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A STEP-compliant process planning system for CNC turning operations

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ABSTRACT

Over the last 50 years, there have been many significant enhancements in computer aided systems which have influenced the CNC technology. One area that can be considered as a bottleneck to these CNC enhancements, and in particular to interoperability in CNC manufacturing is G&M part programming (ISO 6983). To overcome this bottleneck, the new standard ISO 14649, known as STEP-NC, is being developed to provide detailed information on component design, process planning and machining strategies to manufacture parts for the next generation of intelligent CNCs. This standard forms the basis of a new paradigm shift in the CNC domain to support digital modelling of CNC manufacturing resources. The research in this paper aims to identify major issues and develop new software tools to demonstrate the feasibility of interoperable CNC manufacturing based on STEP-NC. Besides the literature review on recent research and development on STEP-NC, this paper proposes a Process Planning System (PPS) with surface roughness chosen as the process planning objective. PPS consists of five modules: program reader, process planner, STEP-NC CAD viewer, STEP-NC CAM viewer and program writer. The reader is responsible for interpreting the geometry and the manufacturing data from a STEP-NC text file into a stored data list. The process planner uses this data list and enables users to evaluate surface roughness based on a mathematical model. Through the STEP-NC CAD viewer, the part geometry can be shown and via the STEP-NC CAM viewer the toolpath can be verified. Finally, the writer converts the stored STEP-NC data of the system into an updated STEP-NC file. An example case study component is used to demonstrate the PPS and show the interfacing of the STEP-NC data.

1. Introduction

From its emergence in 1952, the Numerical Control (NC) machine tool has undergone significant improvements and has provided an ever-increasing important part in manufacturing. Many other relating technologies, including Computer Aided Design (CAD), Computer Aided manufacturing (CAM), Computer Aided Process Planning (CAPP), have advanced greatly coupling with the enhancement of computer technology. The term used to refer to an NC machine has evolved into Computer Numerically Controlled (CNC) machine, while the capability has been upgraded to support multi process, large volume range and high precision and geometrical complexity component production. It is possible to machine a complicated part involving different processes such as milling, turning and laser hardening on one CNC machining centre in a single setup, which is also contributing to the efficiency and machining quality like precision and surface roughness.

Compared with these machine tool and process developments however, the early NC machines and today's modern CNCs utilise the same standard for programming, namely G&M codes formalised as ISO 6983. This old fashioned programming language is famous for its low band-width information transferring ability, as it just describes the machine switch functions and the cutting tool movements. The manufacturing knowledge from the previous CA*x* (CAD/CAM/CAPP) systems has to be transformed into a set of low level machine tool actions by a post-processor, which isolates the CNC from the manufacturing chain. As a result of this single direction flow means, any information on the shopfloor level cannot be relayed back to the planning department. On the other hand, the increasing computing capability enables the CNC controller to manipulate more manufacturing information. However, only with the availability of comprehensive manufacturing knowledge the next-generation CNCs can realise the dream of intelligent control.

Generally, it is commonly recognised that the ISO 6983 standard has become a bottleneck for the advancement of CNC manufacturing because of the data noncompliance through the CAD/CAPP/CAM/CNC chain [1]. To eliminate this problem, a new standard known as STEP-NC has been developed since the late 1990s, which is formalized as an ISO 14649 [2]. As the replacing

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data interface for CNC, one of the expected benefits from STEP-NC is bringing the component geometry information into the controller. However, STEP-NC goes much further with a comprehensive data model that overcomes the lack of process planning information in ISO 6983 files [3]. Unlike the G&M codes, STEP-NC associates the machining objectives (CAD design data) with solutions (CAM process data required) in an object-oriented way. It does not need to define precisely the detailed axis movement of the machine tool, although it has the mechanism to incorporate it in the STEP-NC file. The aim of an STEP-NC is to provide the CNC with a comprehensive manufacturing data model and an interface to establish an intelligent controller. Furthermore, the new data interface is compliant with an STEP (ISO 10303), which is the major ISO standard for product information exchange throughout the product lifecycle. Through incorporating STEP data, STEP-NC builds up a bi-directional information highway between the CAD/CAM and CNC systems, without using the post-processor [4] and makes interoperable process planning and manufacturing feasible and a future reality [5].

STEP-NC provides a real opportunity and challenge to promote the improvement of manufacturing capability utilising high level and detailed information. As the potential interface for CNC, STEP-NC is still an evolving and improving international standard. It is expected that the implementation of STEP-NC will bring great changes to current CAD, CAM and CNC. These changes will provide industrial users and software vendors with new challenges to identify the new boundaries of current CA*x* systems [6]. For example, the STEP-NC compliant CNC will incorporate a CAM system which will take over some of the tasks from the offline CAM system, namely to adjust and optimise the STEP-NC programs, according to the available manufacturing resources and implement greater intelligence across the CA*x* process chain. Thus, both offline and shopfloor (CNC) CAM systems will play a critical role for STEP-NC to be a success and gain any significant advantage of an STEP-NC compliant CNC manufacture.

To date, the majority of STEP-NC research has focused on milling operations. In this research, a Process Planning System (PPS) for the next generation controller for turning is proposed. This paper introduces the PPS and outlines the mathematical model on which process planning is carried out. Finally, an example component is used to demonstrate the application of the system.

2. Literature review

Since its emergence, an STEP-NC has been one of the most popular research areas in the field of CAM engineering for more than ten years. This section reviews the specific area of STEP-NC based research and development for turning operation, process planning and new CNC controllers. It is worth mentioning that currently two versions of STEP-NC are being developed by an ISO. The first is the Application Reference Model (ARM) version of ISO14649 (i.e. ISO14649) and the other is the Application Interpreted Model (AIM) version of ISO14649 namely AP 238 [7]. These versions and developments with them in relation to interoperability and the CNC process chain are reviewed by Newman et al. [8].

The use of STEP-NC in manufacturing of asymmetric rotational parts have been explored by Rosso Jr. et al. [9]. They investigated the implementation method of STEP-NC to combine the turning and milling operation to solve the issue of complete machining of an asymmetric component on a single turning machine. The paper concluded that there is no need to develop new STEP schema specific for asymmetric parts, as the ISO 14649 Part 10 [10] is capable of supporting the feature representation of complex components. Chung and Suh [11] also addressed the problem of complete machining. They proposed a nonlinear process planning method utilising STEP-NC for the optimisation of complex parts and a branch-and-bound approach is used to minimise the total cycle time. Heusinger et al. [12] proposed a methodology for implementation of a standardised CA*x* process chain for rotational asymmetric parts, employing a technology-oriented process model. In this approach, the STEPTurn programming system has been developed to generate the STEP-NC program, which is converted into the program for ShopTurn to enable a test component machined on a current machine tool. Yusof et al. [13] extended this research direction to investigate the STEP-NC implementation on turn-mill operations and develop a STEP-NC compliant CAM system, for representing and machining of turn-mill parts. Yusof et al. [14] investigated the combination of ISO 14649 Part 11 [15] and Part 12 [16] to fulfil the STEP-NC challenge for turn/mill operations. In this research, a prototype system entitled SCSTO was developed to show the benefits of STEP-NC replacing G&M codes, such as the elimination of post processors.

Xu et al. [17] reported a *G*-code free CNC machine retrofitted from a conventional lathe based on STEP-NC. In this research, a new package called STEPcNC has been developed with a converter used on an existing CNC machine tool to enable it to be STEP-NC compliant. During this process, STEP Tools STIX software has been used to read and process STEP-NC information, where STIX is a C++ library providing useful functions to extract manufacturing information from STEP AP 238 format files. Then, 6K programs (a machine native format) for the CNC system were generated by the interface STEPcNC, based on the manufacturing information contained in an STEP-NC. However, this kind of program is still low level and the machine specific language is similar to G&M codes [8].

Regarding STEP-NC compliant controller development, Chen et al. [18] proposed a software-based framework for a STEP-NC control system. A RTCORBA-based soft bus was utilised to communicate among the functional modules in this system. Lan et al. [19] proposed a framework for a multi-agent-based STEP-NC controller with a prototype system, developed from the STEP Tools Inc. software tool of ST-developer.

Based on the analysis of the STEP-NC information content and the role of CNC on the shopfloor in an intelligent manufacturing system, Suh and Cheon [20] proposed a conceptual framework of an intelligent CNC system. The framework was extended to include an implementation method for a milling machine [21]. In order to support and integrate with the new controller, a shopfloor programming system, PosSFP, was proposed by Suh et al. [22]. It can recognise features from a CAD file to generate a process plan, and finally the complete STEP-NC file. Together with the controller, it enables a STEP-compliant based CAD/CAM/CNC chain solution. This PosSFP system can be implemented in two different ways according to the relationship with the controller: built-in and external. In the research area of STEP-compliant process planning, a three-stage process planning model was proposed by Liu et al. [23] using a feature-based approach, which divides process-related issues into three levels: offline process planning, shop-floor process planning and real-time process planning.

Suh [24] also reported on TurnSTEP, which can be used as a tool to create CNC turning programs. It is one of the earliest STEP-NC compliant systems, primarily aiming at evaluating the validity and effectiveness of the STEP-NC data model for turning [25]. Then, Suh et al. [26] gave a detailed and upgraded TurnSTEP implementation method with novel architecture for an intelligent turning CNC controller. This architecture is similar to those developed for milling by the same team [20,21]. TurnSTEP works like a combination of CAPP and CAM system which processes

STEP compliant CAD input data, generates STEP-NC data and turns them into the traditional part program (G&M code) for virtual NC or conventional NC. Choi et al. [25] introduced the development process and data management capability of TurnSTEP system. To enable web-based manufacturing, this paper presents an XML method to use the extension mechanism of XML to represent the EXPRESS data of STEP to realise an information exchange across the web.

Unlike other research which generates G&M codes or other machine-specific programs from STEP-NC to accommodate the current CNC machine tools [17,26,27], Shin et al. [28] proposed an approach to extract manufacturing information from G&M codes to generate the STEP-NC program for turning operations. This is challenging due to the low level and lack of process planning information contained in this conventional part program. However, according to the STEP-manufacturing road map presented by Suh and Lee [29], it is an essential step to realise the replacement of G&M codes with an STEP-NC for interoperable manufacturing era.

3. STEP-NC process planning system (PPS) architecture

For the next-generation interoperable CNC controller, a multi-agent-based intelligent STEP-NC controller has been proposed by Lan et al. [19], which is comprised of many agents. These agents undertake specific tasks and accomplish them by interacting with others to carry out the various functions of an intelligent controller in a desired manner. The STEP-NC Process Planning System which has been adapted from this approach and consists of three agents based on this architecture namely: the program interpreter agent (STEP-NC data reader), process planner agent and program generator agent (STEP-NC data writer). The emphasis of this research is the implementation of the process planning agent.

PPS consists of five modules namely: program reader, process planner, STEP-NC CAD viewer, STEP-NC CAM viewer and program writer, as shown in Fig. 1. In the process planner module, project optimisation is achieved by adjusting specific parameters and the workingstep sequences, etc. Process planning has numerous criteria that can form the objective of the plan (e.g. minimum processing time, cost, etc.). To limit the scope of this research, the surface roughness has been chosen as the optimisation objective. With the mathematical model outlined in Section 4.2, the user compares different machining strategies with different parameters (e.g. feeds, tool types, etc.). The intended toolpath of the machine is generated by the toolpath generator. The toolpath planned can be shown and evaluated in the STEP-NC CAM viewer, as described in Section 5.

The basis of PPS is the STEP-NC data and consequently, the system contains other function modules including program reader, program writer and the STEP-NC CAD and CAM viewers. With the input of the system being a STEP-NC Part 21 file, the data reader checks and translates the file into an internal data format (Java ArrayList). The data is organized by the relationship inherited by the STEP-NC file, utilising the advantage of the object-oriented programming language Java, such as strong types, inheritance and polymorphism [30]. The process planner provides a graphical interface to display and modify the particular information associated with each feature and operation. After changing the manufacturing parameters, it is essential to check whether these changes contribute to enhance the final part based on the roughness mathematical model. Then, the updated data list is transferred to the Data Writer to generate a new STEP-NC compliant program with the manufacturing information stored in ISO 14649 format. The ultimate output is a STEP Part 21 physical file (.stp file). During the process, there are several visualization

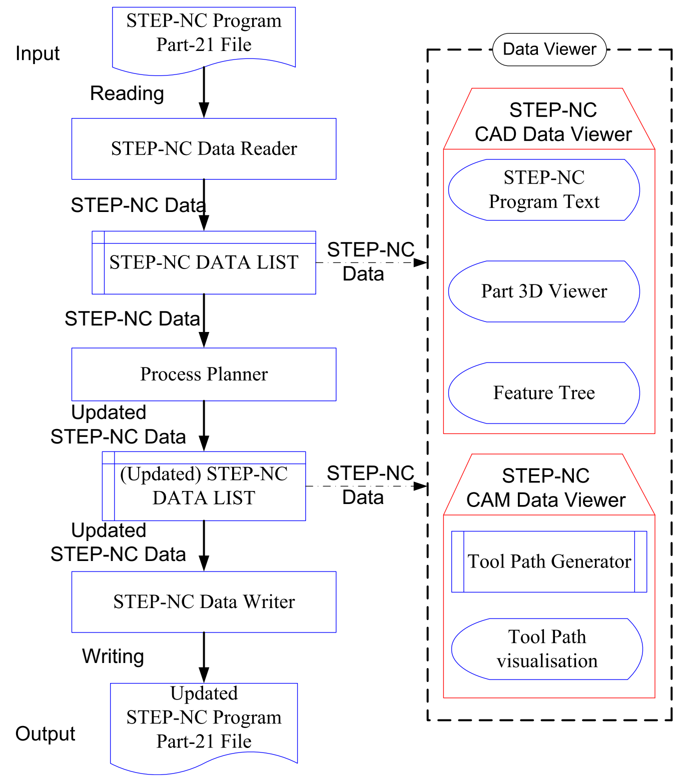

Fig. 1. Architecture of the PPS.

tools that have been realised to view the STEP-NC data, the final part, the manufacturing features and the toolpath generated by the toolpath generator.

4. Process planner

4.1. STEP-NC process planner

According to Liu et al. [23], process planning is divided into three levels: off-line, shopfloor and real-time. At the off-line process planning level, an NC program is generated with the CAD design information and other technology requirements of the final part. The activities involved in shop-floor process planning consist of:

i) Manufacturability analysis: assessing the whole machining ability with all the resources available.
ii) Workingstep-level planning: optimising the parameters for every single workingstep.
iii) Part-level planning: determining the best workingstep sequence for a particular project.
iv) Manufacturing resource planning: choosing suitable tools, clamps, etc.

At the level of real-time process planning, the toolpath and additional machine function switches (e.g. turn coolant on/off, etc.) are produced according to the current machine status. PPS is applicable to both the shopfloor and the real-time process planning levels. The process planner module can be applied at the shopfloor process planning level, while the toolpath generator would typically be used at the real-time level.

Manufacturability analysis is achieved by the operators according to their experience, while the other three activities are achieved by PPS through system interfaces to modify the stored STEP-NC data. These interfaces are shown in Figs. 2 and 3. The first interface (Fig. 2) is used to adjust the workingstep sequence and the interface in Fig. 3 is for changing workingstep parameters, which generates a surface roughness report.

In Fig. 2, the interface shows SETUP 1, with its workingsteps listed in the WS-IN window and the workingsteps in the WS-REST window related to other setup(s). Using this interface, the user can add workingsteps into the chosen setup and delete workingsteps from the chosen setup. The user can also adjust the sequence of the workingsteps within a setup. If another setup is chosen, the WS-IN and WS-REST data will change correspondingly. However, the logic of workingstep resequencing is based on the users' judgement of the specific manufacturing environment. It is further a major challenge to realise an object-oriented optimisation without considerable knowledge of manufacturing resources.

In Fig. 3, the parameters of a workingstep are visualized in different groups. It is feasible to change some of them according to the user's experience. Before saving the changes, the user can gain help by pressing the roughness report button from the surface roughness prediction mathematical model to determine whether the changes contribute to enhance the quality of the part. The pop-up shows the surface roughness report based on the data of the workingstep. The surface roughness prediction mathematical model is outlined in the next section.

4.2. Surface roughness model

There are many different options for the workingstep parameter optimisation based on a wide range of goals. As described previously, surface roughness has been chosen to be the optimisation objective in this research. As is commonly known, the surface roughness is mainly caused by the height of the residual area, which causes the surface when the magnified look like a threaded uneven pattern. The roughness value of a part can only be obtained by measurement after it is completed, which is merely the criterion to determine whether it is qualified or not. From using the detailed workingstep and operation data in STEP-NC, it is possible to provide a standardized approach to predict and verify the surface quality of the product. As there are many elements that influence the surface quality of a part, with many of them being dependent on a particular manufacturing resource, the process planner can at most reach a level to compare different ways of machining, using the mathematical model of the residual area's height as depicted in Fig. 4.

In turning operations, the tool and the workpiece have a relative helical motion which inevitably results in the residual area on the surface. The surface roughness is mainly caused by the height of the residual area together with the influence of other factors. Theoretically, the residual area height is the surface roughness. The height of the residual area depends on the major tool cutting edge angle (in STEP-NC, it is called side cutting edge angle) K_r, minor tool cutting edge angle (in STEP-NC, end cutting edge angle) K_r', tool nose radius, r, and the feed rate, f. According to the relationship of the values of tool nose radius and feed rate, the residual area height is shown in three different cases, as shown in Fig. 4 [31,32].

For a large tool nose radius with a low feed rate ($f<2r\sin K_r'$) as shown in Fig. 4(a), the residual area height (h) depends on the r and the f, where r is the tool nose radius and f is the feed rate [31]

$$h=f^2/8r \tag{1}$$

For a high feed rate with a small tool nose radius ($f\geq 2r\sin K_r'$) as shown in Fig. 4(b), the residual area is thought to be caused by the tool nose, r, and the minor cutting edge, K_r'. The height is calculated as follows [31]:

$$h=r\left(1-\cos K'_r+F\cos K'_r-\sin K'_r\sqrt{2F-F^2}\right) \tag{2}$$

where $F=f\sin K_r'/r$.

When $r=0$ as shown in Fig. 4(c), the residual area height depends on the feed rate f, the major tool cutting edge angle, K_r, and the minor tool cutting edge angle K_r', where r is the tool nose radius and f is the feed rate [31]

$$h=\frac{f}{c\tan K_r+c\tan K_r'} \tag{3}$$

In the case of the example shown in Fig. 3, Eq. (1) is used above with the values of $r=1.0$ mm, $K_r'=10^\circ$ and $f=0.3$ mm/rev. This, as shown from the roughness report dialogue, gives a value for h of 0.01125 mm.

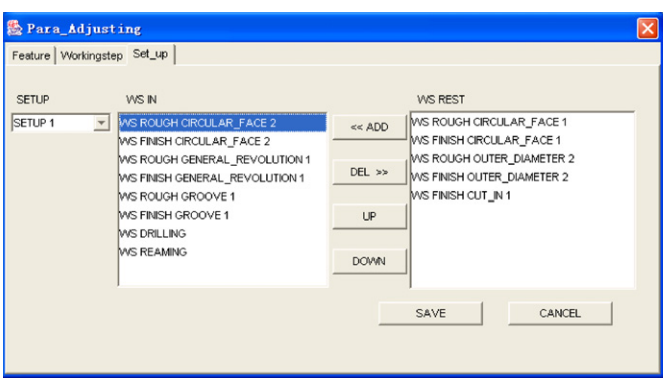

Fig. 2. The interface of the workingstep re-sequencing.

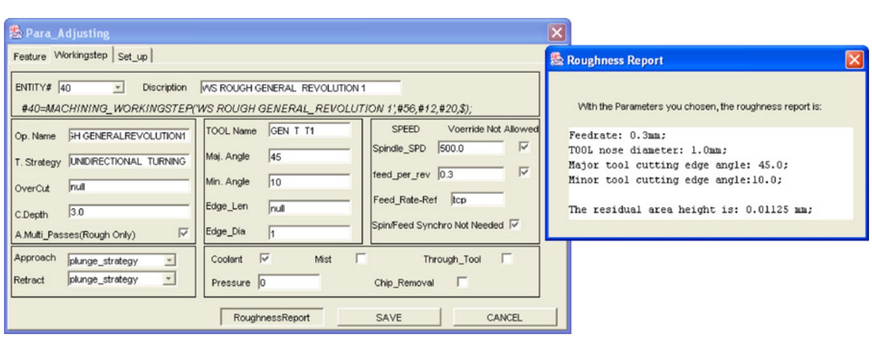

Fig. 3. The interface of Para_Adjusting for workingsteps.

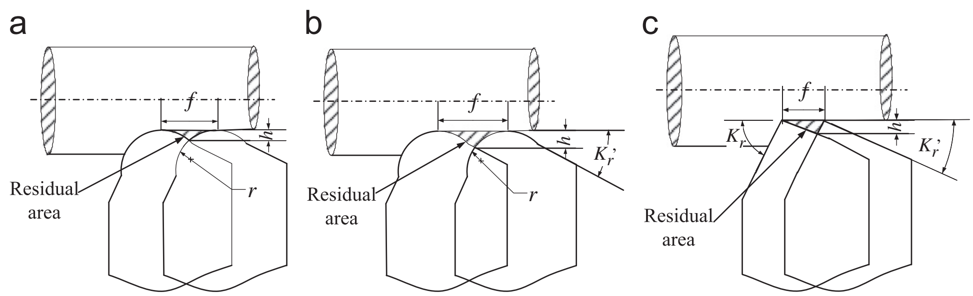

Fig. 4. The residual area height (h). For a large tool nose radius, (b) for a high feed rate and (c) r=0.

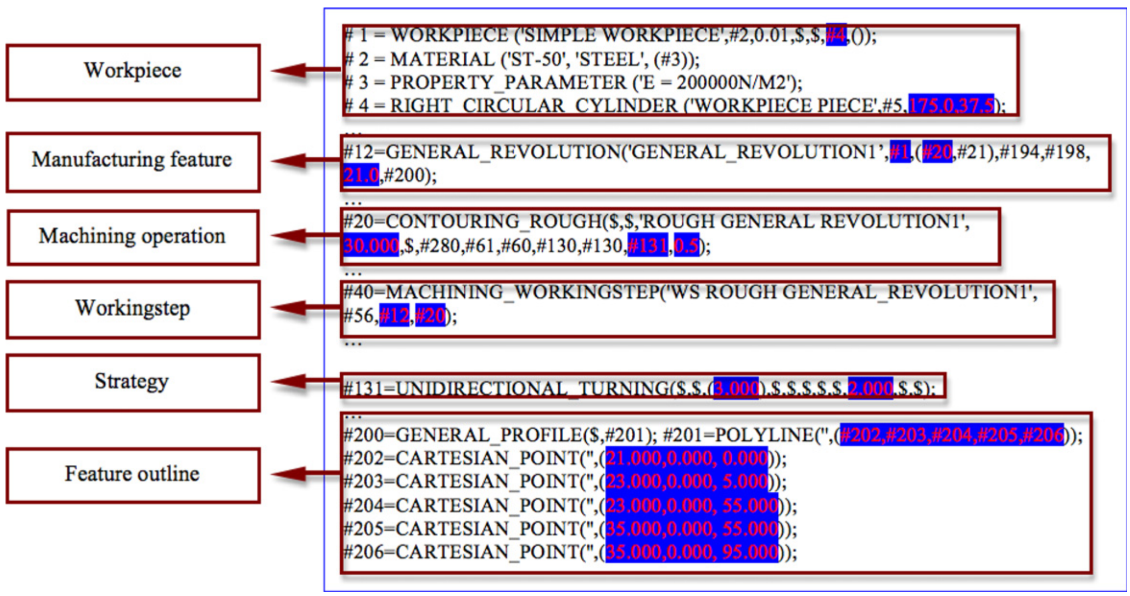

Fig. 5. Example program segments.

5. Toolpath generator

The STEP-NC CAD and CAM viewers provide the user with a virtual and graphical interface of the part geometry and the machining toolpath. The major capability developed in these viewers is the toolpath generation to get the tool cutters centre lines.

5.1. The selection of the toolpath planning unit

There are three feasible options for the toolpath planning unit based on an STEP-NC, which are the manufacturing-feature, machining-operation and workingstep. According to the STEP-NC standard, manufacturing features contain three different kinds of information: geometry shape dimension, quality requirement, workpiece information including material category, dimensions, etc. These three forms of information do not provide enough data to generate the machining toolpath. The other decisive factors of the toolpath are the turning technology and strategy, which are stored in machining-operations. Both the manufacturing-feature and machining-operation need to be combined with each other to generate the final path. Consequently, the workingstep, containing the manufacturing-feature and the machining-operation, has been chosen to be the path planning unit. It can be described as using an operation to machine a feature. Additionally, the workingstep is an executable unit in an STEP-NC, which means, the consequence of workingsteps is the correct procedure to undertake the machining of the product.

5.2. The procedure of toolpath planning

5.2.1. Material removal

Firstly, it is essential to determine which piece of material to remove from the stock. In the example program of ISO14649-12 as shown in Fig. 5 for the case study part shown in Fig. 6, line #40 represents a workingstep in the program, with a feature (#12) and an operation (#20) defined. According to the feature of #12, its workpiece is defined in #1, and its feature outline is defined in #200.

From the program line #4 in Fig. 5, it is obvious that the rough workpiece is circular with length of 175 mm and radius of 37.5 mm. The feature outline is defined by five points in its own coordinate system, which is shown in Fig. 7 [16]. It is thus easy to determine what material needs to be removed from this workingstep.

5.2.2. Machine strategies

With an STEP-NC, to identify the material removal strategy, the attribute of the operation named machining strategy is used. Examples of machining strategies defined for turning are namely (a) unidirectional turning and (b) contouring turning, as shown in Fig. 8. As previously discussed, the machining strategy is crucial to the toolpath planning, which is specified by the operation. Within the workingstep in the manufacturing workingstep segment (#40), the operation (#20) to rough the feature (#12) in the program is also shown in Fig. 5.

In this machining-operation segment (#20), the first $ identifies that the toolpath of the operation is not specified yet. This is due to the fact that it is expected to be generated at the intelligent STEP-NC CNC. The retract plane is represented by the number 30.000 in millimetres, and the machining allowance of this operation is identified by the number 0.5 in millimetres.

The machining strategy is defined in line #131. From this line, the following information is specified:

i) Unidirectional turning.
ii) Multiple turning: this is omitted but could be determined by the controller intelligently with the final incremental cutting depth being 3.000 mm and the height of the tool retraction height being 2.000 mm. While the maximum depth to be removed is apparently much bigger than 3.0 mm, consequently the property value is true.
iii) Cutting depth list: each entry of the cutting depth list stands for the thickness (not the total depth) that shall be removed in the respective pass until all the material to be machined is removed. If there are more passes needed than list entries, the last entry shall be used for the remaining passes [15]. In this program, the 3.000 is the cutting depth of the last pass, and the depth for other passes should be implemented by the controller. As shown in Fig. 7 above, the maximum depth is 15.96 mm (considering the allowance at the chamfer position). The whole cutting depth could be assigned as (0.96, 3, 3, 3, 3) in millimetres.
iv) Feed direction: the direction could be specified to be parallel to the *Z*-axis pointing to smaller values of *Z*.
v) Lift direction and stepover direction: because neither of them are given in the program, in this paper, the ordinary manner is the choice: vertical lift and horizontal retreat.

With parameters above, the final toolpath could be calculated as shown in Fig. 9. To achieve the allowance of 0.5 mm for this roughing operation, a contour shape cutting is added as the last cutting before retract. In similar way, the toolpath of the rough operations in the first setup could be illustrated in the STEP-NC CAM viewer, as shown in Fig. 10. There are two more operations belonging to the same setup in this figure, which are not

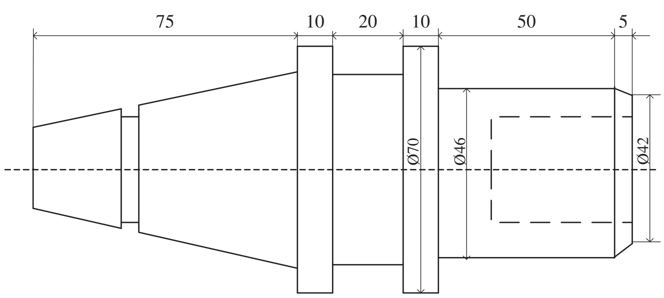

Fig. 6. Example part and its workpiece.

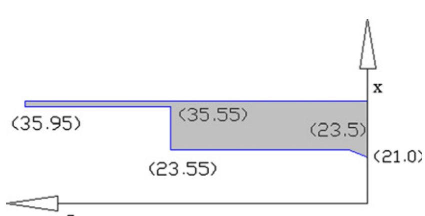

Fig. 7. The material to be removed.

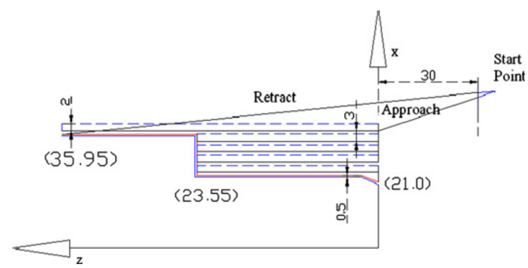

Fig. 9. The planned toolpath.

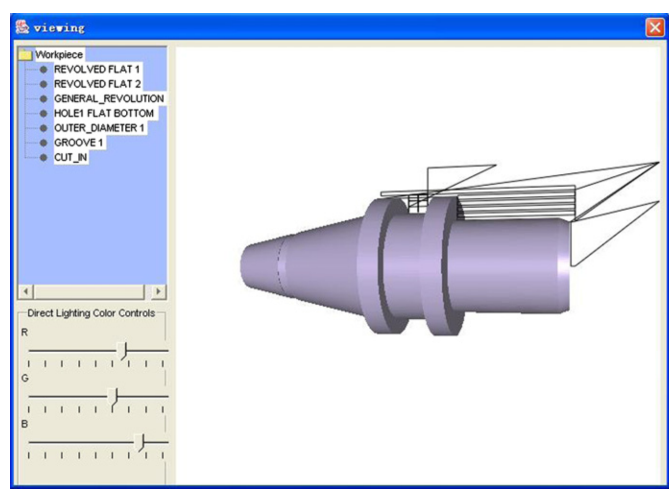

Fig. 10. The toolpath in STEP-NC CAM data viewer.

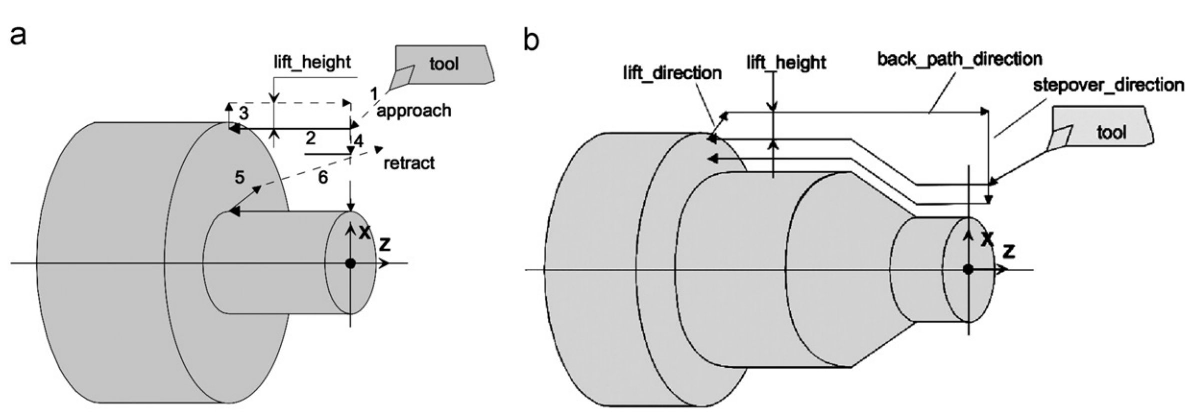

Fig. 8. Examples of machining strategy. (a) Unidirectional turning and (b) contour turning.

discussed in detail like the operation of the General_Revolution feature.

6. Discussion

In this paper, the first part gives an introduction of the background of this research. It identifies the shortcomings of the current ISO 6983 standard used as the interface of CNC, which isolates the CNC from the previous chain. In this case, the ultimate aim of CA*x* chain is the generation of a suitable part program for aiming the CNC machine. From the literature review, it is recognised that all the researchers believe that STEP-NC will replace the current ISO 6983 to be the data interface for next-generation CNCs, despite insisting on different implementation methodologies. It is also believed that the introduction of STEP-NC into manufacturing will bring a fundamental change to the whole of manufacturing. The current boundaries of CA*x* systems will dramatically shift, especially between CAM and CNC. As the primary aim of STEP-NC is to feed CNC with more manufacturing knowledge, the shopfloor CAM capability is almost the most important characteristic of this reviewed research.

However, most of the research focuses only on the correct interpretation of the new data model and the possibility of bi-directional information exchange in the manufacturing chain. With this rich information on the shopfloor level, CNC should be more capable of doing the real-time adjustment and optimisation according to the specific circumstance. Although this kind of optimisation is not a new topic, the implementation method of old algorithms in new conditions utilising the rich information in STEP-NC is an important research area. In this research, a roughness-oriented optimisation algorithm has been retrofitted into the STEP-NC intelligent controller design. It uses the basic parameters contained in STEP-NC to give a roughness report according to the machining strategy.

The shortcoming of this approach is that the roughness report generated in this research is only a mathematical prediction. The real roughness is tied to many other factors such as the system rigidity of the physical machine tool and cutting tool status. However, it can be still used to compare different sets of parameters, assuming the other factors stay the same. To improve this optimisation method, a comprehensive knowledge of the various manufacturing resources is indispensable. Based on the data of a more complete system, an experimental formula could be worked out to predict the actual surface quality. Furthermore, based on different optimisation objectives, the manufacturing knowledge in STEP-NC can be used for various objective-oriented optimisations, depending on which one is the most important aspect, such as time, quality or cost.

The other contribution of the authors is the investigation of feature-based toolpath generation. Obviously, any part design which is to be CNC manufactured should be converted to the actual machine axis movements to remove material from the workpiece. The only change STEP-NC brought here is that this task will be taken care of by the CNC controller instead of the traditional CAM system. Even though the computer hardware of the CNC is powerful enough to handle this STEP-NC data, the vendors of commercial CAM packages will lose the commercial advantage associated to their proprietary toolpath generation algorithms. That is one reason why the implementation of STEP-NC encounters a lot of resistance from commercial companies. Another possibility is that the CAM vendors can work together with controller developers and sell their products together. Fortunately, researchers have noticed this problem with a number of new practical STEP-NC implementations. Shin et al. [28] investigated an algorithm to utilise the current part programs to generate STEP-NC data, which will save and reuse the most valuable and important part of the part program to remove the obstacles to an STEP-NC implementation. This research only focuses on turning operations. The authors believe that future research efforts should be directed to other machining processes such as milling or turn-mill.

7. Conclusions

This paper has proposed and demonstrated the PPS process planning system based on an STEP-NC, which can serve as the interpreter and process planner for the whole architecture of the STEP compliant NC controller. The major conclusions of this work are:

i) STEP-NC data can be used for generating a standardized data for generic process planning and toolpath generation for turning operations.
ii) With the incorporation of the surface roughness module, PPS can be integrated with STEP-NC data to generate process plans to manufacture a part with a prediction of surface quality.
iii) This research has investigated the opportunity of process optimisation utilising the manufacturing knowledge contained in STEP-NC. With the more sufficient information in STEP-NC, the shop-floor is entitled more privileges to optimise the manufacturing variables towards intelligent manufacturing.

This research illustrates the potential that a STEP-NC data model provides the basis for standardized process planning and CNC machining.

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