International Journal of Engineering Research and Technology.
ISSN 0974-3154 Volume 7, Number 1 (2014), pp. 29-39

http://www.irphouse.com

STEP-NC Standardized CNC Milling Machine using Fussy-logic Cutting-force Control System

Tinton Dwi Atmaja, Dalmasius Ganjar Subagio and Noviadi Arief Rachman

Research Centre for Electrical Power and Mechatronics
Indonesian Institute of Sciences
Komplek LIPI, Jl.Cisitu No.21/154D, Bandung 40135, Indonesia.
Tel.+62-22-2503055, Fax:+62-22-2504773.

Abstract

Over the years, G-codes (ISO 6983) have been extensively used by the CNC machine tools for part programming and are now considered as a bottleneck for developing next generation of CNC machines. A new standard known as STEP-NC (ISO 14649 and ISO 10303-238) is being developed as the data model for the new breed of CNC machine tools. STEP-NC conventionally can read in a STEP AP-203 or AP-224 file and convert it into G-code format that the targeted CNC machine tool can understand. STEP-NC also enables control, intelligent control and machining. A fuzzy-logic controller (FLC) is designed to automatically adjust feed rate in order to regulate the cutting-force of milling processes and the control the servo and the force. A FLC will be designed to modify a cutting parameter to follow a set point of a desired cutting force. Feed-motor current and Spindle-motor current will be analyzed as a cutting force sensor. The combination of this cutting-force FLC and STEP-NC standard potentially emerges an open, interopable and intelligent CNC Milling Machine. Furthermore, this combination can be used in any CNC machine that has the ability to execute the machining tasks.

Keywords: CNC Milling Machine, STEP-NC, Fussy-logic, Cutting-force.

I. Introduction

CNC milling machine is developed from traditional milling machine so CNC milling machine can make more complex sharp with better accuracy. High accuracy CNC machines are required in many manufactures because the demand of precision components and consistency of quality are growing [1]. The most important factor of the precision components is the accuracy of machine tools. Mainly, position errors are originated from geometric, cutting force, dynamic loading, etc. [2][3]. Today's CNC machine designs are well developed with capabilities such as multi-axis control, error compensation, and multi-process manufacture. In the meantime, these capabilities have made the programming task increasingly more difficult and machine tools themselves less adaptable. Some effort has been made to alleviate this problem, in particularly the trend towards open architecture control, based on OSACA and open modular architecture controller (OMAC), where third party software can be used at the controller working within a standard windows operating system. Many controller was use for high precision machining and high speed machining; i.e. CNC milling controller GSK 983M [4]. In this paper, we would like to develop similar controller but in this case will be a fuzzy-logic controller to regulate the cutting force and modify cutting parameter. The combination of this cutting-force FLC and STEP-NC standard potentially emerges an open, interopable, and intelligent CNC Milling Machine which is capable to be implemented into any CNC machine without changing the hardware system.

II. Cutting-Force Fuzzy-Logic Control System Analysis

Fuzzy-logic control, an artificial-intelligence-based method, is a viable alternative to model-based control schemes. This research will analyze fuzzy-logic controller to the cutting parameter.

A. Cutting-force model

A mathematical model is used to predict dynamic cutting forces as a function of machining conditions in two-flute end-milling process which is a complex dynamic process (e.g., non-linear, time variant). Furthermore, various vibrations that occur during cutting can cause variation in cutting forces [5]. Derivation of a rigorous mathematical model is beyond the scope of this study. Therefore, the mathematical description of cutting forces that Zheng et al. Proposed [6] was adapted to use in numerical simulation later. It was assumed that cutter was perfectly aligned with respect to its spindle axis. Also, tool, dynamometer, and workpiece were assumed to be rigid in this model. Only a full immersion case (the difference between the entry angle and exit angle of a flute is 180°) was considered in this work as shown in Fig. 1 [7].

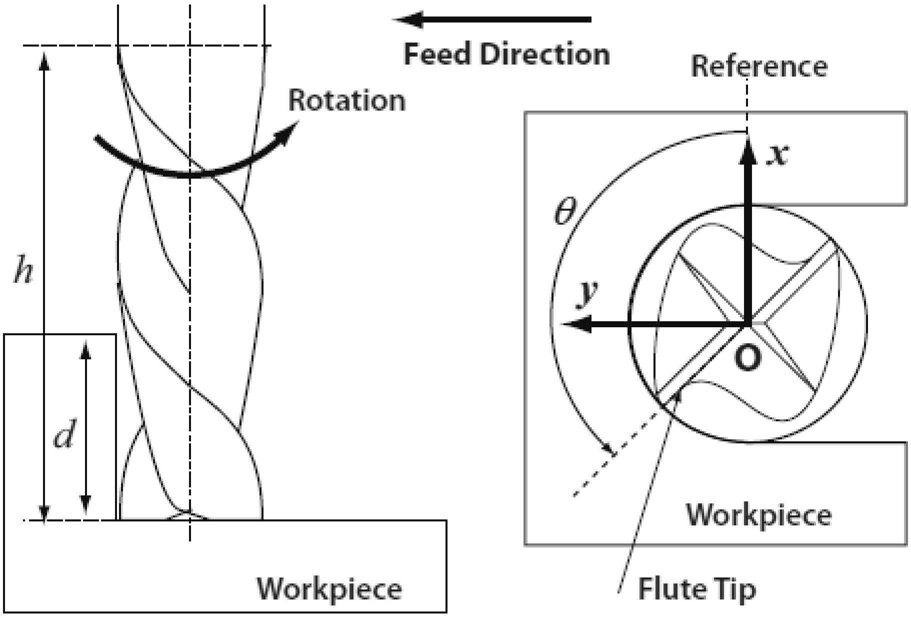

Fig. 1. Geometry of a two-flute end-milling cutter and workpiece in full immersion

Cutting forces in x and y axes are described as [7]:

$$F_x = \frac{K_s K_{rt} f_t d}{2} + \frac{K_s f_t h}{4\pi} \sin\left(\frac{2\pi d}{h}\right) \sqrt{1 + K_{rt}^2} \sin\left(2\theta - \frac{2\pi d}{h} + \psi\right)$$
$$F_y = \frac{K_s f_t d}{2} + \frac{K_s f_t h}{4\pi} \sin\left(\frac{2\pi d}{h}\right) \sqrt{1 + K_{rt}^2} \sin\left(2\theta - \frac{2\pi d}{h} + \psi\right) \quad (1)$$

Where K_s is the tangential specific cutting force, tan ψ $1/K_{rt}$, K_{rt} is the radial-to-tangential cutting-force ratio, f_t is the distance that the center of the tool travels is, which is equal to $f/(N_s \cdot M)$, f is the feed rate (mpm), N_s is the spindle speed (rpm), M is the number of flutes, θ is the rotational angle of the flute tip, h is the length of cut, and θ is $2\pi N_s t/60$. It was assumed that only a single flute engages the workpiece at any given moment (i.e., $0 \leq \theta \leq 2\pi d/h$).

The parameters K_s and K_{rt} are dependent on the tool and workpiece material, and power functions of average chip thickness, $\bar{t}_c$(=$2f_t/\pi$ in the given experimental condition) [6]. These parameters were obtained by curve-fitting Eq. (1) to the measured cutting-force data.

B. Fuzzy-Logic Cutting-Force Controller

The cutting force is shown to be a sinusoidal function of which amplitude and dc-offset change in response to time-varying cutting conditions. As a result, a linear transfer function is not easily obtained. Therefore, a fuzzy-logic controller (FLC) was designed instead of linear control algorithms [7].

1) Control of cutting forces by adjusting feed rate

In this section, a controller that modifies a cutting parameter (i.e., feed rate) to follow a set point of a desired cutting force F_d, is designed. The representative force for feedback can be average, minimum, maximum, or RMS values sampled over a period. The reason of using such “quasi-static” quantities is that feed backing dynamic force signal sampled in high frequency makes the overall control system unstable. A cutting-force is a rapidly changing sinusoidal signal. As a result, the control action would strive to follow F_d by adjusting the feed rate in a similar sinusoidal pattern. Therefore, the cutting force is defined as a maximum value of the magnitude of the force vector per spindle rotation.

The block diagram in Fig. 2 shows the double-loop structure of the FLC. An inner-loop PD controller adjusts the input of a feed-motor drive to follow the desired feed rate f_d. Sampling rate for the inner loop is 1ms, and the discrete notation is k. The FLC of the outer loop obtains the maximum cutting force, compares with F_d, and determines an appropriate increase or decrease of the reference feed rate f_{ref} to yield the desired feed rate f_d. Finally, the outer FLC loop delivers f_d to the velocity controller. For k’, the sampling step of the FLC, the following relationship holds: k’=n·k, where n is the number of sampling steps of the velocity-control loop, which is required to complete a single sampling step of the FLC.

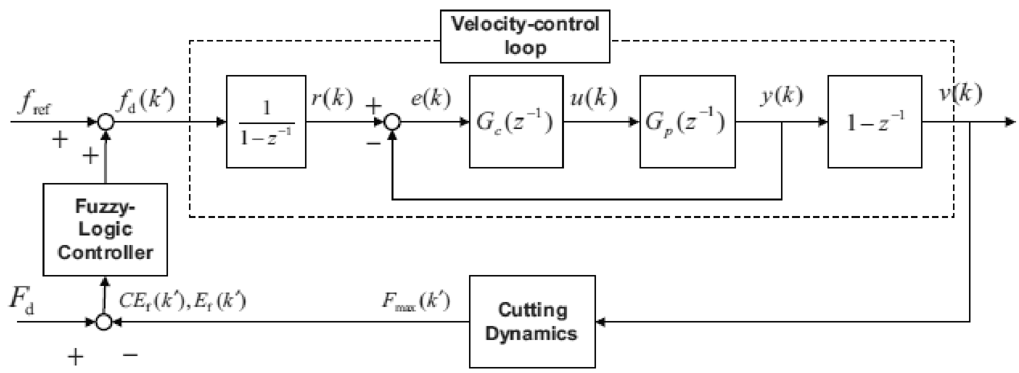

Fig. 2. Block diagram of the fuzzy-logic cutting-force controller [7]

2) Servo-controller design

A discrete-domain transfer function (i.e., input voltage u(k) to output position y(k)) of y-axis feed system of the CNC vertical machining center is obtained using a frequency-domain system identification, assuming that the model is the second-order system:

$$\frac{y(k)}{u(k)} = G_p(z^{-1}) = \frac{0.00257z^{-1}+0.00241z^{-2}}{1-1.820z^{-1}+0.820z^{-2}} \qquad (2)$$

A PD controller was designed. Firstly, a proportional gain is selected such that a closed-loop-system response to a step input (i.e., r(k) = 100µm) has a fast rise-time. Secondly, a small derivative gain is added so that no overshoot is observed in the step response because the cutting tool should not over-run a desired position in milling processes. The PD controller is a function of tracking error e(k):

$$u(k) = 0.001396e(k) - 0.0001e(k-1). \qquad (3)$$

Now an interpolation loop generates a trajectory that y(k) should follow:

$$r(k) = r(k-1) + f_d(k') \cdot T_s, \qquad (4)$$

where T_s is the sampling rate of the velocity-control loop.

3) Force-controller design

The difference between the measured cutting force $F_{max}(k')$ and the reference cutting force F_d, is E(k'). The value of E(k') and its difference CE(k') are calculated in the FLC loop. The input variables are normalized as follows:

$$\overline{E}(k') = \frac{E(k')}{F_d} \text{ and } \overline{CE}(k') = \frac{CE(k')}{F_d} \quad (5)$$

III. The STEP-NC Standard

A. Current Standard

The operation of a CNC machine tool is controlled by a program written in the G-code programming language called NC or part program [8]. An NC program contains an ordered sequence of blocks and is executed sequentially, one command at a time. When a program is executed, the control will encounter the first command in the program; execute it, and then go on to the second command. The control executes each command in the same order encountered. A block is made up of words. Characters and numerical digits are the elements that constitute a word. For example is shown below.

N10 G01 X200 Y300 Z100 F200 M03 S800

Over the years, G-codes (ISO 6983) have been extensively used by the CNC machine tools for part programming and are now considered as a bottleneck for developing next generation of CNC machines. A new standard known as STEP-NC is being developed as the data model for a new breed of CNC machine tools. The data model represents a common standard specifically aimed at the intelligent CNC manufacturing workstation, making the goal of a standardized CNC controller and NC code generation facility a reality. It is believed that CNC machines implementing STEP-NC will be the basis for a more open and adaptable architecture [9].

B. STEP-NC Standard for More Open and Interoperable CNC Milling Machine

Today a new standard namely ISO 14649 [10] recognized informally as STEP-NC is being developed by vendors, users and academic institutes worldwide to provide a data model for a new breed of intelligent CNCs. The data model represents a common standard specifically aimed at NC programming, making the goal of a standardized CNC controller and NC code generation facility a reality.

Currently two versions of STEP-NC are being developed by ISO. The first is the Application Reference Model (ARM) (i.e. ISO 14649) and the other Application Interpreted Model (AIM) of ISO14649 (i.e. ISO 10303-238 [11]). Machining information can now be bi-directionally transferred between a CAD/CAM system and a STEP-NC controller. One critical issue is that the tool path movement information is optional and ideally should be generated at the machine by the STEP-NC controller [12]. Some of the benefits with using STEP-NC are as follows [13].

- STEP-NC provides a complete and structured data model, linked with geometrical and technological information, so that no information is lost between the different stages of the product development process.

- Its data elements are adequate enough to describe task oriented NC data.
- The data model is extendable to further technologies and scalable (with conformance classes) to match the abilities of a specific CAM, SFP or NC.
- Machining time for small to medium sized job lots can be reduced because intelligent optimization can be built into the STEP-NC controllers.
- Post-processor mechanism will be eliminated, as the interface does not require machine-specific information.
- Machine tools are safer and more adaptable because STEP-NC is independent from machine tool vendors.
- Modification at the shop-floor can be saved and fed back to the design department hence bi-directional information flow from CAD/CAM to CNC machines can be achieved.
- XML files can be used as an information carrier hence enables Web-based distributed manufacturing.

C. Force Sensor

Spindle-motor and feed-motor currents were compared as a practical alternative to the dynamometer. A DC value that represents the current is required to obtain a linear relationship with the quasi-static force.

1) Feed-motor current as a cutting-force sensor

The output torque of the motor T_m is proportional to the rotor current I. This torque accelerates the equivalent feed-system inertia J_e. In addition, this torque is used to overcome viscous damping B, columbic friction T_f, and the cutting torque T_c acting on the feed system. The equation of motion can be expressed in equation (6) [14]:

$$T_m = K_t I = J_e \frac{d\omega}{dt} + B\omega + T_f + T_c \quad (6)$$

where K_t is the torque constant of the motor. The cutting torque is expressed as $T_c = K_f \cdot F_c$, where F_c is the cutting force and K_f is the cutting-force-transmission gain. In this expression, T_f is important for the feed system, where a strong columbic friction exists in the guide way [14].

2) Spindle-motor current as a force sensor

Power transmission of the spindle system is very different from that of the feed system. Mechanical power of a drive motor is delivered to a cutting tool through a pulley-belt-gear system. This system results in a low bandwidth of spindle-motor current as a force sensor (<5 Hz), and thus the dynamic force information is highly distorted. Furthermore, the rotational angle should be known in order to calculate x-or y-directional components from the cutting torque. Due to these limitations, it is not practical to use the spindle motor current to predict dynamic cutting forces as done with feed-motor current. Instead, average or maximum cutting force per tool revolution is useful for implementation of the FLC. The same mathematical model, Eq. (7), can also be used for the spindle system. Because the spindle is revolving in one direction, the disturbance torque is now expressed as: $T_d = T_f + K_f F_{c,t}$.

IV. Result & Discussion

Nowadays, CNC technology is changing from special enclosed control model to general open-type real-time dynamic control model gradually [15]. Comparing with the traditional enclosed CNC system, the open architecture CNC system has more merits, such as interoperability, portability, interchangeability, extendibility, etc. Aiming at the characteristic demand for an open CNC system of ‘‘PC+PMAC’’ open architecture, components (such as DC servo motors, servo drivers, and gratings) are commonly selected to build a three- axis motion control system with PC and PMAC (programmable multi-axis controller). The commonly used workpiece material is an age-hardenable aluminium alloys also called in trade name as Duralumin (also called duraluminum, duraluminium or dural). The main alloying constituents are copper, manganese, and magnesium. The correlation between cutting temperature, microhardness and photomicrographs reveals that phase stability of Duralumin is always maintained with bonded tools [16]. Many machining process over STEP-NC use turning and milling process. The objective of turning and milling process is to assure relative motion of the tool with respect to the workpiece [17].

A. Cutting Force Control Using Fuzzy-Logic Improvement

In this paper, the spindle motor current and the FLC were used to maintain a constant cutting force on workpieces. As the current-force relation is a function of feed rate, in order to update the cutting force accurately in real time the current-force relation at different feed rates needs to be predetermined as the feed rate continuously changes [7]. Thus, the spindle-motor current, which was equivalent to the maximum cutting force, was set as F_d.

The transfer function between cutting force and feed rate is known to be nonlinear and time varying, and thus it is difficult to design a model-based controller, which can effectively cope with persistent variation of cutting dynamics. Because the FLC is based on the knowledge of an experienced human operator, exact information on the transfer function is not required. In this work, the FLC was successful in maintaining a reference cutting force in real time in both numerical simulation, and experiments for two-flute end milling of aluminum workpieces when the tool dynamometer as used.

The spindle speed during milling processes is usually set as a constant. Therefore, parameter variation due to speed change in the spindle system is not an issue unlike in the feed system. As the spindle-current-to-force relation varies with feed rate, this relation could be predetermined within an expected range by extrapolating data sampled at a different feed rate. Such an automated calibration feature could be incorporated in the force controller in the future.

A useful feature could be added to the proposed machining process controller as future work. The difference between the initial feed command and one that makes the spindle current constant is identified as a linear function of wear width of milling cutters when the feed system is in a steady state and the depth of cut does not change [18]. In this way, the tool wear, another important variable in the process control, could be estimated intermittently using the spindle motor current.

B. STEP-NC Standard Supports for Controlled CNC Machine

Modern CNC machine tools, though capable in functionalities, lack adaptability, portability and intelligence. This is due to the fact that a 50-year-old language is still employed by these machine tools. NC programs following this format are only meant for execution on a specific machine tool. They cannot be reinterpreted by a CAM system or a SFP system for a different machine tool. Automatic generation of a 100% optimized NC program is not possible as design information and know-how about the machine tools and materials is represented in different formats and on different databases. The operator can now be supported at CAM, SFP and NC level by complete information containing understandable geometry (features), task oriented operations, strategies and tool definitions. Availability of design data at the machining stage also enables a reliable collision check, accurate simulation and feedback from the machining stage to the design stage. Further discussion will bring STEP-NC adaptability to control conventional CNC, enabled control to interoperation, enabled intelligent control; and enabled machining.

Two of the main questions needed to be answered: “Does a STEP-NC file contain enough and just enough information for CNC machining?” and if it does, “Can it be used on a traditional CNC machine tool without making changes to the system hardware?” The main research is to do with the development of “translators” which can read in a STEP AP-203 or AP-224 file and convert it into G-code format that the targeted CNC machine tool can understand. Using the tool and operation parameters specified in the AP-238 file, the STEP-NC Adaptor created Gibbs CAM tooling, process and geometry elements and executed Gibbs CAM functions to generate tool–paths corresponding to the AP-238 machining features. Once again, the cut part rendering was used for visual verification prior to post processing the data to generate conventional G-code output. This work has demonstrated the ability of STEP-NC to completely automate CAM processing and tool–path generation. It has also significantly reduced the lead-time in the CAD/CAM to CNC programming time by up to 75% [19].

Various information from several control system to operate together is one of the challenge to be processed. After working closely with some of the popular CNC controllers or Open Modular Architecture Controller, several research teams around the world have been able to process STEP-NC information internally. This is made possible by developing for, and integrating a STEP-NC Interpreter into, these controllers that can faithfully performs the machining tasks as specified in ISO 14649. The dream of performing intelligent control on a CNC machine has never been truly realized. The main reason is that the information (G-code) available to a CNC machine is too low-level information, with which only minimum amount of optimization work can be carried out in real time or near realtime. With STEP-NC, both design and process planning information is available to a CNC machine. It is possible for the CNC machines, or their controllers, to perform high-level, intelligent activities, such as automatic part setup; automatic and optimal tool path generation; accurate machining status and result feedback; complete collision avoidance check; optimal working step sequence; adaptive control and on-machine inspection. The researchers at the NRL-SNT (National Research Laboratory for STEP-NC

Technology) in PosTECH, Korea have developed a Feature-Based STEP-NC autonomous control system based on an Open Architectural Virtual Manufacturing System [20][21][22].

It can be said that the ultimate goal for the STEP-NC enabled machining is to support Web-based, distributed and collaborative manufacturing, a scenario of "design anywhere/build anywhere". This is possible as a STEP-NC program can separate the "generic" manufacturing information (what-to-do), from the manufacturing information (how-to-do) that is native to a specific machine tool. Therefore, a generic STEP-NC program can be made machine-independent and has an advantage over the conventional, G-code based NC program which is always generated for a particular CNC machine. Recently, there has been a trend of using XML (or rather ISO10303 Part 28) instead of EXPRESS language (or ISO 10303Part 21) to represent the STEP-NC information. The reason for this is obvious. The XML processing ability can easily support the e-Manufacturing scenario. CNC machine tools can share information with other departments in and outside the company over the Internet/Intranet. Then, a communication approach based on VRML, Java Applet and HTML, which is the key to create the prototype system, had been described. Comparing with the traditional EAI communication between VRML and Java Applet, this approach has two advantages: (1) the design of the system's control panel becomes more flexible. (2) The reading/writing ability can be achieved by the Java Script imbedded in the HTML, overcoming the weakness that Java Applet needs to be complied with digital signature and configure the complex system environment to allow it read/write the local files [23].

STEP-NC also supports distributed manufacturing scenario through, for example, Ethernet connections to accomplish data collection, diagnostics and maintenance, monitoring and production scheduling on the same platform. There are still issues to be addressed and challenges to be met. These challenges come from the drive for a uniformed STEP-NC information model; development of STEP-NC enabled intelligent controllers, capture of necessary manufacturing knowledge to support decision-making at the machine tool level as well as other under-developed pertaining technologies. The challenges co-exist with the opportunities that if seized in time can yield a multitude of benefits that STEP-NC promises.

V. Conclusion

The study in this paper concludes that a control system that increases the metal-removal rate, while maintaining a constant cutting force, is presented in. The advantages of this control system are: (1) a fuzzy-logic algorithm is simple to design and yet shows a good force-tracking performance, and (2) the control system measures spindle-motor current to sense cutting force instead of using an expensive and impractical tool dynamometer. In the other side, STEP-NC can provide a uniform NC program format for CAM, SFP and NC, avoiding post-processing and entail a truly exchangeable format. Part programs following the STEP-NC standard are interoperable in a sense that they can be adapted to any CNC machine tools that have the ability to execute the machining tasks. CNC machines implementing STEP-NC can have a more open and adaptable architecture, making it easier to integrate with other manufacturing facilities, e.g. workpiece handling device.

Acknowledgement
We would like to thank Mrs. Dian Andriani of Chonnam National University, the researchers of Gwangju Institute of Science and Technology, and the researchers of University of Adelaide who support us with unlimited access for qualified international resources. And we also would like to thank all researchers of Research Centre for Electrical Power and Mechatronics – Indonesian Institute of Sciences for supporting our study.

References

[1] Chana Raksiri, Manukid Parnichkun, "Geometric and Force Errors Compensation in a 3-axis CNC Milling Machine," International Journal of Machine Tools & Manufacture, vol. 44, pp. 1283–1291, 2004.
[2] R. Ramesh, M. A. Mannan and A. N. Poo, "Error compensation in machine tools — a review: Part I: geometric, cutting-force induced and fixture-dependent errors," International Journal of Machine Tools and Manufacture, vol. 40, pp. 1235-1256, 2000.
[3] Mahbubur Rahman, Jouko Heikkala and Kauko Lappalainen, "Modeling, measurement and error compensation of multi-axis machine tools. Part I: theory," International Journal of Machine Tools and Manufacture, vol. 40, pp. 1535-1546, 2000.
[4] GSK CNC. (2007) CNC Machine and CNC Equipment, CNC Milling Controller GSK 983M. [Online]. http://gskcnc.com/cnc_controller.php
[5] M. Hashimoto, E. Marui, S. Kato, "Experimental Research on Cutting Force Variation During Primary Chatter Vibration Occuring in Plain Milling Operation," International Journal Mach. Tools Manufactur, vol. 36, pp. 183-20, 1996.
[6] L Zheng, Yun Shun Chiou, Steven Y. Liang, "Three Dimensional Cutting Force Analysis in End Milling," International Journal of Mechanical Sciences, vol. 38, pp. 259-269, 1996.
[7] Dohyun Kim, Doyoung Jeon, "Fuzzy-Logic Control of Cutting Forces in CNC Milling Processes using Motor Currents as Indirect Force Sensors," Precision Engineering, vol. 35, pp. 143–152, 2011.
[8] Sotiris L. Omirou, Antigoni K. Barouni, "Integration of New Programming Capabilities into a CNC Milling System," Robotics and Computer-Integrated Manufacturing, vol. 21, pp. 518–527, 2005.
[9] X.W. Xu, S.T. Newman, "Making CNC Machine Tools More Open, Interoperable and Intelligent—a Review of the Technologies," Computers in Industry, vol. 57, pp. 141–152, 2006.

[10] International Organization for Standardization, "ISO 14649-10:2003 Data model for computerized numerical controllers," 2003.
[11] International Organization for Standardization, "ISO 10303-238 Application protocol: Application interpreted model for computerized numerical controllers," 2007.
[12] R.D. Allen, S.T. Newman, J.A. Harding, RSU Rosso Jr., "The design of a STEP-NC compliant agent based CAD/CAM system," in the 13th International Conference on Flexible Automation and Intelligent Manufacturing (FAIM2003), Tampa, FL, USA, 2003, pp. 530–540.
[13] X.W. Xu, Q. He, "Striving for a total integration of CAD, CAPP, CAM and CNC," Robotics and Computer Integrated Manufacturing, vol. 20, pp. 101–109, 2004.
[14] Altintas Y. , "Prediction of cutting forces and tool breakage in milling form feed drive current measurements," ASME Journal of Engineering for Industry, vol. 114, pp. 386–92, 1992.
[15] Pengfei Li, Tao Gao, Jianping Wang, Hongzhao Liu, "Open Architecture of CNC System Research Based on CAD Graph-driven Technology," Robotics and Computer-Integrated Manufacturing, vol. 26, pp. 720–724, 2010.
[16] S.M. Darwish, A. Niazi and A. Ghaneya, "Phase stability of duralumin machined with bonded and brazed carbide tools," International Journal of Machine Tools and Manufacture, vol. 32, pp. 593-600, 1992.
[17] M. Kovacic, M. Brezocnik, I. Pahole, J. Balic, B. Kecelj, "Evolutionary programming of CNC machines," Journal of Materials Processing Technology, vol. 164-165, pp. 1379–1387, 2007.
[18] Kang-Jae Lee, Taik-Min Lee and Min-Yang Yang, "Tool Wear Monitoring System for CNC End Milling Using a Hybrid Approach to Cutting Force Regulation," The International Journal of Advanced Manufacturing Technology, vol. 32, pp. 8-17, 2007.
[19] Mark Albert. (2002, July) MMS Online, Plugging Into STEP NC. [Online]. http://www.mmsonline.com/articles/plugging-into-step-nc
[20] Suk-Hwan Suh, Jung-Hoon Cho, Hee-Dong Hong, "On the architecture of intelligent STEP-compliant CNC," International Journal of Computer Integrated Manufacturing, vol. 15, pp. 168 - 177, 2002.
[21] S.H. Suh, D.H. Chung, J.H. Lee, J.H. Cho, H.D. Hong, H.S. Lee, "Developing an integrated STEP-compliant CNC prototype," Journal of Manufacturing Systems, SME Transaction, vol. 21, pp. 350–362, 2003.
[22] S. H. Suh, B. E. Lee, D. H. Chung and S. U. Cheon, "Architecture and implementation of a shop-floor programming system for STEP-compliant CNC," Computer-Aided Design, vol. 35, pp. 1069-1083, 2003.
[23] He Hanwu, Wu Yueming, "Web-based Virtual Operating of CNC Milling Machine Tools," Computers in Industry, vol. 60, pp. 686–697, 2009.