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A review of STEP-NC compliant CNC systems and possibilities of closed loop manufacturing

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Abstract. A new programming interface, ISO14649, named STEP-NC, has been introduced recently to overcome the drawbacks of the conventional CNC system. Enhanced machining flexibility, interoperability, and adaptability are the key features of this new programming strategy. STEP-NC technology is based on object-oriented concepts and considers machining processes rather than tool motions as in ISO 6983 for machine tool operation. As such, high level machining features and machining parameters are transferred to the CNC controller, which are eventually used for generating axis movements and other operations. The bi-directional data communication facility of this new strategy enables last minute shop floor level modifications of machining operations at the controller level and establishes a communication pathway to feed major modifications, if required, back to the CAD level as well. Accordingly, the new programming interface allows seamless integration in the CAD/CAM/CNC chain and paves the way for Closed Loop Manufacturing facilities. Most CNC controller vendors have not released STEP-NC compliant controllers yet. Therefore, researchers are developing Open Architecture Control systems to execute STEP-NC and operate CNC machines. This paper reviews research and development of STEP-NC controllers in the last decade and the capabilities of Closed Loop Manufacturing with STEP-NC based systems.

1. Introduction

The manufacturing industry plays a vital role in the global economy. Product manufacturing for diverse customer requirements is one of the challenges in manufacturing today. Computerised Numerical Control (CNC) machines have played an important role in manufacturing precise, accurate, and high quality products from the inception of technology. On the other hand, CNC machines are important to get high productivity rates, uniformity of product, reduced rejection, reduced tooling costs, and less operator involvement [1]. G and M codes have been used to command CNC machines since the introduction of CNC machines in 1950's. In 1960's, the Electronic Industry Association (EIA) developed a standard named RS274D to program CNC machines. Later in 1982, this was adopted by ISO and a new standard was introduced, called ISO6983. In this method, preparatory functions and miscellaneous commands, defined in ISO 6983, were used to move the cutting tool with respect to the axes. In the last 60 years, the same programming format has been used to program CNC machines, remaining unchanged. This low level programming method describes only the elementary actions and tool movements. The CAD-CAM-CNC numerical chain broke with this format and

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prevented the feedback from the shop floor [2]. On the other hand, sustainable manufacturing with environmental conscious and energy efficient manufacturing systems have become the modern trend in manufacturing. As a result of the rapid advancement of computer based technologies, feature based CAD/CAPP/CAM systems with highly advanced capabilities and powerful CNC controllers were introduced in the manufacturing industry. However, a weak interconnection between CAD/CAPP/CAM systems and CNC controllers, and hence the lack of provisions for closed-loop control of machining processes, have remained a major deficiency in ISO 6983 standard. Different CNC controller vendors have added new supplement commands to their own controller to improve some deficient features of ISO6983. This created further incompatibility in the part programs generated for different CNC machines [3].

Because of these problems, the requirement to develop a standard to describe the product data throughout the life cycle arose, which is independent from the controller and the computer system. In order to address the above requirements, a new standard called Standard for the Exchange of Product Model Data (STEP), ISO 10303, was introduced to exchange CAD data between CAx systems. Later, STEP compliant data interface was developed to exchange the product data between CAD/CAM systems and CNC controllers. This standard is known as STEP Data Model for Computerized Numerical Controllers (STEP-NC) and defined under ISO14649 [1]. As opposed to ISO6983, STEP-NC provides feature based programming with an object oriented data model, information on the features to be machined, tool types, operations to be performed, and sequence of operations [3].

Since existing commercial controllers could not understand STEP-NC codes, interpreters were developed during the early stages to convert STEP-NC code to ISO 6983 format, which could be uploaded directly to CNC machines. However, this type of controllers did not support the full capabilities of STEP-NC format. As such, interpreted type CNC controllers were introduced as the next step, where STEP-NC files can directly be uploaded to a controller, and the tool path and axis commands are generated within the controller. Recently, STEP-NC based intelligent controllers were developed to perform more optimized NC operations with self-adaptive capabilities.

2. ISO 14649, STEP-NC architecture

The application of STEP methods to NC machines is defined as STEP-NC [4]. STEP-NC, ISO 14649 is a set of standards, which are defined under the subtitle of "Data model for computerized numerical controllers". It has a number of parts as listed below [4]:

ISO 14649 - Part 1: Overview and fundamental principles;
ISO 14649 - Part 10: General process data;
ISO 14649 - Part 11: Process data for milling;
ISO 14649 - Part 12: Process data for turning;
ISO 14649 - Part 111: Tools for milling;
ISO 14649 - Part 121: Tools for turning [4, 5].

2.1. STEP-NC program organization

The structure of STEP-NC data is mainly divided into two sections. The first section of the part program is the header section marked by the keyword "HEADER". In this section, some general information and comments such as author, date, organization etc. are included. The second main section is the data section and it starts with the keyword "DATA". The data section is divided into three main parts, namely Workplan and executables, Manufacturing features, and Geometry description [6].

The starting point for executing a part program is the PROJECT entity in the DATA section. The PROJECT describes the main *"Workplan"* which contains executables (manufacturing tasks or commands) and details of Workpiece to be machined. There can be three types of executables, namely *"Workingstep"*, Program structure, and NC function. *"Workingstep"* details a single manufacturing operation using one cutting tool. The next executable is program structure, and it can be either a *"Workplan"* or an execution flow statement. The last type of executable is NC function, and it may include setting of the workpiece coordinate system, security plane, and other auxiliary commands [6]. Figure 1 shows the overall structure of the STEP-NC data model.

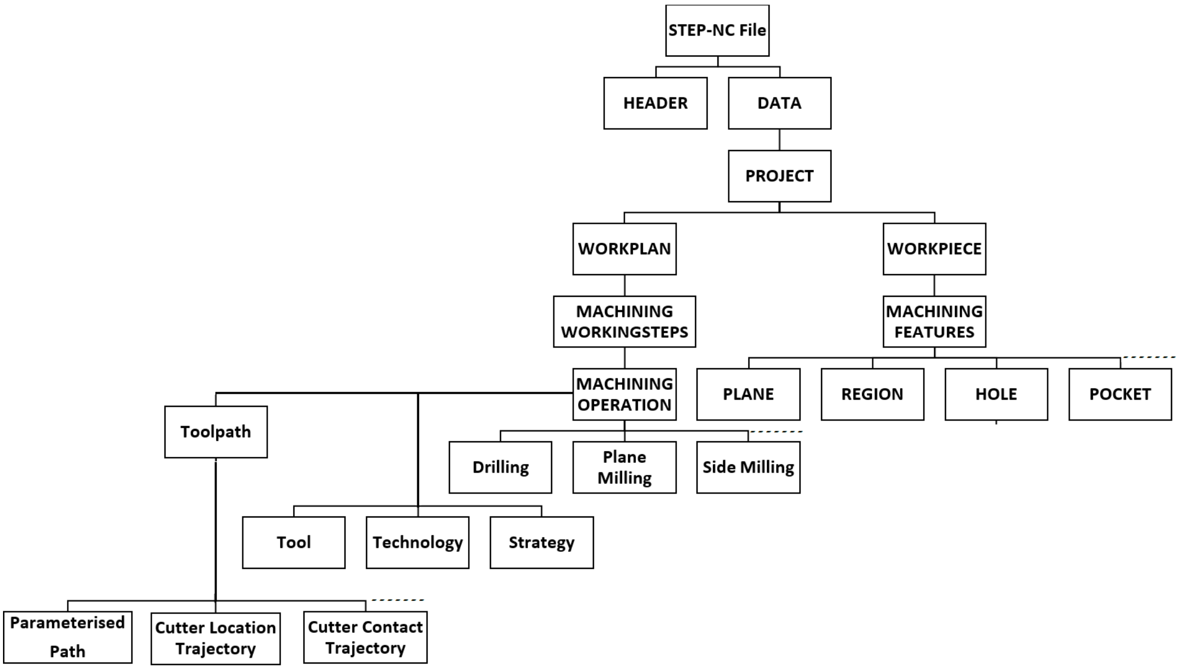

Figure 1. Structure of the STEP-NC data model [7].

3. STEP-NC based controllers

According to the research carried out in the last decade or so, STEP-NC controllers can be classified into four categories, according to their functions [2, 8].

3.1. In-direct STEP-NC controller

This category uses the existing legacy of CNC controllers and G/M codes to program toolpaths. An interpreter is added to the front end of the system to translate STEP-NC code to ISO6984 format. As such, this is called In-direct STEP-NC controller and can easily be implemented in the existing CNC machine tools [2]. Several prototypes, interpreters, and front end applications were developed to be used with existing CNCs [9-11]. However, the innovative features available in STEP-NC format cannot be effectively implemented with this type of controller, and hence the major benefits cannot be achieved [2].

3.2. Interpreted STEP-NC controller

The second category of controllers, Interpreted STEP-NC controller, does not require G codes anymore. The STEP-NC file can be uploaded directly to the machine controller for processing. File interpretation, feature based data extraction, toolpath generation, and axis drive command generation are totally integrated in the machine controller [1].

Most of the early developments in STEP-NC controllers, including the Interpreted type controllers made in different countries and different research groups, have been reviewed by Xu et al. [12].

Because of the closed nature of the commercial CNC machines, the user cannot upgrade existing CNC machines with new hardware and software from different manufacturers and vendors. Most manufacturers are of the view that conventional CNCs are powerful enough to handle machining tasks. Therefore, CNC and CAM vendors are not keen on promoting STEP-NC for future development

[13]. The Open Architecture Control (OAC) technology provided a solution for this problem and most researchers tend to use OAC for their implementation [14].

3.3. Intelligent STEP-NC controller
CNC controllers of this type, identified in the third category, are equipped with the features in the second category, but are also capable of performing NC tasks intelligently and autonomously. Accordingly, real time optimization of machining parameters and toolpaths can be performed with the help of online process data. Automatic collision free toolpath generation, automatic cutting condition selections, status monitoring and recovery, and machining status and feedback results may be incorporated as intelligent functions of the controller [15].

3.4. Collaborative Intelligent STEP-NC controller
The fourth category is STEP-NC enabled machining, which supports web-based, distributed, and collaborative manufacturing with all the facilities available in the second and third categories. This is the ultimate goal of the STEP-NC compliant CNC controllers [3]. A web based platform provides an information protocol for manufacturing operations which take place around the globe via the internet. The final requirement of the various stakeholders of CAD, CAPP, CAM, and CNC is to achieve a manufacturing solution with the seamless DA-BA-SA (Design-Anywhere, Build-Anywhere, Support-Anywhere) facility [16]. The fourth category of STEP-NC compliant controllers fulfils this requirement.

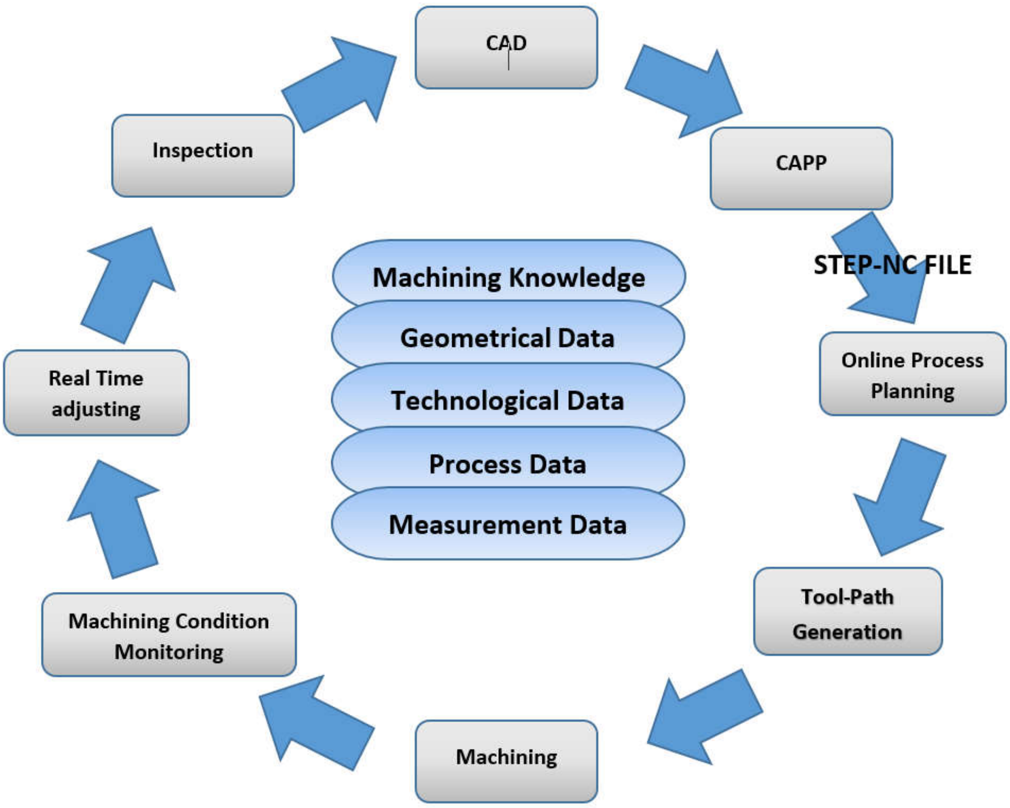

Figure 2. Closed-loop and self-learning STEP-NC machining System [16].

4. Development of STEP-NC compliant controllers with closed loop capability
The Research Division of Numeric Control Technology in the Harbin Institute of Technology proposed an indirect type open CNC controller named HITCNC [17]. This was further developed into an adaptive controller by Hu et al. by effectively utilizing the high level information in the STEP-NC

file, the machining process condition data, and the inspection results [18]. Online and real time machining process control was developed on a 5 axis CNC machine. The STEP-NC interpreter adjusts the technological parameters according to the machining knowledge, the machine tool status, and the cutting tool condition. The feedback sensors provide the necessary data on the machining process conditions to estimate the optimal technological parameters using an adaptive control algorithm. After completing a "*Machining Workingstep"*, it can be verified by online inspection for the required tolerances [18, 19].

Manufacturing knowledge obtained through the feedback from the machining to the product design and production engineering phases was demonstrated by Danjou et al. [20]. In this method, machining data is extracted from a CNC machine and validated in order to effectively use the results. The extracted knowledge is stored in a Manufacturing Process Management (MPM) system to provide a guideline to generate similar programs in the future. The CATIA environment is used for CAD/CAM and the NC Simul Machine simulator is used instead of a real CNC machine to simulate toolpath. The proposal is to use a parser to translate the generated G code program to STEP-NC [20-22].

This concept was developed by Wosnik et al. [23] using the drive signals feedback to the CAPP system for process monitoring and optimization. Algorithms have been developed to process and exchange drive signal data in the application of open digital servo drives in machine tools. Wosnik et al. proposed a method to compare previous force profiles in similar machining conditions with the feedback data and update process force calculation models and machining parameters [23].

A STEP-NC enabled machine condition monitoring system was developed by Ridwan and Xu [24]. It consists of three sub-systems. The first sub-system is to generate optimum machining parameters for time critical machining operations and quality critical machining operations. A simulator has been developed to verify the optimization algorithms, the real-time process control, and the monitoring algorithm. The second sub-system is the adaptive execution of the Canonical Machining Command program with fuzzy feed rate optimization. This will help to keep a constant load within the machine tool's capability and reduce chatter amplitude. The last sub-system is the knowledge based evaluation system which utilises accurate, informative, and updated machining know-how to achieve automated and intelligent machining operations [24].

The STEP-NC compliant intelligent CNC controller was developed with the RCM3700 embedded microcontroller to drive a 2D plasma cutter. The program can be directly uploaded to the controller since there is a STEP-NC interpreter. Next, the interpreted data is fed to the High level controller which evaluates its feasibility of machining and decides the machining operation to execute. A machining inspection facility and web based monitoring and execution facility has been developed by the researchers [25, 26].

5. Development of STEP-NC compliant controllers CLM with inspection

Inspection is an important element in CLM. It can be used to get precise measurements and monitor the performance of the machine tool. One of the parts in the Data model of ISO14649, Part 16, describes touch probing operations on a CNC machine tool or on a CMM. The interface between the programming system and the CNC controller is defined for inspection with this data model. Zhao et al. proposed a framework of STEP-NC enabled, real time CLM system, which uses on-machine touch probes. The machining and inspection information is saved in a STEP-NC file by using CAPP software according to the design requirements. Apart from the "*MachiningWorkingsteps"* the file contains "*InspectionWorkingsteps"*, which should be carried out before machining, in between "*Machining Workingsteps"* and after machining. The inspection results are analyzed, compared with design requirements feedback to the STEP-NC data model if necessary, to generate or modify machining operations. Zhao et al. have reported a case study according to Example 1 given in ISO14649-11 [27] by adding some inspection points and generated an intermediate file to demonstrate the correctness of the data model [28].

In manufacturing, human workers' problem solving capabilities, dexterity, and cognitive capabilities are very important. These will help to improve flexibility, adaptability, and reliability of

IOP Conf. Series: Materials Science and Engineering **399** (2018) 012014 doi:10.1088/1757-899X/399/1/012014

the system. Zhao et al. proposed a consolidated data model and a system structure for process planning, inspection and feedback with cognitive manufacturing capabilities. Pre-processed STEP part 21 file, with machining features and tolerance, is the input for the system. The developed algorithm traces the tolerance related features together with geometrical data and decides what geometry is to be measured and the tolerance limit. The machining working steps are rearranged according to the chosen machine accuracy and the tightness of the tolerance, and newly generated "*InspectionWorkingsteps*" are inserted. The machining and inspection commands generated according to the new process plan are passed to the CNC machine for execution. After each inspection operation, the measured data is analyzed and updated online for subsequent machining operations [29].

A similar study was conducted by Ali et al., who have developed a STEP-Compliant framework for the generation of inspection files for discrete components [30].

Breacher et al [30] demonstrated a closed loop process chain, which includes the generation and execution of the STEP-NC program and feedback. This paper describes Part 16 of ISO14649, Data for touch probing based inspection, which uses integration of the inspection tasks. The STEP-NC data file is converted to a suitable format to extract geometrical and inspection data. The data is reorganized and exported into a STEP AP203 format while sorting according to the inspection criteria. The final inspection data is fed to the CMM and the measured information is fed back to complete the process chain and further modifications if required [29].

Traceability is one of the many important aspects in the manufacturing process. By recording manufacturing information, such as machines, tools, raw materials, employees, time, and storage conditions, etc. it is possible to trace back the origin of product defect in the process [32, 33].

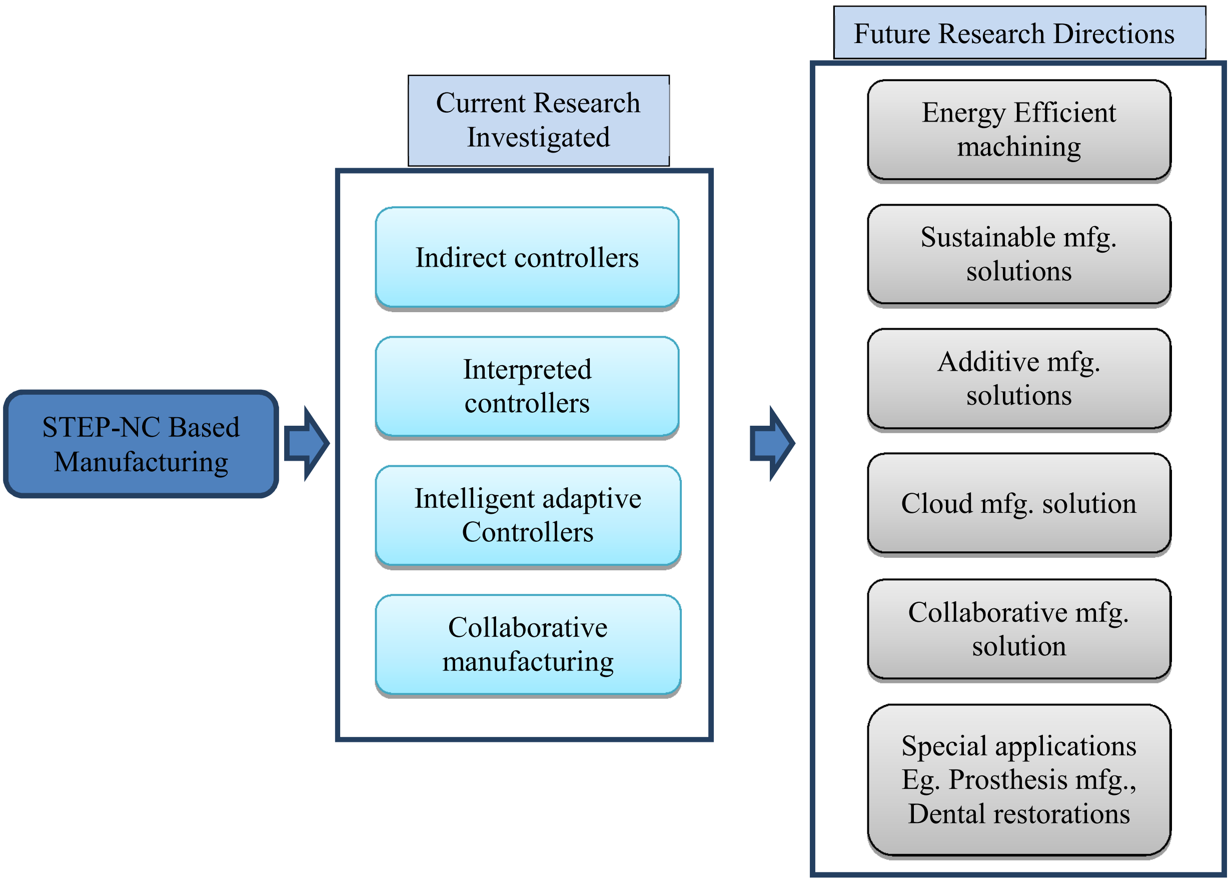

Figure 3. Current and future research directions.

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Although there are few traceability functions available in the STEP-NC standard, it does not define any monitoring or traceability capability. Campos and Miguez [34] proposed a new set of traceability commands which could be incorporated into the STEP-NC code. The new traceability functions are time, tool position, sensor data, process start/stop, position deviation, operator, and tool data, controller events, and alarms. NC-Explorer and STEP-NC software developed by STEPTools, Inc. is used as core tools to process STEP-NC files and programming the interfaces [34].

6. Future research directions

Nowadays, long-term sustainable strategies rather than traditional short-term financial considerations are implemented in the manufacturing industry, to ensure competitiveness [35]. Therefore, different paradigms such as flexible manufacturing, lean manufacturing, sustainable manufacturing, and cloud manufacturing solutions have been introduced into the manufacturing environment. Energy consumption in the machining domain is one of the most interested in building a sustainable machining future [36]. The STEP-NC machining technologies have introduced a good platform to enable energy efficient manufacturing environment in CNC machining. This will be one of the main research areas to be addressed in machining. Currently, there is a great amount of research published on energy efficient machining with STEP-NC, but there are more topics to be researched to develop industrial level intelligent controller. In the future, energy efficient, sustainable, intelligent manufacturing solutions with the STEP-NC technology will enhance the different application areas, such as additive manufacturing, cloud manufacturing, and medical and dental applications etc. Figure 3 shows some future research possibilities in STEP-NC manufacturing.

7. Conclusion

The ultimate goal of STEP-NC enabled machining is to develop a vendor-neutral, tool-neutral, and controller-neutral architecture for intelligent CNC machining which supports Web-based, distributed, and collaborative manufacturing [37, 11]. This paper provides details on the development of the STEP-NC programming interface, architecture, and a literature review on STEP-NC based research carried out around the world. Special emphasis is placed on closed loop manufacturing systems and inspection data feedback systems. All this research can be categorised as the development of intelligent manufacturing systems for STEP-NC compliant machining and inspection systems. This will contribute to shaping up the future advanced, green, intelligent, autonomous, and collaborative CNC controller designs.

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