International Journal of Current Engineering and Technology
E-ISSN 2277 – 4106, P-ISSN 2347 – 5161

Available at http://inpressco.com/category/ijcet

Research Article

Impeller Tool Paths Programming for Rough Machining in an Intelligent NURBS Step- Nc Format

Hacene Ameddah[†*], Kamel Zidani[†] and Rabah Manaa[‡]

[†]Mechanical Engineering Department, Faculty of Technology, University, Hadj Lakhdar Batna. Laboratory of Innovation in Construction, Eco Design and Seismic engineering. Rue Mohamed Elhadi Boukhlouf, Batna, 05000, Algeria
[‡]Mechanical Engineering Department, Faculty of Technology, University, Hadj Lakhdar Batna. Laboratory of Research in Product. Rue Mohamed Elhadi Boukhlouf, Batna, 05000, Algeria

Accepted 15 Jan 2016, Available online 26 Jan 2016, **Vol.6, No.1 (Feb 2016)**

Abstract

The research work reported in this paper focuses on introduces a fully STEP-compliant CNC by putting forward an interpolation algorithm for Non Uniform Rational Basic spline (NURBS) curve system for rough milling tool paths with an aim to solve the problems faced by the current CNC systems. The most important components used in aerospace, ships, and automobiles are designed with free form surfaces. An impeller is one of the most important components that are difficult to machine because of its twisted blades. The research is based on the premise that a STEP-NC program can document "generic" manufacturing information for an impeller. This way, a STEP-NC program can be made machine-independent and has an advantage over the conventional G-code based NC program that is always generated for a specific CNC machine. Rough machining is recognized as the most crucial procedure influencing machining efficiency and is critical for the finishing process. A key feature of the system is the use of STEP-NC data model (ISO 14649-10: 2003; ISO 10303-238, 238: 2003), which enables more design information (e.g. geometry, workpiece information and tolerances) to be incorporated both prior to and during machining processes. The relevant algorithm for the curve was simulated in CAM software. The results have shown that the algorithm for rough milling is feasible and effective.

Keywords: *Tool path, STEP-NC, Impeller, Rough machining, NURBS interpolation*

1. Introduction

The contemporary product design and manufacturing environment requires a bidirectional and seamless data flow throughout all stages of data transactions. The establishment of STEP (STandard for Exchange of Product data) offers manufacturers a new method to exchange product data in the entire product life cycle.
As an extension to STEP, STEP-NC provides the potential to finally close the gap between design and manufacturing in the drive for a complete, integrated product development environment. The STEP-NC data model is a long overdue improvement in the domain of computer numerical controls (CNC) where G-codes have been in use for more than half a century. STEP-NC brings richer information to CNCs presenting an opportunity for the development of more intelligent, interoperable and informative machining.

The manufacturing of a single twisted ruled surface needs at least four freedoms and a freedom of rotation workpiece should be added when machining an integrated impeller. For such complex shapes, five-axis machining is generally adopted (Young, H T., Chuang, L C., 2003). Furthermore, the two additional degrees of freedom have many advantages such as high productivity, machining quality, and more flexible tool-path planning methods (Pin ghan, Wu., Yuwei, Li.2008). Therefore, it is wise and necessary to adopt a five-axis machine tool to manufacture impellers with twist blades. In order to solve complex free-form surface CNC machining, major manufacturers of CNC systems, such as Heidenhain, Siemens, Fanuc, have utilized basis spline (B-spline), and Non uniform rational basis spline (NURBS) interpolation methods for free-form surface machining and achieved good machining results (Cheng, *et al* 2002) (Koninckx, B., Vanbrussel, H., 2002).

Recently, NURBS based CAD graphical representation and interpolation methods have been adopted by the STEP standard and supported by the new machine tool control language STEP-NC (Lei, W.T.; Wang, S.B., 2009). This feature allows users to use tool tips to program machine tools directly without complex post-processing. Numerical coordinate transformation and nonlinear error processing are achieved within the CNC system (Ibaraki, S., *et al*, 2010) (Mann, S.; Bedi, *et al*, 2010).

*Corresponding author: **Hacene Ameddah**

The STEP-NC—AP 238 and ISO 14649 standard is the result of a 10-year international effort to replace the RS274D (ISO 6983) G and M code standard with a modern associative language that connects the CAD design data used to determine the machining requirements for an operation with the CAM process data that is used in creating a machining solution to satisfy these requirements (M. Hardwick & Y. F. Zhao *et al*, 2013).

Research on computer integrated design and manufacture based on feature extraction (FE) so far has been largely focused on finding all or some possible features, and the task of manufacturing analysis is shifted to process planners. An attempt has been made to propose a system of FE for 3D components to automate planning activities in a computer integrated manufacturing environment (Borkar B. R., Puri Y. M., 2015).

(Yu Zhang, Xiao-Lan Bai, Xun Xu, Yong-Xian Liu 2012), proposes STEP-NC based high-level NC machining simulations solution integrated with computer-aided design/computeraided process planning/ computer-aided manufacturing (CAD/ CAPP/CAM). It turned out that the research provides a better informed simulation environment and promotes the development of modern manufacturing.

(Alireza Mokhtar, Xun Xu, 2011) considers interacting features in a feature-based model for process planning tasks. For each feature, precedence information is generated considering both roughing and finishing operations. A rule-based system is developed and implemented based on the information about machining precedence of the interacting features. The STEP-NC data model is used as the underlying data model.

Machining precedence of interactive and no interactive STEP-NC features is discussed by (Alireza Mokhtar Xun Xu Iñigo Lazcanotegui, 2010), Local and global precedence of machining features are defined on the basis of geometric constraints, such as geometric interaction of features and feature approach face and technological constraint such as access direction of the cutting tool. A software tool has been developed to visualize the STEP-NC part model and to generate the graphs of feature interaction and feature precedence.

The output can be then used to augment the STEP-NC data in order to generate the optimal sequence of operations.

Effective approach of collecting, transmitting, and handling complete product manufacturing information during machining process is necessary for realizing high efficiency manufacturing (Po Hu & Zhenyu Han & Hongya Fu & Dedong Han, 2015). The architecture and implementation of closed-loop machining system (CLMS) is discussed and the method of realizing machining process control is introduced. An integrated information flow is built based on object-oriented description method to transfer complete product manufacturing information in CLMS. The functional and informational model of CLMS is established by using integration definition method. Online and real-time machining process control is implemented on an open STEP-NC controller which is collecting and analyzing information of machining process condition and inspection results during machining process.

(Xianzhi Zhang & Aydin Nassehi & Stephen T., 2014) focuses on the recognition of 2½D features, but it can be extended to more complex features. Case studies are used to validate the use of the proposed method on typical milling features.

In order to guarantee good openness, open platform and standard interface are applied in the development (Liang & Xia Li , Hong bin, 2013). Technology of module collaboration and design of data flow are studied. A five-axis real-time interpolator for non-uniform rational B-spline surfaces machining is realized. Based on these technologies, a five-axis CNC is developed in the manner of software realization, which consists of interpreter, task coordinator, axis group, etc. The software CNC system has been applied on a tilt-rotary type five axis machine tool, where the milling experiment has been performed successfully.

Since the establishment of STEP-NC model of data, lots of research works have been carried out on the design and implementation of STEP-NC controller. According to reference (Suh SH, Lee BE, Chung DH, Cheon SU, 2003). To realize of the machining freeform surfaces, the description of NURBS surface in STEP-NC standard is investigated. A five-axis STEP-NC prototype system with a series of software has been built, where the functions of path planning, CC calculation, tool offset and inverse kinematics transformation are transferred from CAM to controller. Milling experiment has been performed. Experimental results prove the proposed method valid. The work provides an effective, new method in the machining freeform surfaces, and demonstrates the potential of STEP-NC data model on the machining of freeform surfaces.

2. STEP-NC—STEP-Compliant Numerical Control

As STEP-NC is an extension of STEP to handle NC processes, it strictly follows the STEP standard. This means that all of the implementation methods (ISO 10 303-21: 1994), (Object Management Group. 2003), defined in STEP for building and exchanging product models apply. Part 21 physical file is the most common type of interface mechanism. In a STEP-NC file, for example, the HEADER contains general information and comments about the part program, such as the filename, author, date, and organization. The DATA section is the main section of the program, containing all of the information about manufacturing tasks and geometries. The data are divided in three significant parts:

1) Workplan and executables;
2) Technology description; and
3) Geometry description.

This section must also include a PROJECT entity that is an explicit reference for the starting point of the manufacturing tasks. The PROJECT entity contains a main workplan that, in turn, contains sequenced executable manufacturing tasks or commands. The order of execution of manufacturing operations is given by the order of executables. In order to change the sequence of operations, only this part of the program file has to be changed.

The workplan combines several executables in a linear order or depending on given conditions if conditional controls are used. In essence, STEP-NC describes "what-to-make," whereas the G-code describes "how-to-make." STEP-NC describes tasks (e.g., predrilling, drilling, roughing, and finishing) that are based on the machining features (Fig. 1) so that the part program supplies the shopfloor with higher-level information (i.e., the information about machining tasks and technological data on top of pure geometrical and topological information). As a result, modifications at the shopfloor can be saved and transferred back to the planning department which enables a better exchange and preservation of experience and knowledge.

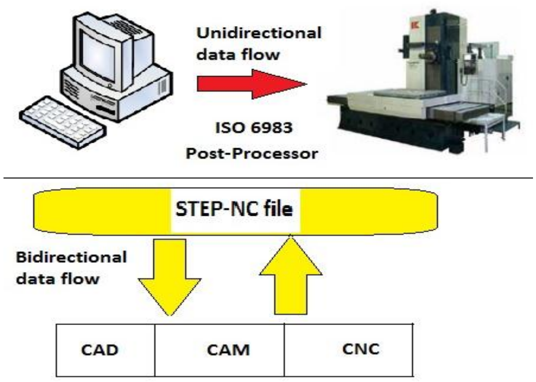


Fig.1 Comparison of ISO 6983 and ISO 14649

3. STEP-NC data model and data format

The fundamental principle of the STEP-NC Data Model is the object-oriented view of programming in terms of manufacturing features, instead of direct coding of sequences of axis motions and tool functions as per defined in ISO 6983. The objects in this case are manufacturing features and their associated process data.

The Data Model is a layer that provides a standard interface between the controller interpreter and the different sources of data supplied. The interpreted data are supplied to the CNC kernel, where axis motions and machine functionality are generated. This new model can accept data from several sources. The data can be generated by a CAD/CAM system, part of libraries and/ or graphic user interface. The data generated from CAD/CAM systems or graphical user interfaces is normally processed automatically with computers, so feature definitions, technology descriptions, readability and completeness have been given higher priority than compressed coding.

The program format follows the same format for STEP as described in a Physical File Format (ISO 10303 Part 21). The first section of the part program is the header section marked by the keyword "HEADER". In this header, some general information and comments concerning the part program are given, e.g. file name, author, date and organization. The second and main section of the program file is the data section marked by the keyword "DATA". This section contains all the information about manufacturing tasks and geometries.

The contents of the data section are further divided into three parts: workplan and executables, technology description, and geometry description. Extra Information in STEP-NC includes a Project entity, Workplan/executables and Geometric description.

The project entity serves as a starting point for executing the part program. Each part program must include an instance of this entity in a "DATA" section of an ISO 10303 Part 21 file. This instance should contain a main workplan that contains sequenced subsets of executables (executable manufacturing tasks or commands) and may also include information of workpiece to be machined (ISO 14649-11:2003), (ISO 14649-10:2003). The executable is the base entity of all executable objects. There are three types of executables: Working step, NC function and program structure. The workplan combines several executables in a linear order or depending on given conditions if conditional controls are used. In STEP- NC, all geometrical data for workpiece, set-ups and manufacturing features are described based on ISO 10303 parts 21 and 42/43. This data is also used directly by the CNC machines to avoid conversions between different data formats that may result in reduced accuracy. Tooling information including tool type, tool geometry and expected tool life, etc. is also included in a STEP-NC file.

4. Toolpaths Programming for rough machining in an Intelligent NURBS STEP-NC Format

4.1 NURBS Toolpaths interpolation

The rough machining is the main process that removes a major part of the material from the blank and carves the pre-form into the rugged profile of impeller. An increase in the material removal rate to raise the overall working efficiency is a key issue in designing the rough machining module. It influences not only the total machining time but the accuracy of the resulting impeller in the finished process. Furthermore, the residual thickness and surface conditions after rough machining will affect the final finishing machining. If the residual thickness is too large, it will certainly lower the working efficiency and result in excessive tool wear. The residual surface conditions also influence the tool life. The centrifugal impeller is typically designed into complicated shapes with overlapped parts that require five-axis machining. In five-axis machining, the tool is allowed to take an arbitrary position as well as the position to form the required surface. Consequently, in order to make good use of the special geometric features (Young, H T., Chuang, L C. 2003). This research work proposes an Intelligent NURBS Step-Nc Code Format machining methodology for rough cutting a free form surfaces as impeller.

The general form of a NURBS curve is defined as follows (Piegl, L.; Tiller, W. 2003)

$$c(u) = \sum_{i=0}^{n} R_{i,p}(u)P_i = \frac{\sum_{i=0}^{n} N_{i,p}(u)w_i P_i}{\sum_{i=0}^{n} N_{i,p}(u)w_i} = \frac{A(u)}{w(u)} \quad (1)$$

$$R_{i,p}(u) = \frac{N_{i,p}(u)w_i}{\sum_{i=0}^{n} N_{i,p}(u)w_i} \quad (2)$$

Where $\{P_i\}$ are the control points, $\{w_i\}$ are the corresponding weights of $\{P_i\}$, and $\{w_iP_i\}$ are the weighted control points. In addition, w(u) is the weighting function, A(u) is the weighted B-spline function, (n+1) is the number of control points and p is the degree of the NURBS curve. $\{N_{i,p}(u)\}$ and $\{R_{i,p}(u)\}$ are the p^{th}-degree B-spline basis functions and the rational B-spline basis functions defined on the non-uniform knot vector U= $\{u_0, u_1, ..., u_{n+p+1}\}$, respectively.
The p^{th}-degree B-spline basis function is recursively defined as follows

$$N_{i,0} = \begin{cases} 1, & if\ u_i \le u \le u_{i+1} \\ 0, & otherwise \end{cases} \quad (3)$$

$$N_{i,p}(u) = \frac{u-u_i}{u_{i+p}-u_i} N_{i,p-1}(u) + \frac{u_{i+p+1}-u}{u_{i+p+1}-u_{i+1}} N_{i+1,p-1}(u) \quad (4)$$
i=0,1,…,n

The m^{th} derivative of a NURBS curve (Piegl, L.; Tiller, W., 2003) is given as:

$$N_{i,p}^{(m)}(u) = p\left(\frac{N_{i,p-1}^{(m-1)}(u)}{u_{i+p}-u_i} - \frac{N_{i+1,p-1}^{(m-1)}(u)}{u_{i+p+1}-u_{i+1}}\right) \quad (5)$$

$$\binom{m}{i} = \frac{m!}{(m-i)!i!} = \binom{m-1}{i} + \binom{m-1}{i-1} \quad (6)$$

$$C^{(m)}(u) = \frac{A^{(m)}(u) - \sum_{i=1}^{m}\binom{m}{i} w^{(i)}(u) C^{(m-i)}(u)}{w(u)} \quad (7)$$

$$w^{(m)}(u) = \sum_{i=0}^{n} N_{i,p}^{(m)}(u)w_i$$

$$A^{(m)}(u) = \sum_{i=0}^{n} N_{i,p}^{(m)}(u)w_i P_i \quad (8)$$

Where $w^{(m)}(u)$, $A^{(m)}(u)$ and $N_{i,p}^{(m)}(u)$ are the m^{th} derivatives of the weighting functions, the weighted B-spline functions and the B-spline basis functions, respectively.

4.2 Generation of trajectory per format of NURBS interpolation

Non Uniform Rational B-Splines (NURBS) have been used by CAD systems for some time (Ameddah, H., Assas, M., (2009),(2011)). That's why it seems so natural that CNCs should be able to employ tool paths that are also defined in terms of NURBS. However, most CNCs today instead require contoured tool paths to be defined using straight lines, or chords. And this long-practiced approach can lead to inefficiencies familiar to almost any die or mold shop. Using chords to define complex geometries accurately results in large, data-dense program files, files that historically have been difficult to manage and slow to execute.

4.2.1 Test and result

In this section, performances of NURBS interpolation algorithm by NURBS curve case are contoured to validate the feasibility of the proposed method (Fig.2).
Case: Star-shape curve (degree 2)
Control points:
$\begin{bmatrix}8\\12\end{bmatrix} \begin{bmatrix}5\\8\end{bmatrix} \begin{bmatrix}0\\8\end{bmatrix} \begin{bmatrix}4\\4\end{bmatrix} \begin{bmatrix}3\\0\end{bmatrix} \begin{bmatrix}8\\3\end{bmatrix} \begin{bmatrix}13\\0\end{bmatrix} \begin{bmatrix}12\\4\end{bmatrix} \begin{bmatrix}16\\8\end{bmatrix} \begin{bmatrix}11\\8\end{bmatrix} \begin{bmatrix}8\\12\end{bmatrix}$
Knot vector:
[0 0 0.111 0.222 0.333 0.444 0.555 0.666 0.777 0.888 1 1 1]
Weights:
[1 1 1 1 1 1 1 1 1 1 1]

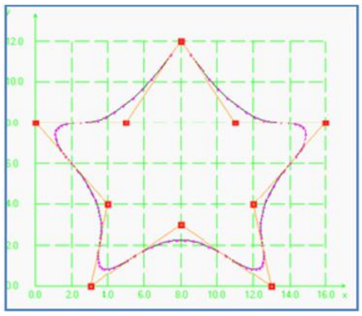


Fig.2 The Star-shape NURBS curve

After inserting these points in our implementation (Ameddah, H., Assas, M., (2009), (2011)) we obtained the Star-shape NURBS curve. These points are inserted in software of CAM for generate NURBS tool path.

4.2.2 Validation

The programs that have developed can generate NURBS curves having complex shapes (Fig.3).

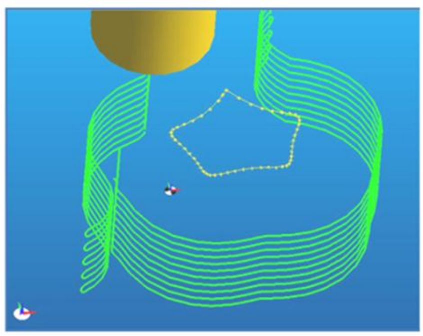


Fig.3 Trajectory of tool in NURBS format

By the given interpolation, a universal NURBS curve was designed and visualized.

The relevant algorithm for the curve was simulated in V.B 6.0. Results have shown that the algorithm is feasible and effective.

4.3 Impeller rough machining in NURBS-STEP-NC Format

Roughing is the most important process in machining any kind of material which removes the major part of the stock material to form a semi-finished product. In order to improve machining time, material should be removed as much as possible. It is a very important phase as it affects the accuracy of machining an impeller in the finishing process.

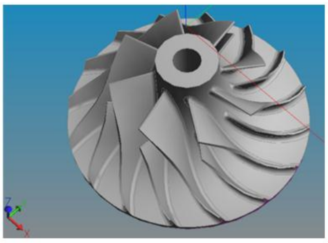
Interpolation technology is very important in STEP-NC machining (LIZHI GU, HAO WU and Qi HONG, 2012), and affects machining accuracy and efficiency directly. Auteurs present a new NURBS interpolation technology based on constant arc length increment and developed a data pre-processing module in STEP-NC machining.

The new entity is defined in EXPRESS language as follows:

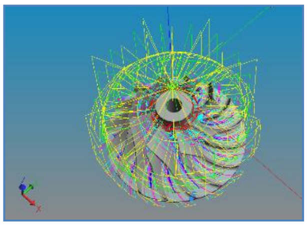
ENTITY
b_spline_surface_with_knots_and_rational_b_spline_surface
SUPERTYPE OF (b_spline_surface_with_knots, rational_b_spline_surface);
END_ENTITY;

4.3.1 Simulation and Verification

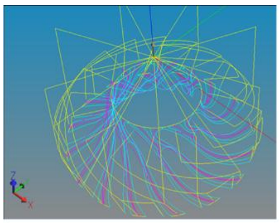
It is very important to simulate and verify the machining of impeller blades after its tool path planning. The verification process is implemented by CAD/CAM software (fig.4)



(a) CAD model



(b)



(c)

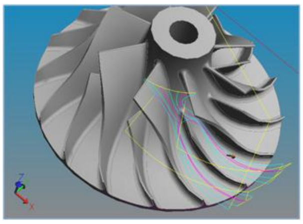
(b) Strategy of rough milling, (c) Strategy of rough machining of Wp r02

Fig.4 Impeller rough machining in NURBS interpolation

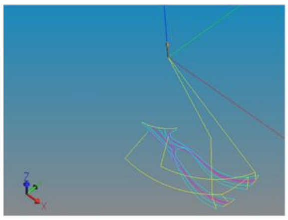
After algorithms of a roughing process are established (Fig.4) it is essential to verify the machining procedures. Some machining processes were verified by experiments where many true impellers were machined and the cost was great.

In our case we have simulate type of impeller (Fig.4-5), in order to observe interference and also to follow the entire machining procedure.

The verification process is implemented by CAD/CAM software; finally the program STEP-NC is given.



(a)



(b)

(a) Strategy of Wp r02-0 degree WS2,
(b) Wp r02-0 degree WS2 without CAD

Fig.5 NURBS Rough machining of Wp r02-0degree WS2.

The Intelligent STEP-NC format of rough machining for Wp r02- zero degree WS2 is given (specifying the integrated B-spline curve):

```
…
#320=CC_DESIGN_APPROVAL(#618,(#645));
#321=CC_DESIGN_APPROVAL(#619,(#644));
#322=B_SPLINE_CURVE_WITH_KNOTS('',3,(#499,#500,#501,#502,#503,#504,#505,
#506,#507,#508,#509,#510,#511,#512,#513,#514,#515,#516,#517,#518),
…
#323=B_SPLINE_CURVE_WITH_KNOTS('',3,(#537,#538,#539,#540,#541,#542),
…
#324=B_SPLINE_CURVE_WITH_KNOTS('',3,(#546,#547,#548,#549,#550),
…
#325=B_SPLINE_CURVE_WITH_KNOTS('',3,(#554,#555,#556,#557,#558,#559),
…
ENDSEC;
END-ISO-10303-21;
```

Conclusions

This paper presented an integrated framework of tool path planning in 5-axis machining of centrifugal impeller with split blades.

A detailed in depth study with explanations of the differences between G&M code and STEP-NC and in what way is the STEP-NC better than G&M code has provided a better insight into the capabilities of both standards. As a result the STEP-NC code generator was developed based in ISO 14649 Part 11, which will focus on the milling process.

A planning template was proposed for rough machining operation. The framework provides several CAM functions that enable automatic generation of quality tool paths. First, the constructing geometry of the impeller was analyzed, decomposed, and re-grouped into appropriate machining regions so that the planning complexity is reduced. The proposed planning templates are also applicable to these simpler machining regions. A complex centrifugal impeller with split blades was successfully cut using the NURBS STEP-NC tool paths produced by the proposed framework on a 5-axis CNC machine tool.

We have developed a Visual Basic program that plots NURBS curves and surfaces exploiting the advantages of this type of curves (continuity, flexibility, smoothing). For a chosen part, the geometric data are generated and sent to CAM software which generates the tool trajectories for the rough machining of the part with STEP-NC format.

The great advantage of this technique is to follow with a minimum of information a curve which, to be approximate with sufficient smoothness.

References

Ameddah, H., Assas, M., (2009), Interpolation by Bezier curves and NURBS Strategies of Machining of Complexes Surfaces In CNC Milling, American Institute of Physics AIP Conf. Proc. Volume 1107, pp. 342-346.

Hacene Ameddah and Mekki Assas, (2011), NURBS Interpolation Strategies of Complex Surfaces in High Speed Machining, International Journal of CAD/CAM (2011) Vol. 11, No. 1.

Alireza Mokhtar Xun Xu Iñigo Lazcanotegui, (2009), Dealing with feature interactions for prismatic parts in STEP-NC, J Intell Manuf (2009) 20:431–445.

Alireza Mokhtar Xun Xu, (2011). Machining precedence of 2½ D interacting features in a feature-based data model, J Intell Manuf (2011) 22:145–161.

Borkar B. R., Puri Y. M., (2015). Automatic Extraction of Machining Features from Prismatic Parts using STEP for Downstream Applications, J. Inst. Eng. India Ser. C (July–September 2015) 96(3):231–243.

Cheng, M.-Y. M.-C. Tsai, J.-C. Kuo (2002) Real-time NURBS command generators for CNC servo controllers, International Journal of Machine Tools & Manufacture 42 (7), 801–813.

Hardwick M., & Zhao. Y. F, and all, (2013), A roadmap for STEP-NC enabled interoperable manufacturing, Int J Adv Manuf Technol (2013) 68:1023–1037.

Ibaraki, S.; Sawada, M.; Matsubara, A.; Matsushita, T. (2010), Machining tests to identify kinematic errors on five-axis machine tools, Precision Engineering 34 (3), 387–398.

IEC TC65/WG6, (1999), Function Blocks for Industrial Process Measurement and Control Systems (Part-1: Architecture).

ISO/DIS 10 303-238 (2003), Industrial Automation Systems and Integration— Product Data Representation and Exchange—Part 238: Application Protocols: Application Interpreted Model for Computerized Numerical Controllers.

ISO 14 649-1 (2003), Data Model for Computerized Numerical Controllers: Part 1 Overview and Fundamental Principles.

ISO 6983-1(1982), Numerical Control of Machines—Program Format and Definition of Address Words—Part 1: Data Format for Positioning, Line Motion and Contouring Control Systems.

ISO 10 303-21 (1994), Industrial Automation Systems and Integration— Product Data Representation and Exchange—Part 21: Implementation Methods: Clear Text Encoding of the Exchange Structure.

ISO 14649-11(2003), Industrial automation systems and integration— Physical device control—Data model for computerized numerical controllers—Part 11: Process data for milling, ISO TC 184/SC 1, May 23.

ISO 14649-10 (2003), Industrial automation systems and integration—Physical device control—Data model for computerized numerical controllers—Part 10: General process data, ISO TC 184/SC 1, May 23.

Koninckx, B.; Vanbrussel, H., (2002), Real-time NURBS interpolator for distributed motion control, CIRP Annals—Manufacturing Technology 51 (1), 315–318.

Lei, W.T.; Wang, S.B. (2009), Robust real-time NURBS path interpolators, International Journal of Machine Tools & Manufacture 49 (7–8), 625–633.

Liang & Xia Li , Hong bin (2013), Five-axis STEP-NC controller for machining of surfaces; Int J Adv Manuf Technol (2013) 68:2791–2800

Lizhi Gu, Hao Wu and Qi Hong, (2012), The New NURBS Interpolation Algorithm Based on Constant Feed Rate and Deceleration in STEP-NC Machining. DOI: 10.1007/978-94-007-2169-2_166 In book: Green Communications and Networks, pp.1393-1400 Green Communications and Networks, Proceedings of the International Conference on Green Communications and Networks (GCN 2011).

Mann, S.; Bedi, S.; Israeli, G.; Zhou, X (Linda),(2010), Machine models and tool motions for simulating five-axis machining, Computer- Aided Design 42 (3), 231–237.

Matthieu Rauch, Raphael Laguionie, Jean-Yves Hascoet, Suk-Hwan Suh, (2012), An advanced STEP-NC controller for intelligent machining processes, Robotics and Computer-Integrated Manufacturing 28 375–384.

Object Management Group. (2003, Mar.) OMG Unified Modeling Language Specification. Version 1.5. [Online] Available: http:// www.omg.org /technology/ documents/ formal/uml.htm.

Piegl, L.; Tiller, W., (2003), The NURBS Book, Springer-Verlag, Berlin Heidelberg.

Pinghan, Wu.; Yuwei, Li.,(2008), Tool path planning for 5-axis flank milling based on dynamic programming techniques, The International Journal of Advanced Manufacturing Technology, 52(9): 195–200.

Po Hu & Zhenyu Han& Hongya Fu& Dedong Han; (2015), Architecture and implementation of closed-loop machining system based on open STEP-NC controller Int J Adv Manuf Technol Accepted: 19 July 2015; DOI 10.1007/s00170-015-7631-z.

Suh SH, Lee BE, Chung DH, Cheon SU ; (2003), Architecture and implementation of a shop-floor programming system for STEPcompliant CNC. Comput Aided Des (2003) 35:1069–1083.

Xianzhi Zhang & Aydin Nassehi & Stephen T., (2014), Feature recognition from CNC part programs for milling operations Newman Int J Adv Manuf Technol (2014) 70:397–412 ; DOI 10.1007/s00170-013-5275-4

Young, H.-T.; Chuang, L.-C.(2004), Gerschwiler, K.; Kamps, S.: A five-axis rough machining approach for a centrifugal impeller, Int J Adv Manuf Technol, 23: 233–239.

Young, H T., Chuang, L C. (2003), An integrated machining approach for a centrifugal impeller. Advanced Manufacturing Technology, 21: 556–563.

Zhang Yu, Bai Xiao-Lan, Xu Xun, Liu Yong-Xian, (2012), STEP-NC Based High-level Machining Simulations Integrated with CAD/ CAPP/ CAM, International Journal of Automation and Computing, 9(5), October 2012, 506-517.