A Unified Manufacturing Resource Model for representation of CNC machine tools

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The capability of any manufacturing system primarily depends on its available machine tools. Thus machine tool representation is a vital part of modelling any manufacturing system. With the rapid advances in Computerised Numerical Controlled (CNC) machines, machine tool representation has become more challenging task than ever before. Today's CNC machine tools are more than just automated manufacturing machines; as they can be considered multi-purpose, multi-tasking and hybrid machining centres. This paper presents a versatile methodology for representing such state of the art CNC machining system resources.

A machine tool model is a conceptual representation of the real machine tool, and provides a logical framework for representing its functionality in the manufacturing system. There are several commercial modelling tools available in the market for modelling machine tools. However, there is no common methodology among them to represent the wide diversity of machine tool configurations. These modelling tools are either machine vendor specific or limited in their scope to represent machine tool capability. In addition, the current information models of STEP-NC namely ISO 14649 can only describe machining operations, technologies, cutting tools and product geometries. However, they do not support the representation of machine tools. The proposed Unified Manufacturing Resource Model (UMRM) has a data model which can fill this gap by providing machine specific data in the form of an EXPRESS schema and act as a complementary part to the STEP-NC standard to represent various machine tools in a standardised form. UMRM is flexible enough to represent any type of CNC machining centre. This machine tool representation can be utilised to represent machine tool functionality and consequential process capabilities for allocating resources for process planning and machining.

1. Introduction

Manufacturing system information is one of the most essential aspects within manufacturing industry, which includes information relating to manufacturing resources. Hence, effective ways of representing this information has always been comprehensively researched in the past. In the modern manufacturing scenario, the complex nature of the manufacturing resources and continuous improvement in the CNC machining system technology is enforcing researchers as well as practitioners to establish more prolific ways of representing manufacturing resources.

Machine tools have evolved over the last 50 years from simple machines driven by punch tape, to today's highly sophisticated computer numerically controlled multi-process, multi-axis workstations. In the 1960's and 1970's CNCs were designed to perform specific manufacturing operations. For example, special purpose CNCs were designed according to their cellular requirement (turning, milling, grinding cells) of the shop-floor. Whereas today, the flexible nature of manufacturing demands a single machining centre which can perform a range of manufacturing operations to overcome the problem of job scheduling between different machine types. The reconfigurable manufacturing concept has emerged in the last few years. It proposes a manufacturing system the modules of which can be added, removed, modified, or interchanged as needed to respond to changing requirements. Indeed, CNC machining centres currently available on the market have ever growing reconfigurability, modularity as well as flexibility to perform the majority of manufacturing operations.

Based on these capabilities, the next generation Computer Numerically Controlled (CNC) machining practice aims to realise the vision of ubiquitous and reconfigurable manufacturing [1, 2]. In response to this vision, manufacturing practice demands a more flexible and interoperable manufacturing environment [3]. For several decades, data for CNC machine controllers has been defined by using a series of "G" and "M" codes [4]. This is now considered as a bottleneck for next generation CNC machine controllers due to lack of interoperable program structure [5]. Machine tool manufacturers use their own supplementary codes to program some machine specific commands because of the limited scope of the available standards. Due to these various program extensions, there has been an explosion of machine specific code generators, known as postprocessors (of which there are estimated to be about 10,000 in existence) [6]. These postprocessors have a data model which translates cutter location data into machine controller specific format. Many CAD/CAM vendors offer universal postprocessors that allows an end user to customise a postprocessor; however making a specific postprocessor requires much more experience and specialist programming skills [7]. ISO 14649 offers a standardised data model for CNC controller which aims to transfer manufacturing context form CAD system to CNC manufacture.

2. STATE OF THE ART IN REPRESENTATION OF CNC MACHINE TOOL RESOURCES

A typical CNC manufacturing system consist of various resource elements such as CNC machine tools, cutting tools, auxiliary devices, material handling devices, fixtures etc. Each and every resource has its specific role in the manufacturing system. Different aspects of the resource information required in the manufacturing enterprises depend on the application area. Objective specific information regarding these resources must be in the standard format when this information needs to be exchanged between various application domains in the manufacturing enterprises. Consequently, various international standards are evolving for representing geometric and functional information of such resources. In parallel to this, machine tool manufacturers started developing their own proprietary techniques for establishing information links between the CAD to CNC manufacturing interface. As a result, the market was flooded with an abundant amount of non-interoperable resource representation software tools. The following subsection describes the contemporary standards and commercial tools for representing this resource information.

2.1 INTERNATIONAL STANDARDS FOR REPRESENTING MANUFACTURING RESOURCE GEOMETRIC INFORMATION

The need for data exchange standards was originally recognized in the late 1970s and led to the development of specifications such as IGES (the Initial Graphics Exchange Specification) in the USA, SET (Standard D'Echange et de Transfert) in France, VDA/FS (Verband der Automobilindustrie-Flächen-Schnittstelle) in Germany and STEP (Standard Exchange of Product Data). IGES is now established as the most widely used format for CAx data exchange. The development of SET was driven by major manufacturing companies in the automotive and aerospace industries, and was designed to address the issues arising from difficulties in using IGES [8]. VDA-FS was specifically designed for exchange of surface models, and has achieved considerable success in the automotive industry. As with SET, the developers of VDA-FS were actively involved in STEP, and were defining the requirements for migration from VDA-FS to STEP [9]. STEP (ISO 10303) is an international standard for product data representation and exchange [10]. As explained before, initial efforts to create specifications for CAD/CAM data exchange resulted in a number of national standards (IGES, SET, VDA-FS) that achieved limited success in providing interfaces between proprietary CAD/CAM systems. Choosing STEP as the standard for product data exchange implies using EXPRESS as the data description language. EXPRESS allows for the building of conceptual schemata based on the Entity-Relationship model and constraint-specification constructs [11]. It was designed to be STEP's modelling language because no other language seemed to be appropriate to represent the richness of product data models. Currently the STEP standard has been extended not only for representing geometry but also features, process plans and data for manufacturing using CNC machine tools.

2.2 INTERNATIONAL STANDARDS FOR REPRESENTING MANUFACTURING RESOURCE CAPABILITY INFORMATION

In parallel with the developments outlined in section 2.1, other standards such as ISO 10303 AP-238 [12], ISO 14649 (STEP-NC) [13], ISO 13399 [14], ISO 15331 (MANDATE) [15], ASME B5.59-2 [16] emerged as results of international effort for representing CNC manufacturing resources. STEP-NC not only provides a full description of the part, but the manufacturing process as well, annotating CAD design data with manufacturing information about the stock, its cutting characteristics and tool requirements. STEP-NC defines data representing working steps, a library of specific machining operations performed at the CNC, so that any controller will be able to calculate the tool path based on definitions contained in formatted routines integrated within the controller itself. It remedies the shortcomings of G-codes [4] by specifying machining processes rather than machine tool motion, using the object-oriented flavoured concept of workingsteps.

Basically, the standard is envisioned to be smooth and seamless exchange of part information between CAD, CAM, and NC programming, by providing a complete and structured data model, no information is lost between the different stages of the process. Post-processors for machine-specific adaptations of NC programs are no longer needed. This rich information content results in higher flexibility, enabling last-minute changes or the correction of technological values within the part program, e.g. when a tool breaks and needs to be changed. A major benefit of STEP-NC is its use of existing data models from ISO 10303 to facilitate seamless data link between product and its manufacture. ISO 10303 AP-238 is the Application Interpreted Model (AIM) of the ISO 14649 Standard. It specifies the integrated resources used to describe the information requirements identified by ISO 14649 [12]. From the analysis of the files generated by ISO10303-238 and from ISO14649 it can be said that the AP-238 is a more verbose way to describe the NC program. A discussion over the advantages and disadvantages of the two standards can be found in Liu, et al. [17] and Venkatesh, et al. [18].

MANDATE is an International Standard written using the EXPRESS language for the computer interpretable representation and exchange of industrial manufacturing management data. Resource management and its representation is the basic function of this standard. It has a Manufacturing Resource Information Model (RIM) which is fundamental to any decision making processes. RIM can represent manufacturing resources in terms of their capabilities and capacities to perform manufacturing tasks. It offers a structure of information based on a flexible resource hierarchy, resource characteristics, resource views and resource status. However, MANDATE includes neither the modelling of the resource shape nor the description of its usage in the meaning of its way of working. For example, it does not describe the way of working of a milling machine. It addresses only the management data of the milling machine in terms of capability and capacity in conjunction with other standards (e.g. ISO 10303, ISO 13584, ISO 14649), to make up a more precise resource model aimed at a specific industrial activity, or a specific function.

ISO 13399 is an International Standard for the computer-interpretable representation and exchange of cutting tool assembly data. Its objective is to provide a mechanism that is capable of describing product data regarding cutting tools, independent from any particular system. The nature of this description makes it suitable not only for neutral file exchange among CAx systems, but also as a basis for implementing and sharing product databases and archiving, regarding cutting tools. ISO 13399 includes the data representation of everything situated between the workpiece and the machine tool. Information about inserts, solid tools (e.g. solid drills and solid endmills), assembled tools (e.g. boring bars, indexable drills and indexable milling cutters), adaptors (e.g. milling arbour and chucks), components (e.g. shims, screws and clamps) or any combination of the above can be exchanged.

The data specification for properties of machine tools for milling and turning (ASME B5.59-2) [16] is a form of catalogue model for the machine tools. This standard defines an electronic data format and associated information model for properties of machine tools for milling and turning. The focus is on properties that describe the performance and capabilities of a machine at an arbitrary instance in the machine's life-cycle (e.g. during specification, after acceptance testing, or at any time during operation). However, the information model of this standard is not defined using a formal modelling language [16]. Hence, this standard does not provide a formal schema for representing any arbitrary mechanical machine element and its kinematic aspects in the manufacturing system. In addition, this standard does not define which machine properties are important for a specific application, nor their respective recommended values.

Figure 1 illustrates two resource information categories namely; geometric information and functionality information with established standards regarding various manufacturing resource domains such as machine tools, cutting tools, fixtures, material handling devices and controllers. Various standards are available for exchanging geometric information of the manufacturing resources. However, there is a certain need for a unified standard which can represent the functionality of the various manufacturing resources as shown in Figure 1.

Resource specific viewpoints	CNC machining system resources: Machine tools	Cutting tools	Fixtures	Material handling devices	Controllers
Geometric information	STEP IGES STL VDA	STEP IGES STL VDA	STEP IGES STL VDA	STEP IGES STL VDA	-
Functionality information	ASME B5.59-2	STEP-NC ISO 13399	-	-	ISO 6983 STEP-NC

Figure 1: Established international standards for exchanging geometric and functionality information

2.3 Commercial tools for modelling CNC machine tools

Various software, such as the VNC of Delmia [19], VERICUT of CGtech [20], Machine Tool Builder and Synchronization Manager in Unigraphics NX3 [21], and ESPRIT [22] have been developed in the recent years for representing virtual machine tools and robots. One of the major focuses of these systems is to represent CNC machine tool resources and enable a NC simulation for a collision free toolpath with an optimised sequence of operations to reduce machining cycle time. However, very few of these can model an entire manufacturing cell with FMS units integrated. In addition, machine tool models and associated information are not exchangeable amongst these software systems due to the absence of neutral file formats. Mazak Corporation [23] have developed a unified machine tool control platform known as CAMWARE/Mazatrol, which offers seamless bidirectional information transfer between the feature based CAD model and corresponding CNC part manufacture. The same technology can be found with Siemens's SINUMERIK controller series [24] and Heidenhain's TNC [25] controllers. However, every controller has its own proprietary data model to store and use machine tool specific information. The disadvantage of the above commercially available systems is that their information regarding the machine tool resource functionality is not exchangeable. In addition, a data model used for representing turning machines can not be used to support the modelling of milling machines or other devices such as material handling robotic arms. This means that these vendor data models of a system are not interchangeable and are application specific.

3. Representation of CNC machine tools within a manufacturing enterprise

The importance of manufacturing resource modelling was realised in the 1980s while building a constructive environment for Computer Integrated Manufacturing (CIM). Since then, research and development efforts have been made towards a CAD/CAPP/CAM integration platform [26], automatic process planning methodologies [27-29], and manufacturing resource modelling [30-33]. One of the major aims of CIM was to alleviate the requirements for the computer aided process planning (CAPP) activity [34], which involves the determination of raw material, selection of the operation sequence and available machine tools.

Machine tool model development is widely used for developing Virtual Manufacturing Systems (VMS). Since most of the virtual models are purely geometry based, there is an absence of constraint details of behaviours for individual objects [35]. While describing various paradigms of virtual reality, Jimeno and Puerta [36] reported that the sole graphical representation of the machine tool is not enough for rendering usefulness of the available machine tools in the manufacturing model. Ehmann et al. [37] pointed out that simulation of machine tools is necessary to minimise the trial errors in design and presented a framework for virtual machine tools. The Smart Machining System (SMS) program is an operational project at the National Institute of Standards and Technology (NIST), USA, with an emphasis on machining information models. Two main categories of machining models were taken under consideration for solving interoperability issues.; models describing the cutting process and models describing the machine tool resources [38]. Thus, a role of resource modelling methodology is considered as a major aspect in the next generation manufacturing paradigms. One of the major challenges in the next generation manufacturing is realisation of Reconfigurable Manufacturing System (RMS), a new manufacturing systems paradigm that aims at achieving cost-effective and rapid system changes, as needed and when needed, by incorporating principles of modularity, integrability, flexibility, scalability, convertibility, and diagnosability [39, 40].

3.1 CNC machine tool elements and modelling objectives

Jurrens et al. [41] started defining the information categories, attributes, and relationships for development of a common representation of manufacturing resource elements. This effort was identified as an industry need by the NIST Rapid Response Manufacturing (RRM) program. Wilczynski and Lipkis [42] started modelling industrial CNC machine tool structures with the knowledge representation language known as “LOOM”. However, the use of LOOM remained controversial due to the high start-up cost and difficulty in handling semantic terms in machine tool modelling. Zhang, et al. [33] proposed an object oriented manufacturing resource modelling (OOMRM) approach for describing manufacturing resource capability and capacity in an object oriented manner. They modelled machine tool capability into three classes, namely shape capability, dimension and precision capability and position and orientation capability. These capabilities were mapped into part specifications, such as feature form, feature precision and feature position. They were able to map available machine tool resources onto the product model. However, this approach is more machine tool resource specific and could not be used for agile or reconfigurable manufacturing systems. A similar object oriented resource allocation/pricing system was also proposed by Erdogan and Teo [43] to manage the resources of a Flexible Manufacturing System.

Suh at el. [32] have pioneered the work in the development of internet based virtual machine tools. A prototype of web based virtual machine tools representing the geometric model of machine tool and kinematic movement of different elements to represent actual machining processes has been developed. The machine tool model includes modules for defining the configuration of the overall machine tool structure, the geometric shape of mechanical units, and the kinematic relationship between mechanical units. This bottom-up modelling approach considers basic mechanical units of the machine tool, such as bed, column, spindle, and table as shown in Figure 2. Although this model is capable of representing machine tools from a functional point of view, classifying machine elements under a parent class decreases the versatility of the resource model. The main emphasis of this model was on presenting functionality of the machine tool, which was well achieved.

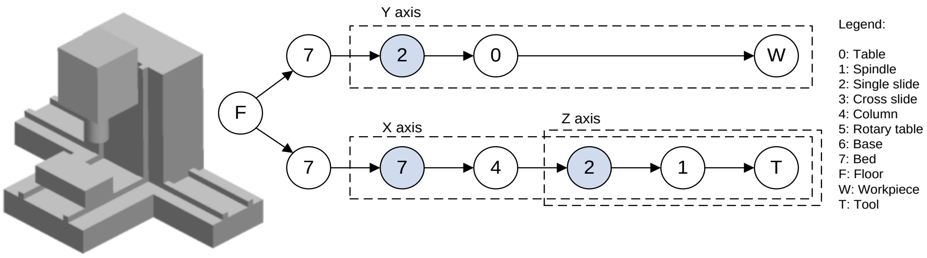

Figure 2: Different machine elements and related connectivity graph representing machine structure [32]

Seo et al. [44] presented a rule based machine tool structural model for supporting manufacturing requirement of the product model. Reconfigurability of the machine tool was focused to cope with the machining requirements of the part. Depending on the user’s input, the model locates a possible combination of different machining elements from the model library. These predefined combinations of machine elements were represented with connectivity graphs. An extension of this module was able to simulate the machining tool path with the help of a virtual reality modelling language (VRML). Yao et al [45] presented similar web based architecture for remote collaborative design of the NC machining process and the NC program. Shabaka and Elmaraghy [39] presented a bottom-up approach for constructing and representing Reconfigurable Manufacturing System. This approach gives a basis for selecting different type of machines and their appropriate configurations to produce different types of parts and features. The developed approach was general in nature and not limited to RMS. It was applicable to any manufacturing system where dynamic and flexible process planning and machine assignments are required.

The key problem of structuring the information models to support the interactions between fixture design, process planning and product design was reported by Bugtai and Young [46]. These issues related to the data structures required for product and manufacturing capability models were discussed and potential object-oriented solutions were proposed using Booch notations. Paris and Brissaud [47] explained the machining process planer's view requirement in the process planning stage. They extracted the process planning point of view from the product model by filtering the information useful in this view. Finally a system was developed which can determine suitable fixturing solutions to machine the part. Mervyn, et al. [48] developed an information model describing fixture design knowledge and specification to improve the product quality and reduce product lead-time. The output of the conceptual fixture design activity is the information model and the conceptual design fixturability feedback. This information model provides product designers with feedback on fixturability problems and also provides a metric for product designers to compare different initial designs in terms of fixturing concerns. Ong et al. [49] proposed a resource support system which includes a virtual machine library, a virtual cutting tool library, a virtual fixture library, and a material library necessary to serve a complete virtual manufacturing system. Yao, et al. [45] divided automatic setup planning into two sub-tasks: setup planning in part level and in station level in which fixtures and machine tools were selected to machine several parts sequentially on machine tools. Machine tool capability measures were also considered, such as tool approach directions (TADs), machine accuracy, table size and motion range, and combinations of fixture and cutting tool geometry.

Tao, et al. [50] proposed manufacturing resource conceptual model (MRCM) for representing capability of the machine tool by abstracting the correlative conceptions and characters of the manufacturing resource, which was then proved to be able to provide uniform and complete resource information by supporting the data exchange in a collaborative manufacturing environment. Arslan et al. [51] developed a decision support system for the selection of machine tools, which guides the selection process and helps a decision maker to solve the selection problem. They created a machining centre database with machine properties and decision criteria. The decision criteria were evaluated as a function of machine properties. Wang et al. [52] proposes a methodology for evaluating the manufacturing ability of equipment in a multi-agent-based virtual manufacturing enterprise by enveloping the manufacturing information of the various equipments as an equipment agent.

Lopez-Ortega and Ramirez [53] proposed a manufacturing resource model (MIS) for representing flexible manufacturing resources such as CNC machine tools, robots, automatic guiding vehicles, etc. EXPRESS was chosen to model these flexible manufacturing system elements. Java language was used to implement the MIS, the server and the client application. This approach was reported to be a sound solution to improve manufacturing integration. However, some information loss was reported while transferring a model from one CAx application to other. Finally EXPRESS based translator was developed to eliminate these barriers and to build a bridge among information islands. Same justification was given by Souza et al. [54] while developing a manufacturing resource models for using EXPRESS. Choi et al. [55] presented a method to express STEP data using XML as a core technology of the repository. They presented a STEP-NC repository that stores and supports exchange of STEP data in XML. TurnSTEP was developed to provide a distributed architecture for e-manufacturing. Campos and Hardwick [56] proposes an information model for tracing CNC manufacturing operations. For each manufacturing operation object in the AP-238 file (e.g. a drilling operation), a new set of traceability objects was created each time the operation is performed. These objects trace the specific resources (for instance a drill tool serial number, or a raw material lot number) and the specific process conditions (time, etc.).

3.2 CNC CONTROLLERS FOR PRESERVING MANUFACTURING CONTEXT

Figure 3 depicts the differences between the current state of art in NC manufacture using ISO 6983 where data flow is unidirectional from the CAD/CAM system to the CNC and bi-directional when using STEP-NC. Although this approach has been partially adopted commercially by some CAM/CNC systems such as by Mazak with their CAMWARE/Mazatrol system, these systems use their own proprietary data format which does not allow integration into a company's product and manufacturing data models. In addition, when using ISO 6983 the information available in the CAD/CAM system is partially lost when post-processed into G/M codes, as the standard does not provide support for most of the information [57].

In comparison, the ISO 14649 standard provides a feature based object oriented data model for the next generation of intelligent CNC's [13]. It is systematically detailed with a structured data interface that incorporates the component geometry through feature-based programming. In addition, Figure 3 also illustrates the major differences in use between the ISO 6983 and ISO14649. STEP-NC describes different types of operations, an extensive feature catalogue, tool library, and technological details for different manufacturing processes. However, there is an inevitable need for a representation of machine tool resources for developing machine specific process plans. Reviewing the capability of STEP and STEP-NC with the various domains of manufacturing systems, authors believe that a STEP-NC compliant machine tool resource model would be the best vehicle for developing a neutral file format for exchanging machine tool resource functionality knowledge.

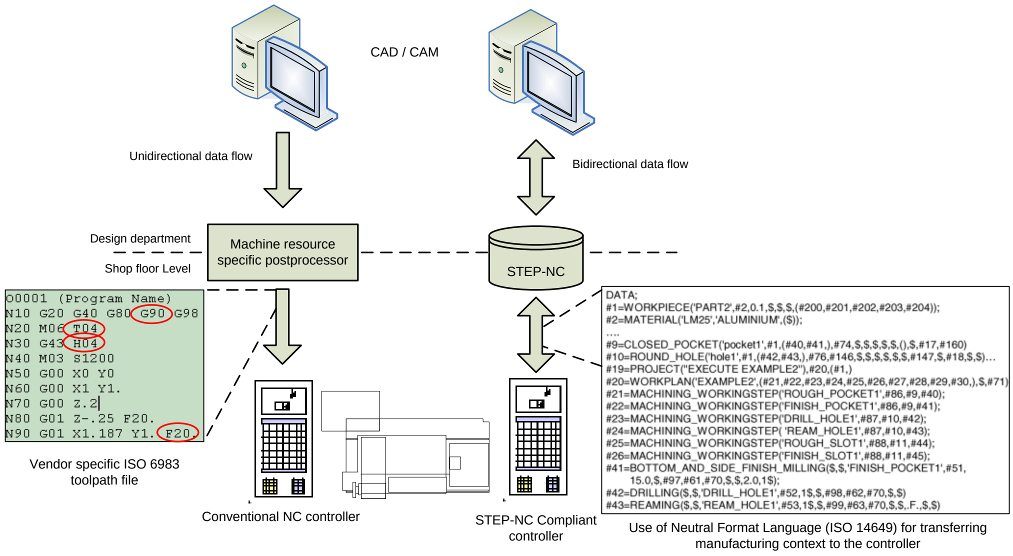

Figure 3: Differences between the data flow using of ISO 6983 in NC programming and with the use of ISO 14649.

Although an abundant amount of literature utilises various objective oriented machine tool resource viewpoints, very few machine tool resource modelling methods are reported in the literature. The necessity for machine tool resource data representation was addressed by Suh [58] in the STEP-Manufacturing meeting held in Funchal, Portugal. He proposed a new work item proposal (NWIP), namely the 'Machine tool data model for general manufacturing processes'. This part of the machine tool data model has been designated as Part 110 of ISO14649. The model presented at this meeting constitutes different machine elements such as spindle, slide, swivel table, column, table, cross slide, base, column base and bed. However, using this approach [32] for process planning would require more machine specific information like maximum feed limit and swing angle of the swivelling head of the machine tool. The process plan also needs simultaneous axis engagement information such as the multi-tasking machine tools. Another comprehensive machine tool resource model was also proposed by National Institute of Standards and Technology (NIST) which contents detailed information regarding machine tool elements [58]. This model considers the majority of standard machine elements including specification of the NC controller. However, machine description in this model still follows a hierarchical classification. Machine tools are classified into milling type and turning types. This approach may limit model validity and could not be used for complicated multi-tasking machining centres.

4. UNIFIED MODEL FOR REPRESENTING VARIOUS CNC MACHINING SYSTEM ELEMENTS

The available literature on CNC machining system representation can be classified into various resource domains as shown in Figure 4. The manufacturing resource information models developed provides only a objective oriented representation of available machine tools as a resource for shopfloor execution systems without having the proper methodology for deriving its capability associated with different machine elements. The reason for this is that the machine tools modelling methodologies in integrated design and manufacturing has been overlooked and not thoroughly explored. These approaches can prescribe what the capability of the machine is, but they can not answer how to derive that capability. They possess the necessary information structure to represent machine tool capability, but very few of them have an integrated data model for describing various machine tool elements. For example, a data model for representing machine tool capability can neither represent fixture library nor cutting tools for various machining processes.

One of the most important objectives of CNC machining system resource modelling is to represent process capability. Process capability of the machine tool depends on different axes attached to the machine elements. For example, attaching one linear axis and one rotational swivelling axis to the machining head of the milling machine enables tool movement inclined to the table plane, as shown in Figure 5, namely a simple drilling operation. The machine is capable of drilling this inclined hole due to the rotational swivelling axis attached to the machining head. The authors believes that keeping the type of machining process detached from the machine model would simplify the capability representation of the machine tool resource model.

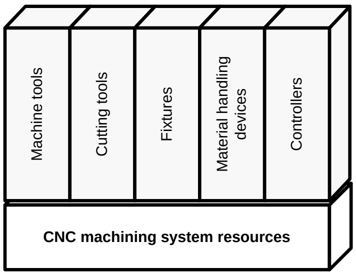

Figure 4: CNC machining system resource domains

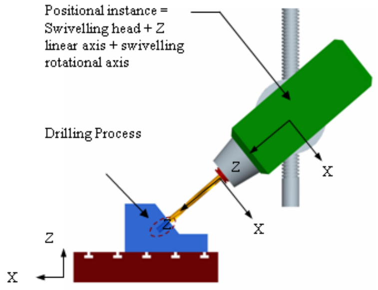

Figure 5: Machine tool resource capability representation

Based on the reviews undertaken in section 2 and 3, the authors believe that a standardised approach to machining system representation is a potential area to be researched. Although some research work on workpiece and tool handling system representation [43, 53] has been undertaken, synchronising these workpiece and tool handling systems representation with a machine tool data model requires a unified data model which can model machine tools with attached auxiliary devices. Other auxiliary devices such as pallet changers, tool magazines, tool bank inventories and workpiece changers are essential elements in the manufacturing system to represent unified functionality of the manufacturing facility.

Hence a Unified Manufacturing Resource Model (UMRM) to have been envisaged a versatile data model which can represent any CNC machining system resources such as machine tools attached with auxiliary devices and material handling systems, as shown in Figure 4. The rest of the paper presents a flexible approach of the Unified Manufacturing Resource Model for representing the diverse spectrum of machine tool configurations. This approach can represent the functional aspect of the machine tool without the limitation of classifying the machines into technological groups (i.e. milling, turning, grinding etc) [59] or application groups (i.e. machining, material handling etc) [60] and easily leads itself for representing multi-process machine tool configurations.

5. A Unified Manufacturing Resource data Model (UMRM) for representing CNC machine tool elements

UMRM has the novel capability to provide the required information regarding CNC machine tools and attached auxiliary devices to automate process planning decisions. Manufacturing resources are represented using STEP compliant method including ISO 10303-21 [61].

5.1 MACHINE TOOL AND MECHANICAL MACHINE ELEMENTS

A machine tool can be considered as an assembly of a various mechanical elements intended to convert a workpiece into finished product. There are numerous manufacturing processes which takes place to manufacture such a product. Some processes remove material with a physical cutting tool, others form the workpiece in to a desired shape and some processes are energy based (eg. EDM, laser cutting, plasma cutting, heat treatment etc). There are also processes which manufacture positive features by depositing material (eg, welding, rapid prototyping, etc). These processes have different technological principles, and thus carry very specific technological data. A common aspect amongst these applications is the assembly of mechanical elements which enable the desired position between workpiece and the tool to execute the desired manufacturing operation.

UMRM considers the machine tool as an assembly of various mechanical machine elements and auxiliary devices linked with each other as shown in Figure 6. The link between two elements may be transitional, rotational or rigid. The purpose of each mechanical element in the machine tool is to alleviate machine capability. When different mechanical elements are assembled, they form a single unit of the machine tool. Assembling several units together would then represent the whole machine tool structure. The description of the possible movements between these mechanical elements demonstrates the positional capability of the machine tools.

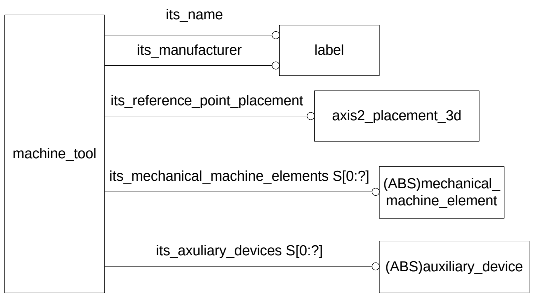

Figure 6: UMRM entity machine_tool

Each mechanical machine element (Figure 7) is identified by its name. It may have one or more mechanical machine elements attached. Each element inherits its functional machine element such as the turret, table, chuck, tool clamping unit or tool locater. This mechanical machine element may have some axes of movement attached to it. Attaching individual axes to mechanical machine elements represents their degrees of freedom. The entity, axis has two subtypes: linear_axis and rotary_axis. When several axes are attached to the mechanical machine element, its represents a mechanical machine element capable of moving in different directions. Finally this mechanical machine element may holds a cutting tool or workpiece. Figure 7 represents entity mechanical_machine_element and different attributes attached with it.

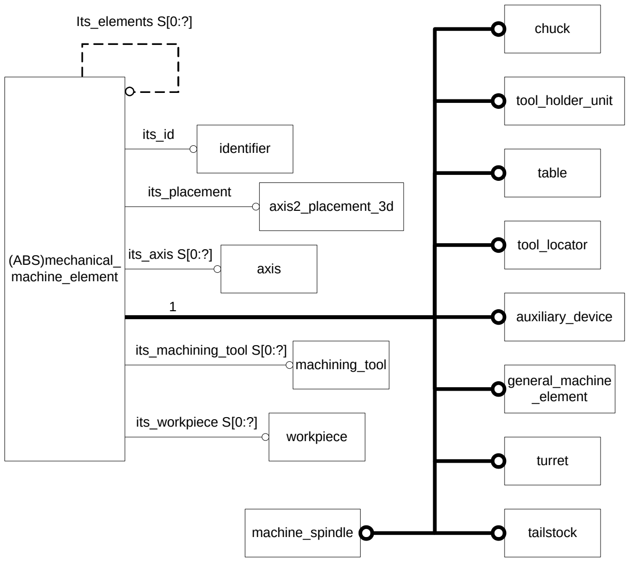

Figure 7: UMRM entity mechanical_machine_element

The major advantage of modelling using a mechanical machine element is to preserve the flexibility of the resource model to represent any customised machine element. The starting point of the assembly is a machine tool frame. Each element of the machine tool can be considered as a mechanical machine element which holds another mechanical machine element. For example, the machine tool frame is one type of mechanical machine element. It holds another mechanical machine element, the double turret holder. The double turret holder holds two turrets. Each turret has a set of tool locaters. Each tool locater holds another machine element such as a small collet chuck, tool clamping unit or bar stop mounted on the turret. This concept of resource modelling can be extended to represent whole tool holder assembly as shown in Figure 8. A machine element 'spindle' holds another machine element 'tool holder'. The tool holder holds another machine element 'collet', and finally, the collet holds the cutting tool. It is possible to model auxiliary systems like pallet changers, workpiece changers, and tool changers with this modelling approach.

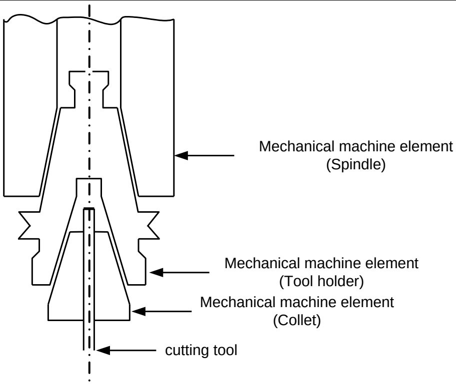

Figure 8: A typical tool holder assembly

5.2 BASIC MACHINE STRUCTURE AND ITS KINEMATICS

The kinematic aspects of the mechanical machine element can be represented with the entity 'axes'. Each mechanical machine element may have a set of axes attached. As shown in Figure 9, axes can be subdivided in to rotary and linear axes. Rotary axes are capable of representing minimum and maximum rpm of the spindle. The rotary index type of movement represents indexing movement of circular or linear turret head. Swivelling motion of the machine head or table can be measured with the entity 'plane_angle_measure'. The linear movement of a mechanical machine element has two types: feed_movement and rapid_movement. These movements are attached with a Boolean operator. The travelling range of the mechanical machine element is referenced from its representation point. This data model considers servo drives attached to the axes. Any displacement of the mechanical machine element is directly proportional to the corresponding servo drive input. Plotting displacements of all servo drives against a single time line would represent the simultaneous movement of all mechanical machine elements.

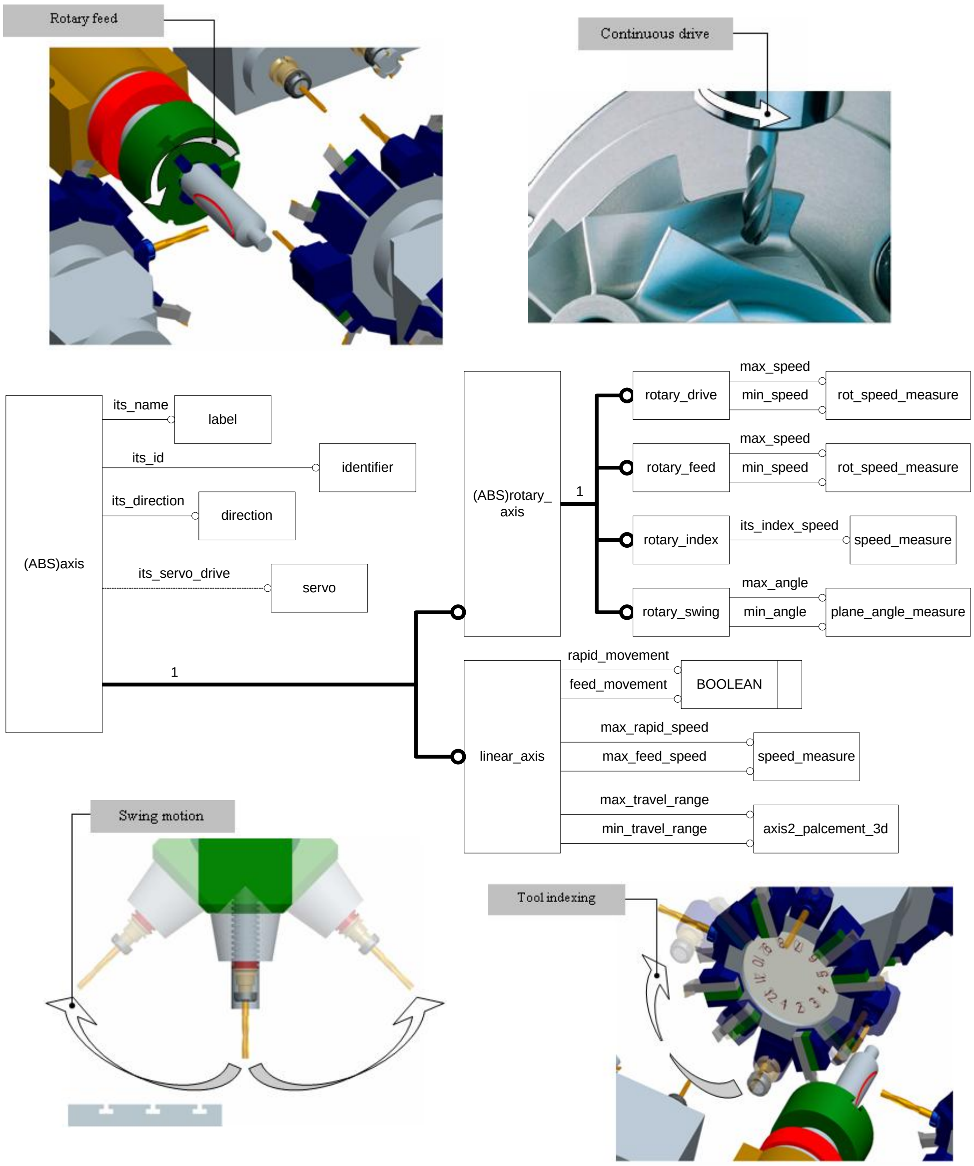

Figure 9: UMRM entity axis and corrosponding representation of various rotary axes

Rotary motion in CNC machining centres can be subcategorized as (Figure 9): Drive motion, which continuously drives the cutting tool or workpiece held in the main spindle; Feed motion, which is known as C axis in the case of turning centres for controlling the rotary feed of the workpiece in a turn-milling operation; Indexing, which is required to index the desired tool mounted on the turret; and Swing motion, which describes the tilting position of the machining head such as in a 5 axis vertical machining centre. All these motions and associated specifications are illustrated in the EXPRESS-G diagram as shown in Figure 9. For example, the entity rotary_axis is capable of representing minimum and maximum spindle speed and rotary spindle feed (C axis). It is possible to synchronise the rotation of the headstock spindle (C-axis) with the axial or radial movement of the rotary head to cut spiral grooves, shown in Figure 9. The rotary index type of movement represents the indexing movement of a circular or linear turret head. The Swivelling motion of the machine head or table can be measured with the entity 'plane_angle_measure' [62].

5.3 TOOL AND WORKPIECE HOLDING ELEMENTS

A machine spindle can be modelled as a type of mechanical machine element which holds various cutting tools such as drills, end mills, boring bars, grinding wheels, face mills, taps etc. Usually, the machine spindle is mounted on the machine slides to facilitate the various degrees of freedom to the cutting tool. A chuck is the most common machine tool element used in the turning centres to hold the workpiece. The two main types of work holding devices used in the turning centres are the jaw and collet chucks. Various attributes of the entity chuck are represented in the EXPRESS-G diagram shown in Figure 10.

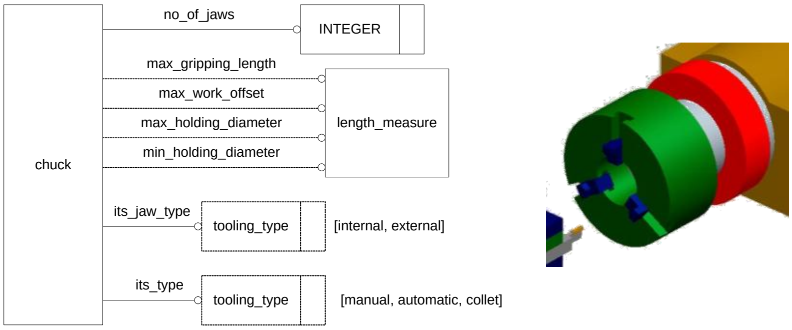

Figure 10: UMRM entity chuck and its attributes

The table is a machine tool element which is mounted on the machine tool slideway to install workpiece fixturing systems. Usually 3 axis machining centres employ a rectangular table which can move with the machine slides associated with it. A circular table is usually used on the 4 and 5 axis machining centres to facilitated rotation of the workpiece. Nevertheless, tables on a vertical turning centre can also hold cutting tools to perform inverted turning and milling operations. Typical machine tool tables have threaded holes or standard T-slots to enable location of a fixturing system. The entity table in the EXPRESS-G diagram as shown in Figure

11 has an attribute clamp_locator for representing location of such bolt holes on the table. This entity is very important for planning a fixturing system on the machine tool while developing a process plan. There are separate rotary tables available on the market to enhance the capability and productivity of the 3 axis machining centres. These tables can be mounted on the machine tool table and also can act as a pallet indexer to machine multiple workpieces in a single machining setup. Such machine tool accessories can be modelled by attaching entity mechanical_machine_element to the parent machine tool.

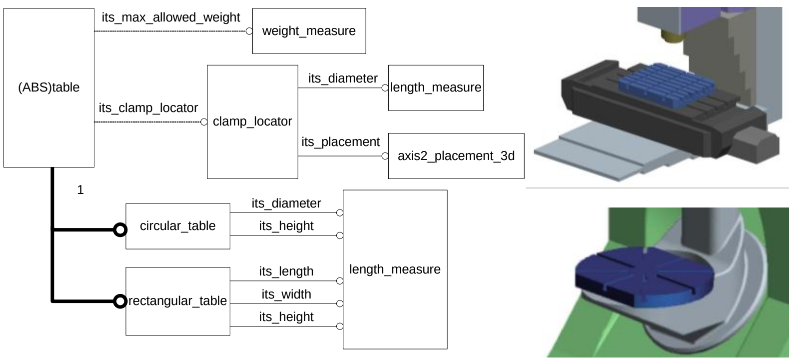

Figure 11: UMRM entity table

The turret is the most important machine tool element for turning centres which holds the cutting tools in different directions. Generally there are three types of turret heads, namely standard type, VDI type, and combination type. Standard type turret heads has a shank type clamping as shown in Figure 12. It has several tool locating sockets which could be square, round, threaded, tapered, or bolting holes as shown in Figure 12. Live tooling are rotating or milling tools which are typically mounted on the VDI turret heads.

This unified machine tool resource modelling methodology considers the tool locating socket of the turret head as an autonomous entity to capture a wide diversity of socket standards under a single entity. The tool locating socket is considered as a part of the tool locater and has been described with the entity tool_locating_socket in the following section. The tool locator is considered as an independent mechanical_machine_element. Thus, the turret carries a set of tool locaters, where each tool locater holds another machine element such as a small collet chuck, tool holding unit or bar stop. Figure 12 illustrates the entity turret and its essential attributes.

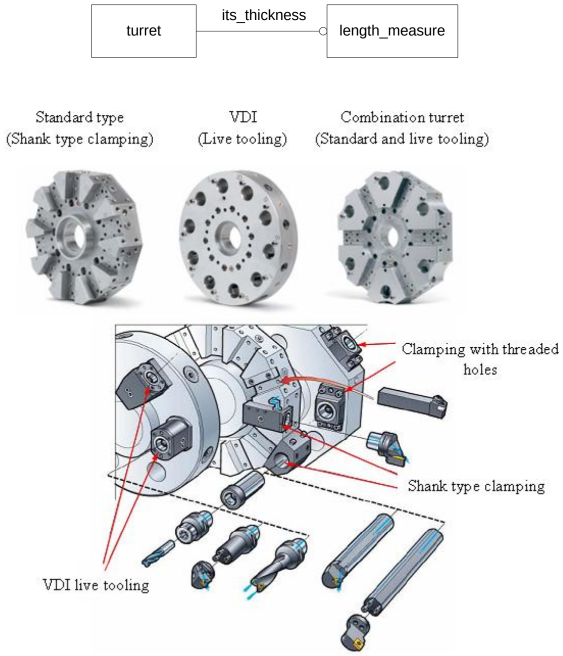

Figure 12: UMRM entity turret and its details

The EXPRESS-G diagram for an entity tool_locator is shown in Figure 13. This entity can represent all types of tool locating sockets of the turret head by using attributes of entity tool_locating_socket as shown in Figure 13. The type of tool can be declared with the attribute named its_tooling_type.

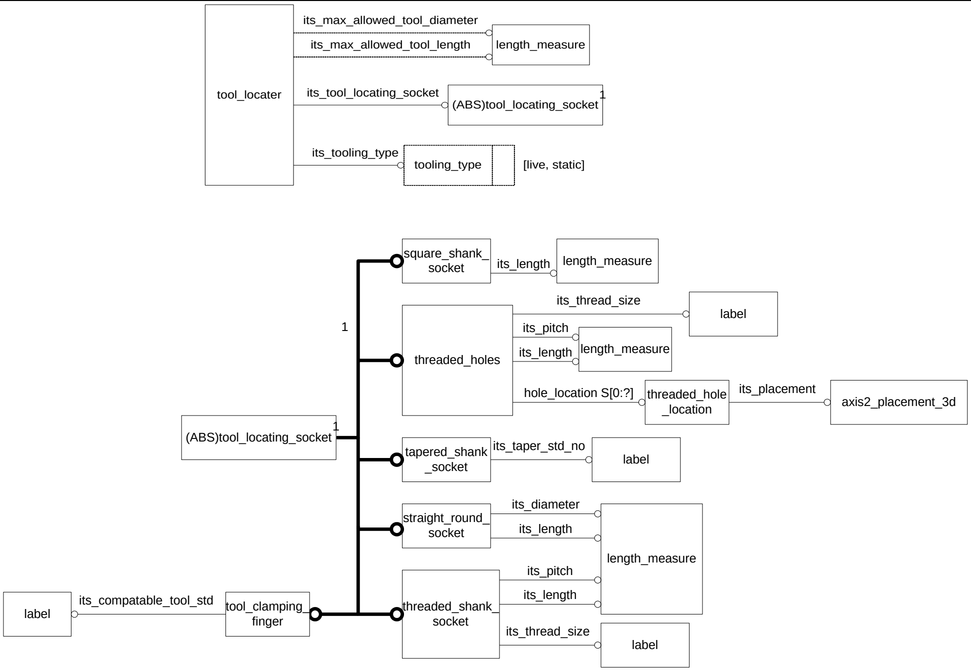

Figure 13: Entities tool_locator and tool_locating_socket

Machine tool manufacturers customise their units for holding tools and workpieces. Though there is an abundant diversity in the design of tool or workpiece holders, the common element among these units is their purpose, namely to hold; either a workpiece and/or a tool. The UMRM for machine tool resources emphasises the role of these elements. Figure 14 illustrates an arrangement of tool locaters around turret. A tool locater has axis orientation and is referenced from its parent mechanical machine element. For example, the turret in Figure 14 has 12 tool locaters. Each tool locater is referenced from the turret presentation point. Their placement and orientation is given in Table 1. It should be noted that any type of turret can be modelled in this way. After referencing the tool locater positions from the turret presentation point, any tool clamping unit or tool holder can be mounted on the tool locater. This new machine element is now referenced from the corresponding tool locater presentation point.

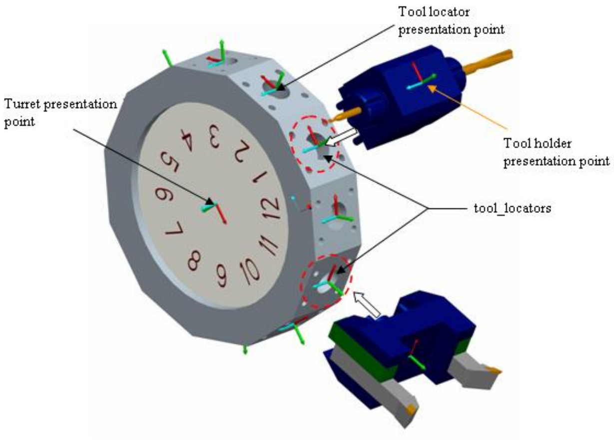

Figure 14: Representation of a turret, tool locator and tool holder

Table 1: Placement and orientation of 12 tool locaters

Representation points	Radius and angle with respect to turret reference point	Axis (Z axis)	Ref_direction (X axis)
Turret presentation point	-	[0,0,1]	[1,0,0]
Tool locater: T1	(144.89, 180°)	[0,0,1]	[-1,0,0]
Tool locater: T2	(144.89, 210°)	[0,0,1]	[-0.86,-0.5,0]
Tool locater: T3	(144.89, 240°)	[0,0,1]	[-0.5,-0.86,0]
Tool locater: T4	(144.89, 270°)	[0,0,1]	[0,-1,0]
Tool locater: T5	(144.89, 300°)	[0,0,1]	[0.5,-0.86,0]
Tool locater: T6	(144.89, 330°)	[0,0,1]	[0.86,-0.5,0]
Tool locater: T7	(144.89, 0°)	[0,0,1]	[1,0,0]
Tool locater: T8	(144.89, 30°)	[0,0,1]	[0.86,0.5,0]
Tool locater: T9	(144.89, 60°)	[0,0,1]	[0.5,0.86,0]
Tool locater: T10	(144.89, 90°)	[0,0,1]	[0,1,0]
Tool locater: T11	(144.89, 120°)	[0,0,1]	[-0.5,0.86,0]
Tool locater: T12	(144.89, 150°)	[0,0,1]	[-0.86,0.5,0]

The capability of a machine tool invariably relies on the use of a variety of cutting tools. The tool holding method employed is dependent on the machine tool resource specification. For example, a machine tool spindle, holding a tool locator with BT 40 tool location socket could only use BT 40 shank for holding a cutting tool. Figure 15 represents various types of tool holding units used in machine tools. The large majority of them hold cutting tools; while some tool holders may hold another tool holder for extending cutting tool length. Generally each tool holder has a tool locating socket and shank as shown in Figure 15. A tool locating socket holds another machine element and shank is used to locate a tool holder in another tool locating socket. Figure 16 illustrates an EXPRESS-G diagram of the entities tool_holder and shank.

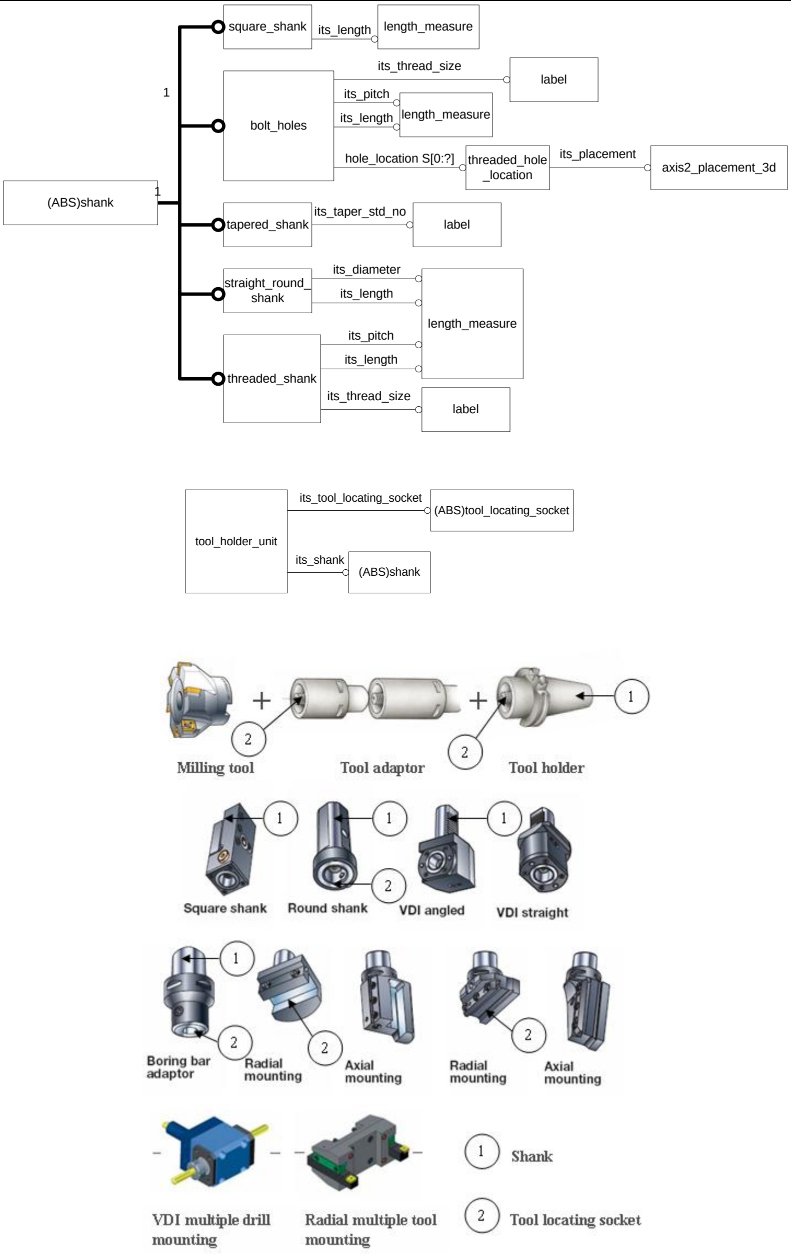

Figure 15: Various type of tool holder units and UMRM entities tool_holder and shank

Figure 16 illustrates an EXPRESS-G diagram for an entity auxiliary_device. This is a subtype of mechanical machine elements and inheritate various auxiliary devices. Kinematic aspects of the auxiliary device can be represented by using entity axis associated with its parent class mechanical machine element. The whole robotic arm assembly can be modelled in this manner to represent its movement and work space configuration.

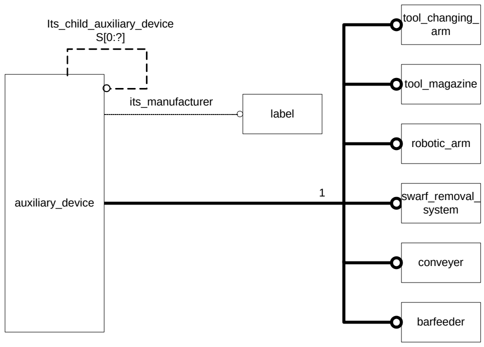

Figure 16: EXPRESS-G representation of the entity auxiliary_device

By far the most common machining centre tool magazine types are the chains, drums, or disks which are usually equipped with a double arm tool changer. Some machining centres have their tool changing position directly on the tool magazine without using a tool changing arm. The tool holding spindle approaches a tool changing position mounted on the tool magazine to grab or release a programmed tool. The important machine tool resource information for modelling tool magazines is given in the EXPRESS-G diagram shown in Figure 17. There are two major important positions considered in the modelling the tool magazine namely, the active_tool_changing_position and spindle_tool_changing_position. All types of tool magazines carry tools in a tool conveyer. This tool conveyer trajectory can be described with the entity representation_item [62]. Figure 17 represents actual tool magazine and tool changing position with tool conveyer trajectory.

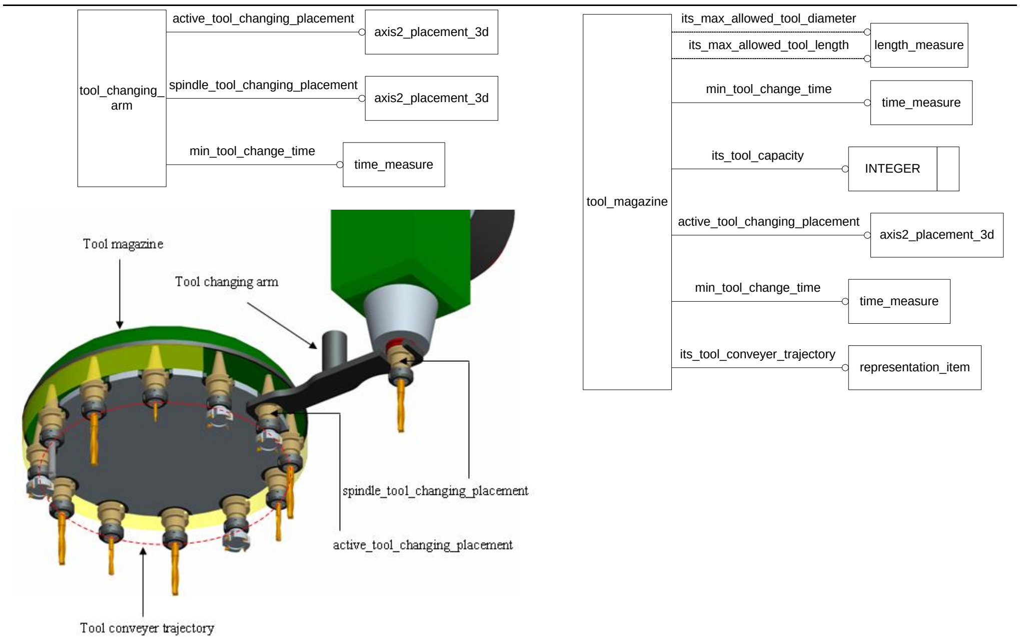

Figure 17: Illustration & EXPRESS-G model of the entities tool_changing_arm and tool_magazine

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6. Representation of CNC machine tools: Case study

6.1 INDEX C65 Machine elements

CAD/CAM systems support turn-mill machines, but due to the complexity of the machine designs it is difficult to completely prove out part program without a kinematic model of the machine. Thus, there are still shortcomings in using the turn-mill machines in manufacturing industry. Some of these shortcomings include: few CAD/CAM systems supporting simultaneous turn-mill machining processes; few tool path generation methods for the special turn-mill machining, and extremely large variety in machine configuration. It is worthwhile to provide an instance of the machine resource model with an example of such highly reconfigurable machine tools.

Figure 18 shows the basic construction of an INDEX C65 [63] multi-turret and multi-spindle lathe. It has a basic mechanical machine element called a machine frame, which holds the other mechanical machine elements such as the stationary work spindle, double turret bed, travelling work spindle and a single turret head. No axes, machining tools or workpieces are attached to the machine frame. It has a distinct representation point which can be referenced from the factory coordinate system to represent the machine location in the factory. The machine frame placement and orientation can be declared with the STEP entity ‘axis2_placement_3d’.

Figure 18 illustrates the use of the entity ‘axis’ for representing the kinematics of different units mounted on the INDEX C65. A stationary work spindle unit is attached only with a rotary axis. It is capable of giving continuous rotary drive movement with a controlled rotary feed. No linear axes are attached to it. The chuck is another mechanical machine element mounted on it. There is a travelling spindle capable of moving in Z and Y axis. Linear movement can be expressed by attaching a linear axis to the mechanical machine element. Each linear axis has a travelling range referenced from the presentation point of the mechanical machine element. The double turret head has swivelling movement (A axis) about the X axis, and is represented by attaching a rotary swing type axis to the turret head. Turret and various tool holders, as described in section 5.3 are another type of mechanical machine elements mounted on the turret head. Thus, proposed data model can exhibit various kinematic links and movement constraints between workpiece and available cutting tools mounted on the machine tool. A controller which uses this data model can model functionality any machine tool or auxiliary device present in the CNC machining system.

6.2 INDEX C65 REPRESENTATION USING A STEP PART-21 FILE

The INDEX C65 is a multi-spindle, multi-turret turning lathe, capable of all 5 axis milling and turning operations. Its capability plays a very important role in the process planning stage. Specific machine details like actual tools present on the machine, axis travel ranges can be represented in the part 21 file [61] as shown in Figure 19. The UMRM is capable of providing such detail for planning this operation on the machine tool. For example, Figure 5 shows an inclined hole drilling operation. In the process planning stage, machine specific details such as maximum tilting angle of the machining head, available tool, travel limits, tool length must be available to map process specific details on the product data. A Part 21 file can then be generated to populate the machine specific resource data to enhance the process planning capability.

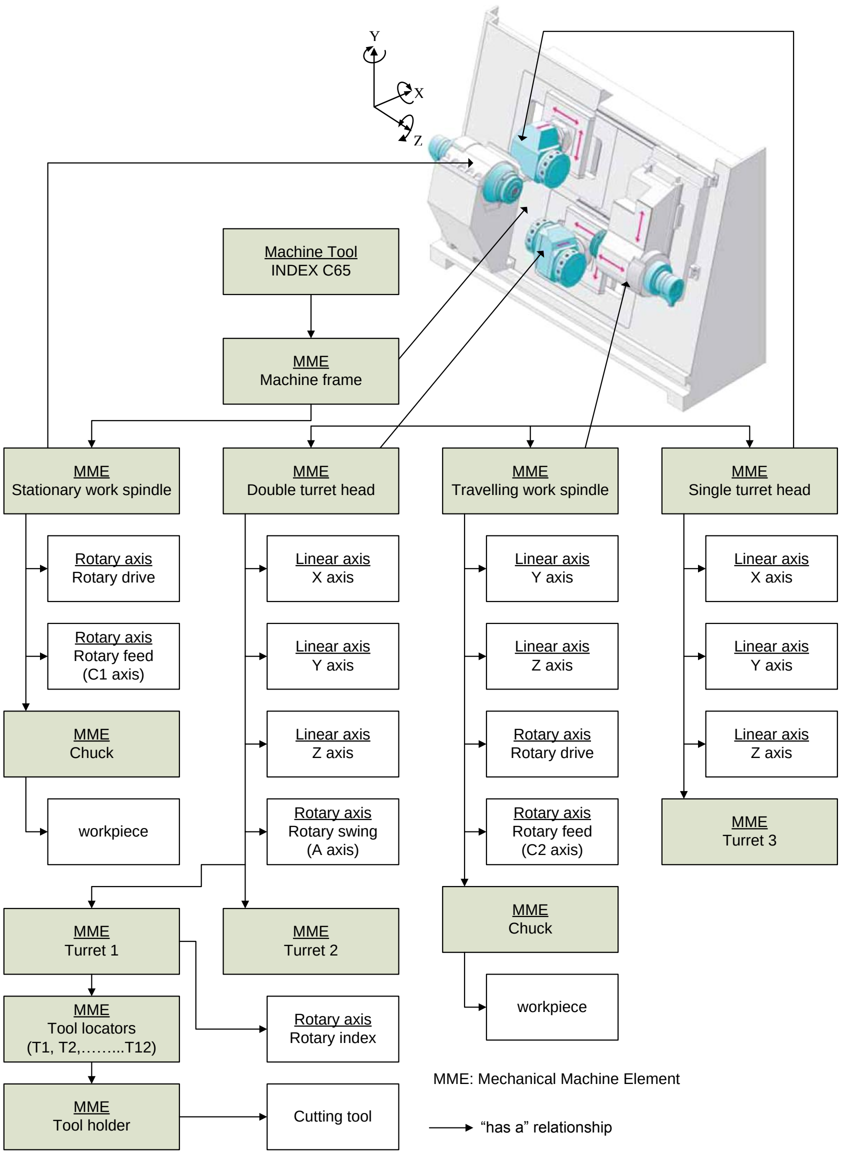

Figure 18: Construction and Model Representation of an INDEX C65

```
ISO-10303-21;
HEADER;
FILE_DESCRIPTION(('INDEX C65 MANUFACTURING CELL','INDEX C65'),'1');
FILE_NAME('INDEX_C65.STP','2008-08-04',('PARAG VICHARE','AYDIN NASSEHI','STHEPHEN
NEWMAN'),('UNIVERSITY OF BATH'),$,'ISO14649',$);
FILE_SCHEMA(('MACHINING_SCHEMA','TURNING_SCHEMA','MILLING_SCHEMA','MILLING_TOOL_SCHEMA','TURNING
_MACHINE_TOOL_SCHEMA','MACHINE_TOOL_RESOURCE_SCHEMA'));
ENDSEC;

DATA;
#1=LOGICAL_MANUFACTURING_UNIT('INDEX C65 MANUFACTURING CELL',(),(#2),());
#2=MACHINE_TOOL('INDEX C65','INDEX','MANUFACTURING LAB',#3,(#7),());
#3=AXIS2_PLACEMENT_3D('MACHINE TOOL PLACEMRNT',#4,#5,#6);
#4=CARTESIAN_POINT('MACHINE TOOL COORDINATES',(0.0,0.0,0.0));
#5=DIRECTION('MACHINE TOOL AXIS',(0.0,0.0,1.0));
#6=DIRECTION('MACHINE TOOL REF DIRECTION',(1.0,0.0,0.0));
#7=MECHANICAL_MACHINE_ELEMENT('INDEX C65 MACHINE FRAME',#8,(),(#12,#13,#14,#15),(),());
#8=AXIS2_PLACEMENT_3D('MACHINE FRAME PLACEMENT',#9,#10,#11);
#9=CARTESIAN_POINT('MACHINE FRAME COORDINATES',(0.0,0.0,0.0));
#10=DIRECTION('MACHINE FRAME AXIS',(0.0,0.0,1.0));
#11=DIRECTION('MACHINE FRAME REF DIRECTION',(1.0,0.0,0.0));
#12=MACHINE_SPINDLE('STATIONARY WORK SPINDLE',$,(#16,#18),(#20),(),(),$,$);
#13=MECHANICAL_MACHINE_ELEMENT('DOUBLE TURRET HEAD',$,(#21,#23,#25,#27),(#29,#30),(),());
#14=MACHINE_SPINDLE('NULL',$,(),(),(),(),$,$);
#15=MECHANICAL_MACHINE_ELEMENT('NULL',$,(),(),(),());
#16=ROTARY_DRIVE('STATIONARY SPINDLE ROTARY DRIVE',#17,$,18000.0,$);
#17=DIRECTION('STATIONARY SPINDLE ROTARY DRIVE',(0.0,0.0,1.0));
#18=ROTARY_FEED('STATIONARY SPINDLE ROTARY FEED AXIS C1',#19,$,33.0,$,0.0010);
#19=DIRECTION('STATIONARY SPINDLE ROTARY FEED C1 DIRECTION',(0.0,0.0,1.0));
#20=CHUCK('CHUCK 1',$,(),(),(),(),3,20.0,.INTERNAL.,$,15.0,60.0,.AUTOMATIC.);
#21=LINEAR_AXIS('LINEAR X AXIS',#22,$,.T.,.T.,80.0,20.0,0.0010,250.0,250.0);
#22=DIRECTION('LINEAR X AXIS DIRECTION',(1.0,0.0,0.0));
#23=LINEAR_AXIS('LINEAR Y AXIS',#24,$,.T.,.T.,50.0,20.0,0.0010,420.0,0.0);
#24=DIRECTION('LINEAR Y AXIS DIRECTION',(0.0,1.0,0.0));
#25=LINEAR_AXIS('LINEAR Z AXIS',#26,$,.T.,.T.,50.0,20.0,0.0010,0.0,380.0);
#26=DIRECTION('LINEAR Z AXIS DIRECTION',(0.0,0.0,1.0));
#27=ROTARY_SWING('ROTARY AXIS A',#28,$,108.0,0.0,0.0010);
#28=DIRECTION('ROTARY AXIS A DIRECTION',(0.0,0.0,1.0));
#29=TURRET('TURRET 1',$,(),(),(),(),50.0);
#30=TURRET('NULL',$,(),(),(),(),$);
#31=ROTARY_INDEX('ROTARY INDEX AXIS',$,$,0.4,$);
#32=DIRECTION('NULL',());
```

Figure 19: Extract of a Part 21 file for INDEX 65 resource representation

8. FURTHER DEVELOPMENTS / APPLICATION HORIZON

Further developments, especially for modelling the application oriented behaviour of the resource elements, are aimed at the extension for developing a Unified Manufacturing Resource Model (UMRM) which can model whole CNC machining system. Resource information can be considered as a core factor in the manufacturing system to support various application areas as shown in Figure 20. For example, in global manufacturing practice [64], the decision of facility selection is preliminary dependent on the manufacturing capability of the facility. Without the availability of information corresponding to the CNC machining system resources, it is very difficult for manufacturers to automate the decision making process and the process planning of the manufacturing activities. Hence, manufacturing resource models must have a consistent data model that can represent the large variety of the CNC machining system elements of such discrete production facilities.

Another vital application area is development of a standardised controller for CNC machine tools. ISO 14649 [13], a data model for computerised numerical controllers, is a result of international efforts towards standardising and integrating information flow, all the way from CAD to CNC machine tools. The proposed UMRM is STEP-NC compliant and offers a flexible approach to model various elements in the CNC manufacturing system. By use of complete resource information, resource specific process planning decisions can be made on the CNC controller. Other potential application areas for exploiting the use of UMRM are resource specific tool path planning, development of a manufacturing decision making system which can provide manufacturing alternatives in the case of an unexpected resource failure, process cost estimation, work scheduling, design of the virtual factory etc. Nevertheless, by measuring servo input of the each and every axis of the CNC machining system, UMRM can be utilised for designing optimum energy efficient [65] process planning. The core requirement to develop these applications is the information regarding available resources.

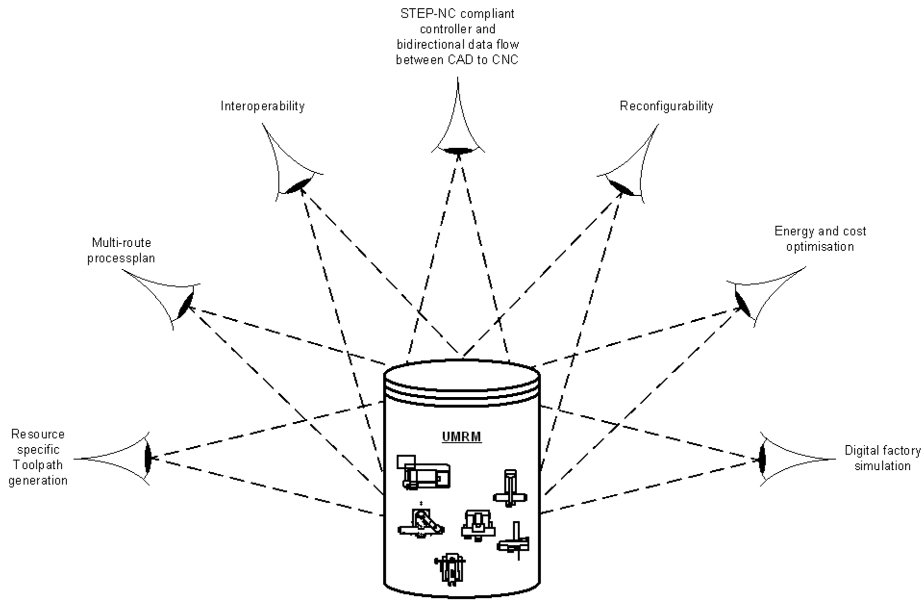

Figure 20: UMRM application horizon

9. CONCLUSION

The authors have proposed the flexible modelling approach for representing various elements in the CNC machining system. The paper also reviews the existing machine resource models and associated international standards which primarily emphasizes a classification of machine tool elements for different types of machine tools. The advantage of the UMRM modelling approach over the current state of art is its ability to unify all machine elements under the parent class “mechanical_machine_element”. This parent class can represent any machine element or assembly of several machine elements. The proposed approach is also capable of modelling the minor details of the machine tool by mounting one mechanical machine element on another. UMRM’s data model enables the virtual manufacturing system to investigate the various attributes of the CNC machining system for various applications. One such attribute is the positional capability of the machine tools that can be achieved by utilizing the entity axis. The proposed machine tool resource model is based on a STEP compliant information modelling framework for presenting machine tool resource data for machine specific process planning stage. Thus, the authors believe this research forms the basis for a major breakthrough in developing a universal CNC controller for integrating a control of various CNC machine tools along with attached auxiliary devices due to its unified resource modelling approach.

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