

An overview on STEP-NC compliant controller development

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Abstract. The capabilities of conventional Computer Numerical Control (CNC) machine tools as termination organiser to fabricate high-quality parts promptly, economically and precisely are undeniable. To date, most CNCs follow the programming standard of ISO 6983, also called G&M code. However, in fluctuating shop floor environment, flexibility and interoperability of current CNC system to react dynamically and adaptively are believed still limited. This outdated programming language does not explicitly relate to each other to have control of arbitrary locations other than the motion of the block-by-block. To address this limitation, new standard known as STEP-NC was developed in late 1990s and is formalized as an ISO 14649. It adds intelligence to the CNC in term of interoperability, flexibility, adaptability and openness. This paper presents an overview of the research work that have been done in developing a STEP-NC controller standard and the capabilities of STEP-NC to overcome modern manufacturing demands. Reviews stated that most existing STEP-NC controller prototypes are based on type 1 and type 2 implementation levels. There are still lack of effort being done to develop type 3 and type 4 STEP-NC compliant controller.

1. Introduction

The advanced of computing technology has heralded a significant change in Computer Numerical Control (CNC) machine tools development. CNC machine tools has come a long way, from the simple machine with controller that had no memory and driven by punched tape, NC machine tools ultimately transformed into an advanced machine tools system that embedded with the high-technology capabilities feature such as multi-axis control, multi-process manufacture, adaptive control and error compensation [1-2]. Machine tools have evolved radically, but the conventional CNC programming language has basically remained almost unaffected based on ISO 6983 (known as G&M code) standard (Figure 1). Even though, existing CNC machining systems are equipped with hundreds of sensors facilitate collection of a huge amount of data and provide opportunities for enhancing the performance of manufacturing processes, the incapability of ISO 6983 to fully utilising this opportunity is one of the reason this standard can be considered as bottleneck and obsolete for CNC enhancement. A number of problems are found with current product data of ISO 6983 and CNC architecture, which are summarized underneath [3-4].

1. **Low level programming language.** The language only focuses describe the cutter location (CL) movement and switching instruction, rather than machining tasks with respect to the part. As a result, expensive CNC machine tool is just act as executing mechanism without any intelligence.
2. **Limited information.** G&M codes controller is only provided with only elementary action and tool movement information command. The CNC part programme only contains a small portion of



the information that is available in any CAD/CAM model. This low level and incomplete data makes modification program in the shop floor is difficult.

3. **Limited control of program.** ISO 6983 is only support linear and circular movement instructions in a rigid sequential. Incapability to support the spline data makes this language unable for controlling five or more axis CNC machines.
4. **Vendor Specific code.** The limited scope covered by ISO 6983 makes each machine vendors has extended the G&M code to include their own specific functions and adaptations. As consequences, a specific post-processor is required for each CNC machine types and interchangeable of CNC programs between different controller and machine tools are restricted.
5. **Top-down programming process.** It only supports one-way information flow from design to manufacturing. If there are any modification done at shop floor level, shop floor knowledge cannot be automatically captured and directly feedback to the designer. So, companies lost their opportunities to improve their manufacturing processes using this invaluable experience.
6. **Vendor specific architecture.** This kind of architecture restricted user to access or modification the system by themselves. Manufacturing industry strictly dependent on the machine vendor to whatever machine features or requirement they needed.
7. **Limited optimisation supported.** Limited information available on the machine level due to only obtain a set of low-level and incomplete information data that make verification, simulation and optimisation are difficult, if not impossible.

Today, a new CNC challenges is not only to deal with shop floor uncertainties events such as product changeover, tool broken, job delay, machine downtime, unavailable tools and fixture, etcetera, but also fluctuating market environment. To dealing with these kinds of market situation, manufacturing companies has to increased productivity and requirements for greater product variability in order to increase or maintain their profit. Thus, to increase productivity and profitability in this globalized and competitive world, manufacturing is considered to be an integrated concept at all levels from machines tool level to production systems to an entire business level operation [5]. This will lead to the possibility of using standard data throughout the entire product process chain in the manufacturing environment and allow data to be share seamlessly with any information loss. Therefore, the next generation of CNC is required [6]: (1) To use a high level and standard data model interface for seamless integration of the entire computer-aided system (CAx) chain system; (2) To be multi-functional, intelligent and autonomous; (3) To have an open architecture with software based implementation technology.

ISO 14649, namely STEP-NC is a new standard for data exchange interface between CAD/CAM system and CNC machine and is considered as the next generation of CNC programming language for replacing ISO 6983 standard. STEP-NC compliant NC system that fully connected to manufacturing information network with legacy data are the foundation to smart NC machining system that represents the brain and knowledge repository of manufacturing system based on high bandwidth information, real time networking, and ability to be react adaptively (self-learning and flexible) [1]. Therefore, CNC manufacturing systems of the next generation are required to provide a number of new features such as high intelligence control systems for autonomy, adaptability to react with dynamically changing environment, re-configurability for agile collaboration, and sustainability for environmental benefit [7]. To achieve this aim, entire components of the CNC machining system have to benefit from the research works to discovery the better solutions and technology enhancements.

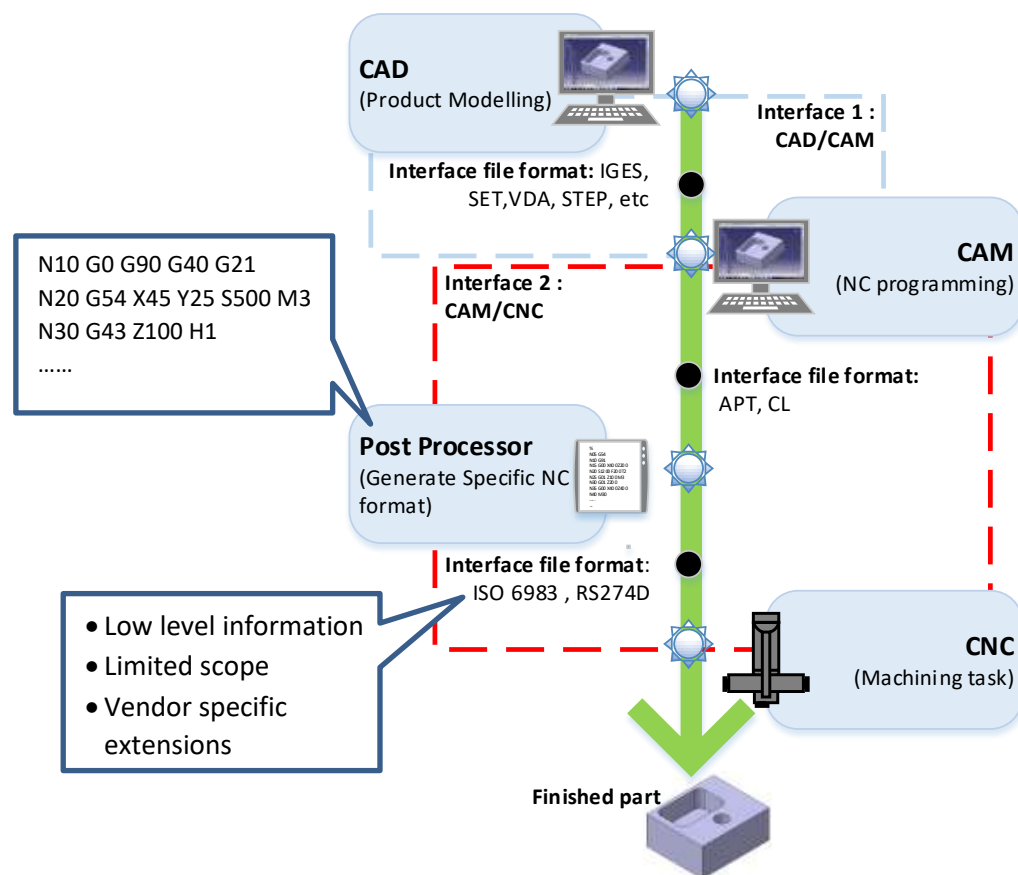


Figure 1. Current Computer Aided System (CAx) data model interface.

Up to 2016, there are many researchers having done in promoting and development of STEP-NC as a next generation of data model interface for CNC system. Based on the data gathered from the Elsevier's Scopus abstract and citation database, there are 376 journal articles/ conference papers/ review papers have been published since 2002. However, there is yet a study to be done to capture the trend of STEP-NC technology development. Hence, the objective of this paper is to review the development of new breed STEP-NC controller. This paper is organised as following: in section 2 overview of STEP and STEP-NC standard. While in section 3 implementation strategies for STEP-NC controller is discussed. Followed by section 4 where STEP-NC state of art and existing prototypes are reviewed. Finally, conclusion and future work in section 5.

2. Overview of STEP and STEP-NC standard

ISO 14649, namely STEP-NC, proposes a new vision of the CAx chain system. It provides a high level and standardized data model between CAx and CNC systems and is considered as the next generation of CNC programming languages. STEP-NC is being developed by the international community with the motivation to formalise the data model interface used at CNC machine level and remedies the shortcoming of the outdated ISO 6983 standard, which yet still dominates the control system of the most CNC machines. Unlike the current standard, STEP-NC does not defines the cutting tool movements as ISO 6983 does, but it treated high level object-oriented information and standardized information such as feature geometry, cutting tool description, operation attributes and work plan from design to CNC system (see Figure 2) [8]. Though it is possible to develop a new breed of intelligent controller NC controller that have capability to act more intelligently than ever before and with the abilities of decision making as well as control of the machine tool. This can be achieved through STEP-NC by providing generic file as a controller input and the machine-specific decisions to be made at a later stage by a CNC and its controller. As a result, part programs may be written once

and used on many different types of CNC machine tool controller providing the machine has the required process capabilities [4].

Basically, STEP-NC is extended version of ISO 10303 (Standard Exchange of Product Data also known as STEP), in which both feature and model structures in STEP-NC are harmonized with ISO 10303. Unlike its other predecessors such as Drawing Transfer File (DXF), the initial Graphics Exchange Standard (IGES) and the Product Description Exchange for Standard(PDES) which primary designed to exchange geometrical data, STEP provides a neutral mechanism by specifying all the product data information throughout the life cycle of a product [4,9]. Implementation of STEP standard within CAD system to CAD system or CAD system to CAM system already solved data exchange compatibility between them. However, the programming interface between CAD/CAM and CNC systems has remained unsolved. Even though, STEP provides the unify input data for a CAM system, the output side of CAM system is still based on outdated ISO 6983. Thus, STEP-NC is introduced to overcome this ISO 6983 shortcoming issues.

Implementation of STEP and STEP-NC data model interface have bring the possibility of using single file standard data format throughout the entire product process chain in the manufacturing environment [3]. A STEP-NC file as a standard and neutral mechanism can be used on numerous machine tool controllers. As a new NC programming interface for machine level, new breed of intelligent controllers that are responsible to interpret STEP-NC program file for generate sequences of axis motions and tool functions is required. Besides that, STEP-NC also include a data model for inspection, simulation and optimisation in real time CNC system environment. Implementation of STEP-NC programming offers new possibilities for adaptive force control as a large part of the intelligence and decision making process is migrated from CAM to CNC [8]. In this system, CNC controller becomes a central element in the design to manufacturing chain system. It brings production to become more flexible and efficient. However, the migration of the way CNC is being programmed from using G&M code programming to STEP-NC demanding time and funding for changes industrial mindset.

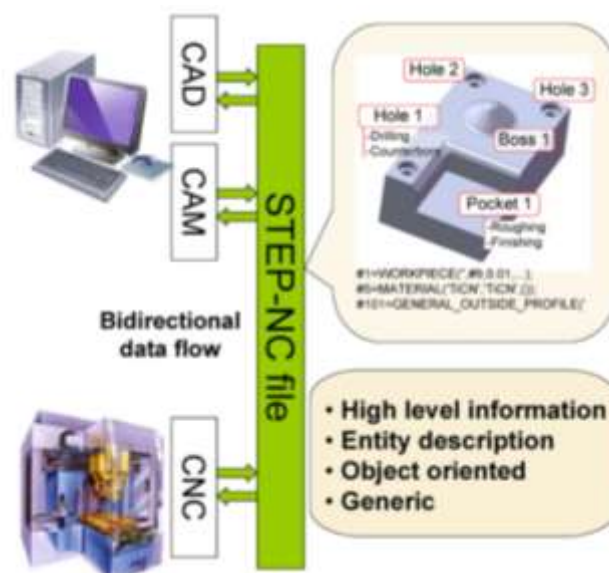


Figure 2. STEP-NC programming approach [8].

Recently, the CNC machining technology involved towards intelligently, interoperable, standardise and reconfigurable for the upcoming generation of CNC machining systems to more flexible and open. The research carried out by researcher to find the best solutions and technology improvement. Suh and Cheon in [6] emphasises a criteria have to be addressed specifically at three different requirement levels (functional level, data model level and implementation level) when developing intelligent CNC system. This requirement levels are presented graphically in the Figure 3. The first level is functional-level requirements that focuses to the capability of CNC system itself to carry out the desired activities

intelligently in order to successfully achieve the machining performance and goal in shop-floor environment. Factors to be considered include autonomy, human interaction, reconfigurable, quality control, adaptive control, resource management, high-speed machining and self-learning.

The second level is data-interface level that related with the data exchange and sharing model used between CAx and CNC and data manipulation with in CNC system. The main concern is to increase data manipulation capability within the system and shortcoming of using ISO 6983 standard. This goal can be achieved by providing CNC system with intelligent product data instead of digital drawings. So the major concerns at this stage are include direct interface with CAD data by using standard data format, comprehensive data model with seamless data exchange, internet based supported, and virtual machining. The last level is implementation-level requirement. This requirement is concerns about structural and topological relationship pf the software modules and the implementation methodology. For more information on the detail description of each criteria's readers are referred to [6].

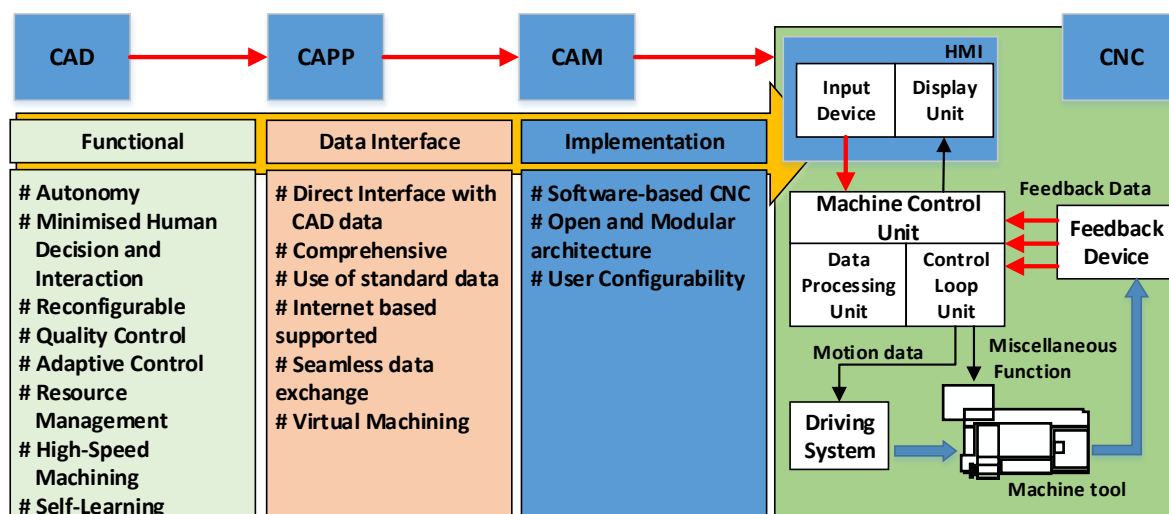


Figure 3. Requirement analysis for developing intelligent CNC system [6].

3. Implementation strategies for STEP-NC controller

STEP-NC as a new language, it is required to have a new breed of CNC controllers that capable to carrying out various intelligent tasks using this new language as an input. At the research front, multiple efforts are being made not only just to expand CNC automation and flexibility capabilities of the machine tool but also to embed intelligence and reconfigurable functionality into the machine. There are various different approaches were introduced by various scholars based on STEP-NC implementation on CNC system, those approaches can be classified into several levels of implementation in the future as present in Table 1. The lack of STEP-NC controllers has been considered as a major hindrance to popularization of STEP-NC [10]. Establishing of seamless connection, stable STEP-NC interpreter and intelligent controller are the key requirement for realise the STEP-NC concept in machine tool environment.

4. STEP-NC state of art and existing prototypes

The development of intelligent CNC systems for next generation of CNC system has been the hot topic of research. Since 2002, STEP-NC technology has been enhanced and attracted large amount of research interests among researchers, academicians, and corporates sector over the world in the race for developing technology for next generation of CNC system. Numerous technologies and various research projects have been carried out all over the world such as project OPTIMAL, project STEP-NC (EP 29708), project Super Model and Project IMS 97006 (Step-Compliant Data Interface for Numeric Controls). All these projects are being carried out with the collaboration of manufacturers (Open Mind, Dassault Cubictek, STEP Tools, Siemens, OSAI, etcetera), the user (Daimler-Chrysler,

Volvo, Wyss, Samsung, etcetera) and academic institutions from USA, Europe, Switzerland and Korea [13].

Table 1. Types of research work strategies related to STEP-NC.

Types	Strategies	Description
1	Conventional control using STEP-NC [4]; STEP-CNC with conventional control [11]; Indirect STEP-NC programming [8]	It has considered as entry level for STEP-NC by simply incorporates with legacy NC controllers. The interpreter module (act as comprehensive post processor) translated the STEP-NC program into specific machine G&M codes and then send them into CNC kernel for executes the codes. There is no intelligence at all inside this system except the capability to interpret STEP-NC program.
2	New STEP-NC enabled control [4]; STEP-CNC with new control [11]; Interpreted STEP-NC programming [8]	At this stage, machine tool motions command is directly executed based on the machining sequences and strategies defined in a STEP-NC file format. At this level, new controller architecture is required and the external data can be integrated in the tool-path generation process. Simply said, this system embedded CAM function inside the controller system. In this case, the STEP-NC controller can be employed with some intelligences, however the problems between CAM and CNC are not totally solved but hidden [12].
3	STEP-NC enabled intelligent control [4]; STEP-CNC with new intelligent control [11]; Adaptive STEP-NC programming [8]	At this point, NC controller is able to perform NC tasks intelligently and autonomously based on the online process data and optimizes machining parameters and tool-paths in real time. Intelligent function may include automatic feature recognition, automatic collision-free tool path generation (including approach and retract motion, automatic tool selection), automatic cutting condition selection, status monitoring and automatic recovery, and machining status and result feedback.
4	Collaborative STEP-NC enabled machining [4];	It has considered ultimate goal for the STEP-NC enabled machining is to support web-based, distributed and collaborative manufacturing system. This controller should be implemented with all the features inside type 3 controller plus cooperative ability via internet. The aims are parallel with e-manufacturing paradigm DA-BA-SA: Design-Anywhere, Build-Anywhere, Support-Anyways.

Most of the existing STEP-NC controllers have been reviewed by [2,8,14]. Korea STEP-NC developed by [15] consists of 5 big modules and the communication between all the modules via COBRA communication. STEP-NC part program file is generated by Shop Floor Programming system (PosSFP) module based on data input in form of STEP AP 203 or AP 224 files. Meanwhile, at Loughborough University, an Agent-Based CAM system (AB-CAM) has been developed by [16] for a generated native STEP-NC part program, and the program is able to convert into G&M code for machining execution. Xu [17] proposed a G&M code free STEP compliant machining scenario by developing a converter to convert STEP-NC files to 6K programs. Wang and colleagues in [18] developed a STEP compliant CNC system based on function blocks to translate STEP-NC data into G&M code.

Table 2. Development History of STEP-NC Controller

Authors	Strategies	Features	Limitations
Yusof and Kamran [20]	Type 2	# Can receive ISO6983 and ISO14649 as data input # Automatic tool changes and online visual video. Provides a shop floor editing facility (Working/offline) and able to generate the physical file output in .txt or .xml format.	# universal interpretation, G&M code to STEP-NC or vice versa cannot be done. # No intelligence and accurate tool path generation; # No 3D simulation # Not Accept STEP-NC P28 file # No support adaptive machining
Xiao et al. [10]	Type 2	# System able to generate and exports STEP-NC files in P21 or P28 format. # Allow shop floor adjusted # Solid 3D part viewer and tool path simulation	# No physical machining reported # Real time monitoring and on-machine inspection not included in the system # No support adaptive machining
Minhat et al [19]	Type 2	# layered structure STEP-NC controller based on IEC 61499 function blocks # Simulation and physical machining for STEP-NC Example 1&2 are performed.	# 3D modeling represents by wireframe only # No support adaptive machining
Xu [17]	Type 2	# G&M code free machining scenario # for turning process	# still use low level language (6K) # if use different NC kernel, new interpreter required # No support adaptive machining
Rauch et al. [8]	Type 1	# 3D visualization- manufacturing data, tree structure, tool path generation. # Shop floor parameter editing allowed # Collision detection simulation # On-machine inspection and real-time machining parameter optimisation	# Still using G&M code
Wang et al [18]	Type 1	# STEP-NC / G&M code mapping # Tool path generation in G&M code	# Still use G&M code for end controller # No Physical machining reported # No support adaptive machining # No support adaptive machining
Newman et al. [16]	Type 1	# STEP-NC enabled controller # Tool trajectory and 3D wireframe done by commercial software	
Suh et al. [15]	Type 2	# Develop without any commercial software # CNC generates the tool path for the cutter and touch probe (by TPG), which can be shown graphically by simulator.	# Tool path generation modules still non-real-time operation

Besides the development of interpreter and converter for STEP-NC controller, there are some researches putting their effort on closed-loop manufacturing system and system feedback in order to ensure intelligent STEP-NC controller can be realised. In [21], Brecher et al. are developed a closed-loop process chain prototype including inspection based on STEP-NC standard. Next two years, Zhao and their colleagues proposed integrated process planning system architecture for joined machining and inspection task together by provides real-time inspection feedback and On-Machine Inspection (OMI) in order to overcome relocating error during offline inspection [22]. Campos and Míguez as reported in [23] achieve vertical integration with STEP-NC in order to have a standardized process monitoring and traceability programming. The traceability is ensured at three different levels: business level, manufacturing level, and shop floor level. This allows monitoring the capitalization. Ridwan and Xu [24] define an automatic correction of cutting parameters based on the machine condition monitoring. They have developed optiSTEP-NC system which helps to perform cutting parameters

optimization. With the similar work, open CNC controller named HITCNC with the ability to interpret high-level product information, inspect the part online, and monitor machining process condition in real time is proposed and developed by Hu and his friends [14]. Summaries related to STEP-NC controller development are presented in Table 2, whereas research work related to bi-direction and intelligent system is shown in Table 3.

Table 3. Research work related to enabled intelligent STEP-NC controller

Authors	Technology	Features	Limitations
Hu et al. [14]	Online Inspection	# Developed system has ability to interpret high-level product information, inspect the part online, and monitor machining process condition in real time is developed.	# Inspection involved depth of cut measurement only. # Surface roughness, features location, feature dimension not yet validate.
Danjou et al [25]	Knowledge Capitalization	# Provides guidelines to the CAM programmer in order the part can be well manufactured at 1st time.	# Involve simple shape only, freeform and complex shape parts not yet defined # Knowledge Database filling manually.
Um et al. [26]	Machine tool selection	# Automatic machine selection based on proposed machine tool data model	# Algorithm validation based on machine catalogue model (offline data) only not based on online machine resource availability. # STEP-NC machine tool data model not yet establish.
Ridwan and Xu [24]	Inspection	# Automatic correction of cutting parameters based on the machine condition monitoring # Optimisation is performed before, during or after machining operations, based on the data collected	# optimisation involve feed rate only. Overall machine performance optimisation not yet established.
Campos and Miguez [23]	Machine control monitoring	# develop a standardized process monitoring and traceability programming # CNC controllers can interpret and automatically execute programmed monitoring and traceability commands	# focusing on data traceability only, no analysis or optimisation process reported
Zhao et al. [22]	On-machine inspection	# Proposed integrated process planning system architecture for joined machining and inspection task together by provides real-time inspection feedback and On-Machine Inspection (OMI) #no data conversions are needed	# No implemented physically yet.
Brecher et al. [21]	Inspection	# Realised a closed-loop process chain with bidirectional information flow and measurement information feedback of inspection operations into the STEP-NC file.	# Conversion data still needed since CMM not support STEP-NC data yet. # No support adaptive machining

5. Conclusions and future work

In order to cope with requirements for modern CNC manufacturing environment, STEP-NC offers a new comprehensive data model remedies for the shortcomings of ISO 6983 and by incorporating various intelligent functions, which are not feasible in existing CNC control system. In order to realize the STEP-NC concept, the development of STEP-NC compliant controller is crucial. As discussed before, to date, there are multiple studies and research works have done over the world regarding

developing a new breed STEP-NC compliant controller. Based on implemented strategies, the research works can be categorized into four levels method (see Table 1 for detail). Considering all these evidences, it was concluded that most existing STEP-NC controller prototypes are based on type 1 and type 2 levels. Even though, the types 3 and 4 implementation level are the ultimate aims on intelligence STEP-NC controller. Up to today, there is no evidence claiming ‘intelligence STEP-NC programming’ controller prototype is fully developed and ready to implement on an industrial machine tool. As a future work, the authors will develop a comprehensive framework of intelligence STEP-NC compliant controller. Feedback element, real-time control and on-machine optimisation for the CNC system also being included. The proposed system will receive generic STEP-NC file as input and machine-specific decisions including tool path generation and machining parameter setup to be made later by controller.

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