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New Method for the Development of Sustainable STEP-Compliant Open CNC System

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Abstract

In the manufacturing sector, the CNC machine plays a significant role for the last five decades. In this paper, a new method for the development of sustainable CNC system based on OAC and STEP-NC technologies is introduced. OAC technology provides a reconfigurable, reusable software and hardware platform. The STEP-NC data interface model introduced flexibility, interoperability, adoptability and intelligence into the CNC. The system has been implemented on an old 3 axis CNC milling machine and found to be quite satisfactory in performance.

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1. Introduction

The Computer Numerical Control (CNC) machine plays a vital role in the growth of manufacturing world since its development. CNC technology uses computers and Computer Aided Design (CAD)/Computer Aided Manufacturing (CAM) software for the generation, parsing and execution of the sequential control. Today, CNC machines are employed in many industries with different controllers and multiple abilities for various applications such as: turning, drilling, milling, packaging, tube welding and robotic cutting [1]. The CNC is composed of many parts whereas; the controller is the heart of a CNC unit that is composed of two parts: hardware and software. The hardware contains various parts: namely motor drives, motion control card and others. While, the software part consists of Programmable Logic Control (PLC) and interpreter for executing machine hardware. The interpreter of the CNC controller acquires the International Standards Organization (ISO) data interface model instructions and translates it into internal commands for moving tools and executing auxiliary functions in a CNC system [2]. CNC machines utilize ISO 6983 data interface model, formally known as G-code, for their operations. The ISO 6983 data interface model program codes are generated by CAM systems that use CAD information. This model defines the information by numerical codes (G, T, M, F, S etc) indicating the movement of a machine and an axis to the controller [3].

The demand of flexibility in the CNC systems was increased in late 1970’s and early 1980’s, because of the rapid growth in the manufacturing world to enable low bunch manufacturing of the extensive variety of parts. In the progression towards the realization of the flexible manufacturing environment, the CNC machines were found to be a critical resource because of their capability of being reprogrammed to produce different parts [4]. In order to overcome that demand, a new ISO standard was developed which is formally known as Standard for The Exchange of Product Data (STEP) or ISO 10303 [5]. The objective of STEP is to provide the means of describing product data throughout the life cycle that is independent from any particular computer system. ISO 10303 significantly improved the interoperability between CAD systems and had also created the need of a similar standard for exchange of information between CNC machines as well as CAM systems. Consequently, in 1999 an international project was started to
specify a new standard entitled ISO 14649 formally known as STEP-(Numerical Control)NC to bring the benefits of STEP to CAM and CNC [6]. The ISO 14649 standard is an extension of ISO 10303. It allows the connections between STEP based Computer Aided Systems (CAx) and CNC machines. The concept of Standard for The Exchange of Product Data-Numerical Control (STEP-NC) is based on “Design anywhere, build anywhere and support anywhere” [7]. The introduction of ISO 14649 provides a platform to recover the information loss between CAD/CAM/CNC and opens the doors for the development of next generation (modern and flexible) CNC systems [4].

The implementation of STEP-NC was firstly originated on current commercially available CNC controllers. This implementation was known as “In-Direct STEP-NC programming approach” [8,9] that translates the STEP-NC data into G codes for operations [4]. There are many approaches that had been carried out by various researchers within the scope of that approach such as [10-13]. During this implementation, it was found that this low level translation is not enough to enable all the features of STEP-NC in the CNC [4].

In order to overcome these problems, a new STEP-NC implementation approach “Interpreted STEP-NC programming” [8,9] was introduced. In this approach, the controller directly reads and interprets the ISO 14649 information as per internal structure of the machine. However, while this implementation it was found that, the commercial CNC machines are of closed nature that will not allow the user to buy hardware and software from several different manufacturers and freely assemble those [14]. Apart from that, manufacturers believe that the conventional CNCs are powerful enough to handle machining tasks. The CNC and CAM vendors seem to have a limited concern in promoting STEP-NC. In fact, they have misread the vision of STEP-NC on the next generation of intelligent control and that will be a drawback to vendors in the future [15]. Due to these reasons, this modification also requires high cost. Overall, these factors have slowdown STEP-NC implementation on commercial CNC machine. But fortunately, the introduction of Open Architecture Control (OAC) technology provides another platform for this implementation [16,17]. The introduction of OAC increases the possibility of STEP-NC implementation by providing more power to Personal Computer (PC)s [18]. The aim of OAC is to enable easy implementation and integration of customer specific controls, reusability of software and integrating user specific algorithms or application. OAC interfaces can play a vital role in the creation of reconfigurable CNC units. The performance of the unit can be easily improved by upgrading hardware platform only [19,20]. Due to all these facilities of OAC, the modern CNC developers favor PC based solutions to provide high flexibility and quality at low cost [21,22].

Based on these technologies in this paper a new method of sustainable CNC system has been presented. The proposed system is of open nature and utilizes ISO 14649 data interface model instructions for operations. The proposed method has been applied on an old three axis CNC milling machine to convert it into more open and modern CNC unit at a low cost. Further design of paper includes the system architecture, its configuration, its validation and ends with conclusion.

2. System Architecture

The architecture of proposed system has been divided into four tasks: hardware configuration, software configuration, integration of hardware and software systems and validation of the developed system as shown in Figure 1.

![Figure 1. System architecture](image)

Task 1 deal with the formation and installation of all the involved hardware. Task 2 involves the development of the software system for operations. Task 3 integrates the Task 1 and Task 2 and completes the system. In last, task 4 validates the developed system experimentally by manufacturing case study components.

2.1. Task 1- Hardware Structure

This task involves the combination of hardware’s to control the CNC machine via PC. In this study, a DENFORD NOVAMILL Automatic Tool Changer (ATC) NS has been used to be connected and derived through PC. The PC contains a Peripheral Component Interconnect (PCI) 7334 motion control card that controls the axis motion of CNC machine. This communication between machine and PC has been done through serial port via Universal Motion Interface (UMI 7764). This configuration converts the old CNC machine into new PC based machine that is independent from its built-in controller.
The systems also contain Input/Output (I/O) card (PCI 6221), rotary encoders (ENC-7742) and limit switches for three axis and tool changer to enable the closed loop environment. Further tool changer control functions utilize compressor for drill bit chamber and clamber. Lastly, the system has been connected with the custom board that connects the low voltage hardware (encoders and sensors) with the PC. This is done because the machine built-in controller is used for supplying the power to high voltage hardware such as: axis motor drives, spindle motor drive and tool changer. The controller power supply was used because it is a very old machine whose hardware is of old type that consumes high voltage for operation. Figure 2 shows the hardware structure of the proposed system.

![Figure 2. Hardware structure](image)

### 2.2. Task 2 - Software Structure

This task carries the development of software system for the used CNC machine. The software system is composed of Machine Motion Control (MMC), ISO 14649-21 interpreter, and 3D Simulation (3DS) modules. The MMC module is responsible for the motion control of three axis CNC milling machine with closed loop facility and its spindle and automatic tool changer. The ISO 14649-21 interpreter module translates the STEP-NC part 21 data interface model information as per internal structure of the CNC machine. This module is also able to generate physical output file in .txt and .xml formats according to user defined (ad hoc) structure. The 3DS module is utilized for the graphical verification of the translated codes before real machining.

This software module has been designed in National Instruments (NI) Laboratory Virtual Instrument Engineering Workbench (LabVIEW). This specific version of LabVIEW was further upgraded through some extended toolkits provided by NI as packages. The LabVIEW platform was chosen because it is a graphical language; therefore, it is easy to use as compared to text coding platforms. It is a very popular and proved to be a very useful tool in control, display, analysis and data acquisition applications. LabVIEW features include libraries of reusable code, support for building Graphical User Interface (GUI),s, use of the dataflow paradigm and automatic memory management [23]. As ISO 14649 data model contains a rich set of information, LabVIEW can be a very useful platform to provide an all in one unit for CNC operation. The major advantage of LabVIEW is that, it provides wide range of connectivity in hardware and software terms which allows an open environment for CNC. In hardware terms, LabVIEW is able to provide a wide range of connectivity through serial ports and wireless [24-26]. However in software terms, it is able to communicate with various third party software like MS office, C, C++, C#, JAVA, MATLAB, SolidWorks, Visual Studio etc. Another major advantage of LabVIEW is that its program library can be directly applied to various tasks without having to change the program code. The parallelization of the code execution can also be easily achieved through this tool [23].

These facilities of LabVIEW can enable access to monitoring, inspection, database, internet connectivity and other functions within a single platform. In other words, it can be a useful source to make an all-in-one platform for CNC machines. These facilities can make LabVIEW a very useful tool in the development of modern CNC systems. Apart from that, so far none had used LabVIEW platform for the automatic tool changing, STEP-NC part 21 file and 3D simulations.

### 2.3. Task 3 – Integration of Hardware and Software

In this task, the developed hardware and software configurations are integrated into a single system as shown in Figure 3 and 4. The corresponding algorithm has been designed in NI LabVIEW for this integration and proper operational executions. This integration had combined all the modules and sub-modules of the system in a systematic sequence according to their functionalities. This task will give the shape of the system to all the modules and compile them into a single CNC controller.

### 2.4. Task 4 – Validation

In this task, the system is tested experimentally by case studying the manufacturing of components. The results of this task validated the performance of the developed system.

### 3. Software Configurations

#### 3.1. ISO 14649-21 Interpreter

The function of this module is to translate ISO 14649 data interface model information as per required structure of CNC machine. It interprets the acceleration, deceleration, spindle speed, feed rate, tool, tolerance etc information from ISO 14649 code, so that machine can be moved throughout linear or circular interpolation and perform operations. This module provides shop floor editing facilities to the CNC system and also able to generate physical file output in user defined structure of .txt and .xml formats. The internal structure of ISO 14649 interpretation module is composed of three sub modules: input data, data extraction and output data, which are composed of various functional blocks. To read more about this module please refer [27-29].
3.2. 3D Simulation

The function of 3D simulation module is to graphically verify the translated code before performing real machining operations. This module is composed of recite, process description, plot points and lines, show live plotting, 360° viewer, decision and input drawing functional modules as shown in Figure 3.

Figure 3. Internal structure of 3D simulation module

The recite functional module is responsible to read the input data. This functional module first reads the complete content of the input data and then passes this information to the process description functional module that extract the process names data from the input code. The plot points and lines functional module is responsible to take the axis positions (x, y and z) data from recite functional module and plot it into graphical form in 3D. The show live plotting functional module applies delay operations in plot points and lines functional module to show the live plotting of input data.

The 360° viewer functional module is responsible to enable the rotational views into the module and shows the plotting in various angles. The decision functional module is responsible for making a decision regarding simulation results. If the results are satisfactory, the 3D simulation module will be closed and data will parse to the machine motion control module. If the results are not satisfactory, the module will recall ISO 14649-21 interpretation module for data modifications. This module also includes the input drawing functional module that is responsible to show the CAD design of the input code drawing file in Joint Photographic Experts Group (jpeg) image format. The combination of all these functional modules builds the 3D simulation.

3.3. Machine Motion Control

The machine motion control module is responsible for controlling the motion of three axis CNC milling machine. In this system, a three axis motion control technique of [23, 30] was utilized for the motion controlling of X, Y, Z axis and spindle of the CNC milling machine. In this study, the limitation of [23, 30] 3 axis motion control is extended to 3 axis motion control with automatic tool changer in a closed loop control environment.

This module is composed of various sub modules such as: encoder connection and calibration, Drill Bit Changer (DBC) DBC mapping, DBC +1, DBC +half, DBC movement, DBC home sequence, DBC move to previous position, DBC sequence and DBC manual operate as shown in the Figure 4.

Figure 4. Internal structure of machine motion control module

The encoder connection and calibration sub module connects the software configuration with the hardware configuration of the encoder (EN-7720) and enables the closed loop control environment into the CNC machine. The DBC mapping sub module is responsible for indication and setting of the tool changer position and tool at head. The DBC +1 sub module is responsible for one complete rotation of the drill bit changer. The DBC +half is composed of same functional modules as that of DBC +1 sub module. The only difference between these two modules is of the rotations of the drill bit changer. The DBC movement sub module is responsible for the linear movement of drill bit changer. The DBC home sequence sub module is responsible to move the machine (X, Y and Z) axis back to home position and switch OFF the spindle drive of the machine. The DBC move to previous position sub module is responsible to move the machine (X, Y and Z) axis back to previous position and turn ON the spindle drive after tool changing operations. The DBC sequence sub module is responsible to perform one complete cycle of the tool changing operations (from tool dropping to tool picking) by utilizing aforementioned sub modules. The DBC manual operate sub module is responsible for the setting of all the automatic tool changing parameters and functions manually. The combination of all these modules completes the CNC control system.
4. Validation

The proposed configurations have been implemented on three axis CNC milling machine (DENFORD NOMAVILL ATC) and number of experiments has been performed. The working principle of proposed system initiate with ISO 14649-21 interpreter module, which takes STEP part 21 file as an input and perform translation functions. After that, translated code read by 3D simulation module and graphical verification of input code has been performed. After the successful verification, the instructions have been passed to machine motion control module and real machining is performed. Figure 5 shows the experimental setup and manufactured parts.

![Experimental setup and manufactured parts](image)

Figure 5. Experimental setup and manufactured parts

5. Conclusion

In this study a new method for the development of sustainable manufacturing environment based CNC system has been introduced. The system is of open nature that allows different vendors to integrate custom hardware and software module with CNC core. The proposed technique is composed of hardware and software configuration. In proposed study different vendors hardware and software are integrated into a single PC based CNC unit to enable more open, interoperable, intelligent and modern CNC environment at a low cost. This integration has been implemented on old CNC machine and successfully converted into a modern CNC system. This integration and conversation reflects towards the sustainability of this study. The system is composed of various software modules, which were developed by various NI LabVIEW functional blocks. The system is based on new ISO data interface model formally known as STEP-NC, it is able to work with STEP part 21 physical file. However, for ISO 6983 a similar approach was adopted in past for that please refer [30].

Generally, the development of these kinds of systems will be lower in cost as compared to commercial systems because it is based on the PC, which provides wide options for the use of third party hardware and software. This development can play an important role in the growth of small industries and shop floor CNC users. These systems can also be used to convert old CNC or manual operated machines into modern CNC units. Overall, in this study the conversation of old CNC system into a new PC based CNC system presents the example of sustainable manufacturing environment and highlights the main contribution of the study as well.

In future the system will be further extended with more modern and intelligent CNC feature with the integration of various third party hardware and software.

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