined, the cutter location (CL) data and the geometry of fixture models. However machine tool model configured in the PLM's machine tool builder application cannot be reused readily in VM systems. Indisputably, VM systems are dedicated manufacturing application for configuring machine tool's functional and contextual information required for manufacturing decision making. Whereas PLM systems may not offer rich environment to configure this information as compared to corresponding VM systems. However this gap can be filled with using contemporary standards such as ISO/TS 14649 Part 201 [13, 16] as shown in Figure 7.

A case scenario has been presented in Figure 6, which highlights how dedicated manufacturing application interfaces for major CAD vendors avoid configuring virtual models of the manufacturing resources multiple times. At the same time, kinematic and technological information has been seen as a weakest link with very limited or no information reusability. Consequently, many PLM vendors have started incorporating comprehensive machine tool builders, which has comparable or better functionalities to those of dedicated VM systems. This approach of incorporating dedicated VM capabilities within PLM can be seen as a development and end users and supply chain players can benefit by using single PLM system for VM applications such as NC code (G and M code) verification. However, this approach may not be effective for end users who cannot afford to deploy PLM within their business and rely on dedicated VM system to exploit their core capabilities.

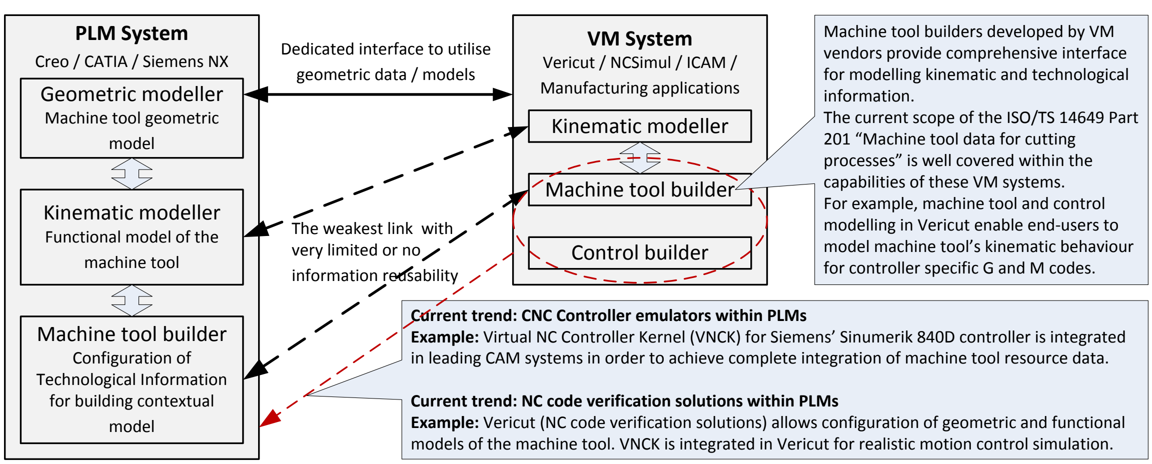

Figure 7: Current trends of commercial PLM systems for incorporating VM applications

The majority of the CNC controllers today have a distinct way of modelling various axes, joints and respective Cartesian transforms. The counterpart of this representation in the VM environment is known as machine specific postprocessors. The present requirements for developing any machine specific postprocessor are the declaration of transformation placement of the various axes mounted on top of each other, information of joints for representing rotary axes, various travel limits and controller specific NC functions for developing controller specific tool paths. However, this information, which is an integrated part of the controller, remains completely isolated in the VM environment due to lack of mechanisms to exchange it with other VM applications such as CAM packages, NC code simulators, etc. Consequently, a notable trend that can be observed within PLM development is to incorporate a virtual controller in order to emulate dynamic behaviour of the machine tool. A typical use case within this trend has been shown in Figure 7, where Siemens 840D control can be found integrated within NX (Siemen's PLM), known as VNCK (Virtual NC Kernel).

Another notable trend towards realistically modelling machine tool movements is to simulate controller specific G codes (or programming syntax). A typical example of this scenario (Figure 8) would be accessing re-positioning routines of two rotary axes in the 5 axis machining centre (for example G08.1 on Hurco WinMax 9). A circular arc toolpath from -90° to 90° in the A axis (attached to the C axis) is not possible without re-positioning of C axis (360°), if the machine tool A axis range is -30° to 110°. This re-positioning routine for out-of-limits toolpaths can be configured in the CAM system (with kinematic model constraints or with the postprocessor) to simulate machine tool movements for collision checking and the corresponding machining codes (G and M) can be executed on the CNC controller. However, many CNC controllers do not require CAM post-processed re-positioned codes, as they are capable of re-positioning required axes when encountered with out-of-limit toolpaths. The prior approach requires accurate information of machine tool travel limits, workpiece position, cutting tool (length and diameter) details, safe retraction plane of the machine in order to apply re-positioning routine. And this information is often modelled on the CNC controller in a non-interoperable manner; making it impossible to use controller specific programming syntax in CAM systems [22]. Thus, offline toolpaths in VM applications may differ when compared to actual machine tool movements for such re-positioning scenarios.

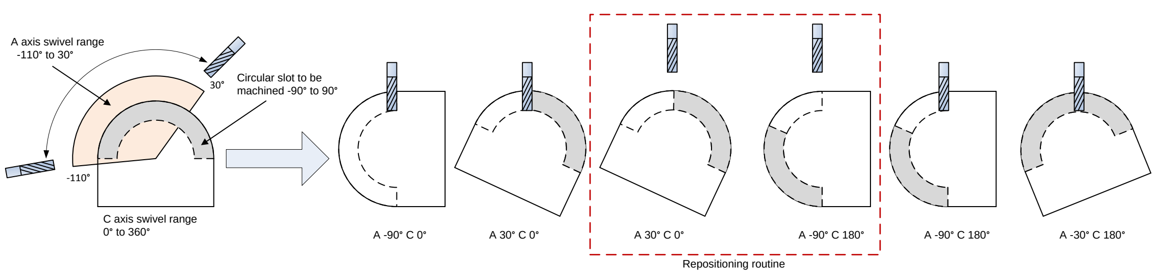

Figure 8: Repositioning routine retraction moves

5. Machining Capability Profile (MCP) using neutral file format

Although there is literature on manufacturing resource modelling [9], there is no report on modelling the controller of a machine tool or a device. The physical and kinematic structure of a machine tool is essential for resource modelling. However, the controller is the brain of a machine tool and the sophistication of the controller determines the machining capability of the machine tool. Machining Capability Profile

(MCP) take advantage of the EXPRESS modelling language and STEP-NC standards, providing a standardised manufacturing resource modelling approach.

The MCP represents CNC machines in terms of their machining capability, which reflects the current status of the machine instead of the nominal capability. An MCP gives a full description of the machine including hardware and the software side (controller), which is one of the innovative aspects of this approach. Modelling of the controller is an important part of the resource model and plays an important role in utilising the resource model for decision making during the manufacturing process. In a new product development process, an MCP profile can be used to check against a specific part together with corresponding process plan to provide a clear idea on whether the part can be machined on the specific machine with the defined method (process plan) or not.

5.1 Use case: Representation of NC programming specification

A data model for representing the controller specific programing syntax (NC dictionary) of the CNC machines has been included in the MCP. An EXPRESS-G representation of NC programming specification has been depicted in Figure 9. In this data model, “NC_programe_specification” entity is the root entity for each dialect. The programming syntax will be specified for each instruction using an entity “its_grammar”. For each instruction, there can be a set of the programming syntax as same instruction can be specified in different formats (NC words). For example, circular interpolation can either be expressed by arc end point (X,Y,Z) and centre (I,J,K) or end point (X,Y,Z) and radius R. As shown in Figure 9, an instruction has been classified into two groups: “interpolation” and “NC_function”. Each instruction has an attribute “modal”, which can be set to true of false to indicate the commands will modal and will not appear on subsequent lines, unless specified otherwise.

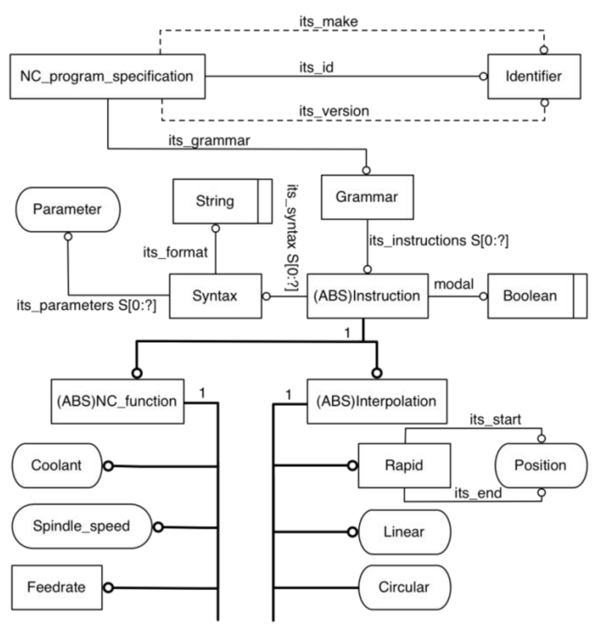

Figure 9: EXPRESS-G diagram of NC programming specifications

To include the programming languages in the MCP, it is possible to use the MCP as an advanced postprocessor for CNC machines to generate the code from existing process plans, which has passed the hardware evaluation in the previous step. It will be very useful to automate manufacturing process from the process planning stage to CNC machines. Compared with traditional postprocessors (PP) pre-packaged in the CAM system, the MCP contains comprehensive information about the machine and can serves as an important link to check new or legacy process plans. In addition, as traditional PP simply translates CL data into machine code without any guarantee of its successful running on the machine because most prepacked processors are generic in nature. Consequently, problems such as improper spindle speed, feed rate can be encountered. These problems can be eliminated by using MCP as it carries machine tool as well as controller specific information to generate or verify process plans.

5.2 Use case: Representation machine tool capability for generation STEP-NC compliant process plans

The following elements are selected in the representative version of the MCP to represent the important capabilities of a machine: i) Table size: checking the workpiece size and weight to fit on the machining table, ii)Feedrate capability: checking feedrate capability, iii) Spindle: checking the achievability of the specified spindle speed, iv) Working area: checking whether the machine has the right room size to perform machining and v) Cutting tools: checking whether the machine has the right tool to perform the task. The resource allocation use case illustrated in Figure 10 depicts STEP-NC compliant process plan for the component can be verified against machine tool specific MCP. The MCP file in Figure 10 represents 3-axis milling machine with a Fanuc controller. It model the basic information of the machine with work envelop, table size, maximum loads on the table, cutting tools availability etc. the second part of the file is the programming syntax of the controller. The language information can be used as the reference for a postprocessor, and it is also useful for enabling knowledge capture from existing part programs [23].

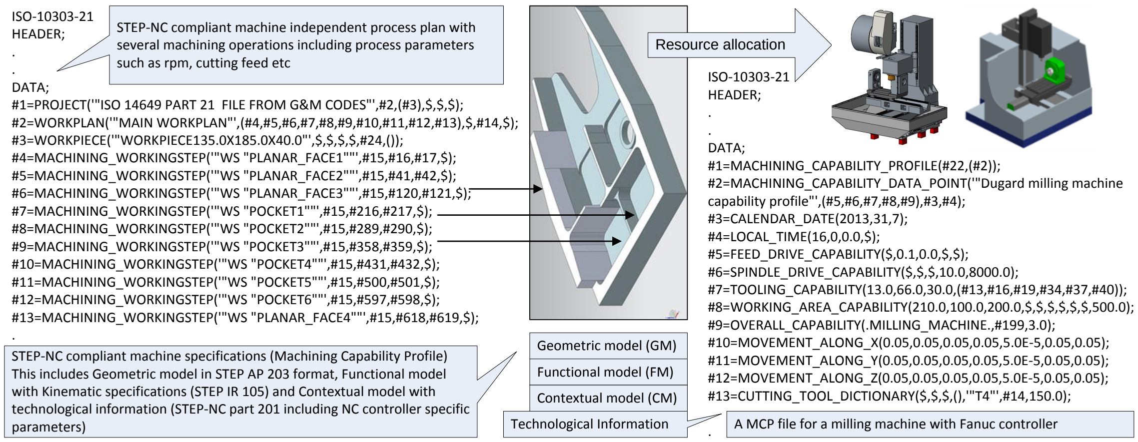

Figure 10: STEP-NC compliant process plan for a component and MCP detailing controller specifications

In Figure 10, the process data of the component has been composed in STEP-21 format. In this STEP-NC file, operations with detailed cutting parameters have been defined. Assuming the part is going to be machined on the 3-axis milling machine modelled in the MCP, the process detailed can be checked against the machine specification at the early stage of product development cycle. The checking process can be very useful at the process planning stage to find the right manufacturing resource. If a comprehensive database of the MCP is available, a manufacturing resource searching and matching can be carried out to find the right resource automatically. Considering the current trend of cyber-physical manufacturing system, Industry 4.0, cloud manufacturing, remote process planning etc. MCP could play an increasingly important role in the future of manufacturing. However, the precondition for this would be an implementation support from CAD/CAM/VM/CNC control vendors in supporting such advances in STEP-NC standards and this is as much a technological decision as it is a business decision.

6. Discussion

It was estimated by National Institute of Standards and Technology (NIST) in 1999 that standardising only geometric information has saved at least $1 Billion dollars per year on the members of the U.S. automotive supply chain. Longview Advisors, Inc. conducted major survey in 2010 [20] on the collaboration interoperability market and found 100% of OEMs are exchanging design/manufacturing data with suppliers. This highlights the importance of International Standards for enhancing reusability of manufacturing information. However, there are major issues with adopting international standards. Manufacturing information exchange standards are designed for end users (manufacturing supply chain owners, component manufacturers) and considered as an end users' point of view. These standards benefit end users by providing them with a common language to describe and represent various aspects in manufacturing and make decisions. End users are the immediate beneficiaries in implementing these standards; thus they contribute in laying requirements from these standards and are eager to implement them in the business processes. However, developers (CAD/CAM/CNC control vendors) may not necessarily respond well to this call.

For many years, large CAD/CAM/CNC control vendors (will be called Solution Providers hereafter) have responded lukewarmly to the pleas of end users for improved interoperability capabilities (for example, case studies reported in the previous section), partly due to the complexity of the problem, and primarily for business priority reasons. Sometimes solution providers find requirements prescribed by end users are very difficult, if not impossible to implement in the software modules. They required allocating major resources in order to cover end users' requirements depicted in standards. They question the value in implementing such new standards to their business. The initial value is too low and it is largely depends on how well a particular standards is supported by their competitors. If no solution provider is supporting that particular standard, there is no value to their business as it will not be used by the end users. A particular standard can only be well accepted if it is supported by many/major CAD/CAM/CNC control vendors; otherwise it will be of no use to end users as data can only be converted but cannot be transferred from one system (CAD/CAM/CNC control) to another.

Another fact is that the solution providers invest more resources in adding end users' requirements in their system in a proprietary way as this becomes their main business value streams, while attempting to conceal the need for data interoperability. Similarly CAD/CAM/CNC data migration service providers consider standards as a threat to their businesses, as they see no business advantage in supporting the development of standards. Listed below are the research gaps, which require attention from various stake holders (academics, VM solution providers, end-users, academic funding bodies) in the area of virtual manufacturing:

i) The majority of the work has been done on the application oriented information representation of manufacturing resources. However, these approaches lack the resource modelling methodology to derive resource capability on the basis of available manufacturing resource elements.

ii) Although a vast amount of research has been conducted on developing computer aided manufacturing applications; the majority of them address very specific manufacturing resource domains. Thus, their validity fails in the multi-domain resource environment. Research is needed for developing manufacturing applications which can address multi-domain manufacturing resources.

iii) Although, commercial VM systems are now capable of producing similar outputs (for similar application domain), the technology and methods used are varied. Research is still mainly devoted to improving information reusability using system specific interfaces/translators rather than expanding on the systems current functionalities by adopting international standards.

iv) The potentials of well-developed international standards are underutilised in the current manufacturing environment. Deployment of standards in the manufacturing environments has not been thoroughly explored due to minimal encouragement from machine tool manufacturers.

v) The development of international standards is not in parallel with industrial needs. The acceptance of standards in the manufacturing environment is preliminary dependent on how well industrial standards satisfy industrial needs.

vi) Research is required for developing multiple views of manufacturing resource information for a variety of manufacturing applications which can utilise well establish standards.

6. Conclusion

In this paper the authors have identified that there is no common methodology to represent the wide diversity of machine tool configurations, functionalities and resulting capabilities. These applications are either machine vendor specific or limited in their scope to represent the range of resources. As a result, the market is flooded with an abundance of non-interoperable resource information representation methodologies compiled in commercial software tools. Consequently, various international standards are evolving for representing geometric and functional information of such resources. However, their inability to cover the broader scope of CNC machining system elements restricts their acceptability within the manufacturing environment. In addition, these standards are application specific; hence they cannot be used for multi-objective decision making in the manufacturing environment.

Similarly, solution providers (machine tool manufacturers, VM application developers) should encourage their participation in developing and adopting international standards to elevate information exchangeability in the supply chain. The authors have shown the fact that VM solution providers do not find significant business value in supporting standards, as their main focus is on enhancing the functionality their products. Likewise, machine tool control vendors invest vast amount of resources in making controllers more intelligent and user friendly by encapsulating resource specific information within the controller. However, there should be end user driven innovation towards enhancing openness of the controller by exploiting and supporting relevant international standards.

The use cases provided demonstrate a novel vision for encapsulating machine tool as well as controller specific information within STEP-NC compliant MCP. It is shown that MCP can replace current postprocessor with the unique capability of describing controller specific syntax in STEP-NC compliant format. This development within STEP domain can be compared with commercial impetus of embedding virtual controller within PLM so that machine tool virtual model can be utilised for the range of manufacturing applications. This research has shown that it is possible to achieve information interoperability using standards, STEP-NC compliant MCP. This research has the potential to have a major impact on the way information is exchanged between machine tool builders and corresponding supply chain. End users can be benefited with interoperable information clusters of MCP; making SMEs more agile and interoperable which will have a major impact on business expansion and revenue streams.

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