



# IMPROVE THE QUALITY OF MANUFACTURING BY USING CNC STEP-NC COMPLIANT FRAMEWORK

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## ABSTRACT

*Now a day's manufacturing is a high competitive market place. Data has been collected from the past decade of manufacturing is been combined with the machine data collection method we get to know traditional manufacturing and inspection to intelligent networked process control. Low-level G and M codes offer very limited information on machine capabilities or work piece characteristics which consequently, results in no information being available on manufacturing processes, inspection plans and work piece attributes in terms of tolerances, etc. and design features to computer numerically controlled (CNC) machines. One solution to the aforementioned problems is using STEP-NC (ISO 14649) suite of standards, which aim to provide higher-level information for process control. In this paper we gain the knowledge in process control in CNC manufacturing and identify the challenges in achieving process control in current CNC manufacturing scenario. The paper then introduces a STEP-compliant framework that makes use of self-learning algorithms that enable the manufacturing system to learn from previous data and results in eliminating the errors and consistently producing quality products. The framework relies on knowledge discovery methods such as data mining encapsulated in a process analyzer to derive rules for corrective measures to control the manufacturing process. The design for the knowledge-based process analyzer and the various process control mechanisms conclude the paper.*

**Keywords:** STEP-NC, Process control, CNC, Manufacturing.

## 1. INTRODUCTION

In modern manufacturing scenarios, the complex nature of industrial processes, the demand for quality products at ever reducing lead times and the strive for attaining higher profitability is enforcing researchers as well as practitioners to attain improved process control of the computer numerically controlled (CNC) manufacturing system.

The complex nature of the different manufacturing processes, their analysis and control has always presented a challenge for the researchers as well as practitioners. Process control has evolved as a term from a number of different industries such as chemical process industries, semiconductor-manufacturing industries and machining industries and thus various researchers have presented a wide range of perspectives regarding this area. In CNC machining, with the existence of complex processes that start from the design of a part to its manufacture, process control is an integral part of the chain.

The pursuit for automated manufacturing process control started in 1950s with the introduction of numerical control (NC) machines

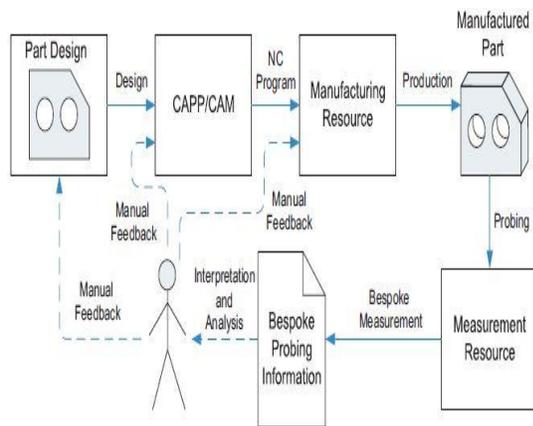


Fig. 1. Current process control loop in the CNC manufacturing.

These machines had their controller coded in their electronic circuitry and the punch tapes were the only means for loading the part programmes onto the controllers. The first numerically controlled machine tool was a three-axis milling machine developed in 1952 at the Servomechanisms laboratory at the Massachusetts Institute of Technology, USA. The continuous development of computer technologies proved beneficiary and the first CNC machine was developed in late 1960s where the hardwired logic of previous controllers got replaced by an onboard computer.

One of the major drawbacks of traditional CNC manufacturing is the reliance over the experience and knowledge of the operator to readjust the process parameters based on his observations manually. The result is the selection of process parameters by the operators based on local historical knowledge and dated machining handbooks. This bespoke approach reduces the repeatability and the effectiveness of a manufacturing company in realizing full production potential.

In addition to process parameters, variables such as tool wear, thermal changes, dimensional inaccuracies and other disturbances affect the manufactured products. These variables are dependent on manufacturing processes, inspection planning and work piece characteristics, which emphasize the need for process control in CNC manufacturing that relies on optimization and control of the machining process.

The first part of the paper provides a brief literature review of the process control techniques together with an outline of the state of the art in CNC manufacturing. It is followed by the definition of the process control and identification of its key elements. The framework for STEP-compliant process control is then outlined and discussed together with the knowledge-based process analyser. The paper concludes with the discussion of the application of the knowledge-based tools in providing the corrective measures for processing parameters.

## 2. PROCESS CONTROL IN MANUFACTURING

Process control in the modern manufacturing scenario has been mainly dependent on the developments in machine tools and their controllers. These developments in machine tool axis movements, acceleration of the spindles as well as axes, position and velocity are controlled by servomechanism control loops, machining process monitoring and control are briefly reviewed below.

Research has already been carried out in different types of machine process monitoring and control techniques. This includes the development of the on-line sensors, which use acoustics, optical, electrical, thermal and magnetic sensing systems. These sensors help in direct observation of the process variables or assist in judgement based on indirect measurements. These process-monitoring techniques are mainly aimed at estimating various machining process variables especially tool condition monitoring, predicting wear, surface roughness and chatter detection.

Process control in machining has been traditionally classified into categories as: adaptive control with constraints (ACC), adaptive control with optimization (ACO) and geometric adaptive controller (GAC). ACC systems are mainly aimed towards adjusting process variable such as force or power in real time relative to appropriate machining conditions to reduce machining costs and increase machine tool efficiency. These systems are capable of maintaining maximum working conditions in an evolving machining process have defined the objective of ACC systems as appropriate feed rate tuning for controlling the cutting force, which is the maximum cutting force relative to threshold tool breakage conditions. ACO systems have also been developed to gain the control over the machining process parameters such as federate, spindle speed or depth of cut for maximizing the process response for attaining better quality products. The primary objective of the GAC systems is to

maximize the quality of the products in terms of finishing operations. GAC systems take structural deflection and tool wear as machining constraints for optimizing the finishing quality.

In recent years, researchers have also made an attempt towards achieving the high precision contour machining and in this regard developed more accurate CNC systems. Rule-based controllers are developed that can improve the contouring accuracy in the awake of machining errors such as friction. It has been also identified that contouring performance of CNC feed drive systems can be improved by taking the dynamics of the axes into account while planning the trajectories of each axis.

The statistical quality control techniques also play an important role in controlling the machining processes. These quality control techniques based on the different control charts are capable of identifying uncertain states of machining process in advance.

It has been established that different machine tools display different stiffness, damping and frequency characteristics. This emphasizes the need for having confidence in the machine for machining parts in tolerance limit consistently, as well as, measuring them. Till now, part dimensional accuracy and inspection has largely been carried out on CMMs, which is widely recognized as being consistent for estimating the appropriateness of the machined parts. In recent years, on-machine measurement using touch trigger probes mounted on spindle in machine tool has been recognized as vital for achieving the

process control in CNC manufacturing. It is realized that by using a CNC machine tool also as measuring equipment, closed-loop process control can be achieved in terms of automatic tool offsets for avoiding machining defects. In this regard, recent research has been concentrated on investigating the capabilities of on-machine measurement conforming to the machine tool's capability.

Another important aspect in machining automation that affects the quality of the parts is preventive maintenance techniques. In recent years, a relationship has been formulated between the equipment maintenance and product quality using the quality control techniques.

Knowledge-based techniques have been applied in various domains of the manufacturing such as prediction and optimization of machining parameters. These techniques play an important role in manufacturing data analysis. The various applications of these tools have also been reported and can be useful in realizing the process control.

### 3. STATE-OF-THE-ART IN CNC MANUFACTURING

The present CNC manufacturing process control loop has remained unchanged for more than 20 years. Today's PC-CNC controllers are still only utilized for low level tool path NC code execution, with no access to high-level information on the major activities of machine set-up, tooling

set-up/management, inspection planning or results feedback. Any error in the final manufactured part cannot be identified or traced back to its source. This is depicted in Fig. 1, which illustrates the feedback in a system that cannot modify the process parameters in CAPP/CAM and manufacturing resources to manufacture the parts consistently.

In order to provide the standardized structured feedback for process control, the following points need to be considered:

- I. The generic format of the interpreted results data and also the required semantics that can be analyzed and fed back into the system need to be defined.
- II. The different standards conforming to the inspection of a component, filtering for the part on the machine tool and tooling requirements need to be investigated so that inspection can be achieved in a strategic and standardized manner.
- III. The acquisition of the know-how pertaining to the machining process parameters will need to be represented in a formalized manner within the knowledge base.
- IV. The different types of the manufacturing errors need to be analyzed and classified.
- V. The types of feedback need to be decided so that feedback related to the local machining and global

manufacturing can be realised and consequently fed back appropriately.

- VI. The different knowledge-based tools are to be analysed to effectively provide the feedback from the past experience data set of the component in to the manufacturing system.

#### **4. VARIOUS TYPES OF PROCESS CONTROL IN CNC MANUFACTURING**

Process control in CNC manufacturing is defined by the authors as the ability to monitor machining parameters and apply corrective measures where appropriate in order to provide confidence in the machine tools to consistently produce parts within desired tolerance limits.

The authors have identified three types of process control relevant to CNC manufacturing: static errors, dimensional errors and surface roughness errors. A fish bone diagram for process control in CNC manufacturing is shown in Fig. 2 and represents the author's view of classifying process control into three types. The first type of process control feedback compensates for the inherent inaccuracies in the machine tool. Tool offsets and compensation for dimensional inaccuracy are compensated as the second type of feedback. The third type is related with the feedback of process parameters for better surface roughness.

#### **5. STEP-NC COMPLIANT PROCESS CONTROL FRAMEWORK**

STEP-NC is a data model which represents an intelligent CNC control and is formally known as the standard ISO 14649. Contrary to the current NC programming standard (ISO 6983), ISO 14649 is not a method for part programming and does not normally describe the tool movements for a CNC machine. Instead, ISO 14649 provides a hierarchical data model for CNCs with a detailed and structured data interface that incorporates feature-based programming where there is a range of information such as the feature to be machined, tool types used, the operations to perform and the work plan.

Though it is possible to closely define the machine tool trajectory using STEP-NC, the aim of the standard is to allow these decisions to be made by a new breed of intelligent controller. It is the aim that STEP-NC part programmers may be written once and used on many different types of machine tool controller providing the machine has the required process capabilities. One critical issue is that the tool path and inspection probe path movements information is optional and should ideally be generated at the machine by the CNC controller. In addition, the standard also includes the data model for feedback of inspection results within the updated STEP-NC file for the manufactured part, which could then be analyzed.

Geometric information is defined by features with machining and inspection operations known as working steps performed on one or more features. These working steps provide the basis of a work plan to manufacture the component. One

important point should be recognized, is that this code is the STEP-NC transfer (physical) file, which is imported/exported into and out of a STEP-NC intelligent controller. This file would be interpreted by the controller, enabling CNC operators to interact at a working step (i.e. machining operation) level via an intelligent MDI or CAD/CAM

system at the controller. It is worth noting that currently two versions of STEP-NC are being developed by ISO. The first is the application reference model (ARM) version of ISO14649 (i.e. ISO14649) and the other is the Application Interpreted Model (AIM) version of ISO14649

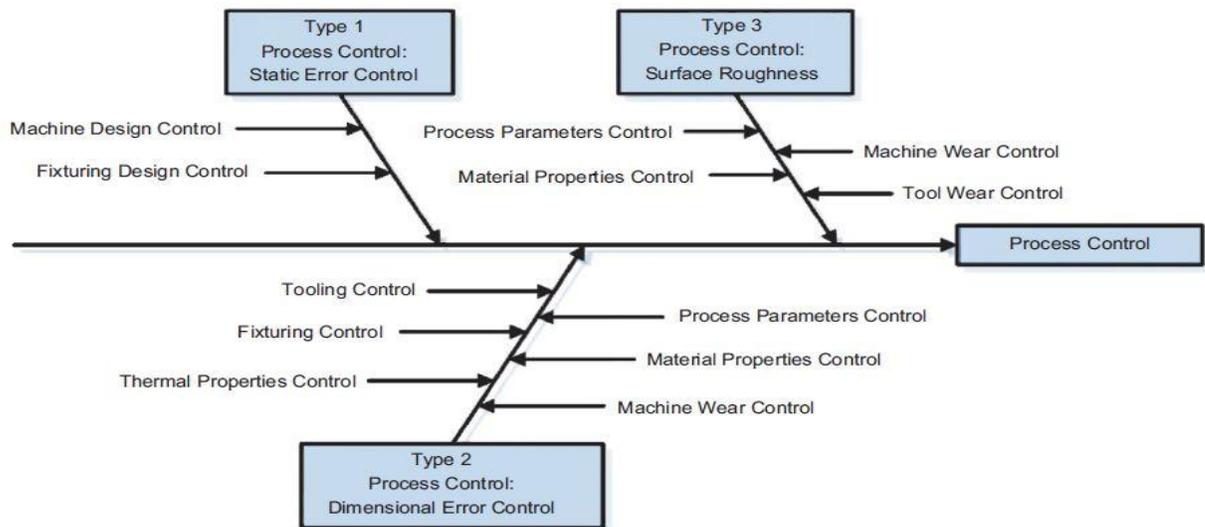


Fig. 2. Process control elements in CNC manufacturing.

A STEP-compliant process control framework based on STEP-NC for closing the CAM to CNC feedback loop has been proposed by the authors in this paper. STEP-NC is seen by the authors as a valuable enabler for process control as it provides CNC control with geometric and process planning data in a consistent format. In addition, these data which can be updated based on process control feedback introduces the possibility of greater standardization in process control for CNC machining. A view of this STEP-NC compliant process control framework .

STEP-compliant information is used at heart of the framework and defines the specifications for the part and its features according to the available standards. This standardized information for the process control defines, the part and feature definition and tolerance definition in conformance to AP 203, AP 240, AP 224, AP 219, ISO-14649 Part-10 The identified inspection features are defined for the part as entities in ISO-14649 part-16 which also enables these features to be linked with tolerances. These STEP data represent the opportunity to provide an overall data



repository for both design and manufacturing information recognized as a product data model.

The functionalities of the various elements shown in the framework are as follows:

#### 5.1. Design interpreter

This interprets the part design specifications or features on the basis of which the manufacturing operations of the part are to be carried out. This interprets AP 203 data into AP 224 in the form of manufacturing features, which is used by a feature-based CAPP/CAM system for the manufacturing of the part. A number of feature recognition systems are available and one such system is outlined by Suh and Cheon .

#### 5.2. Feature-based CAPP/CAM system

This phase carries out the process planning based on the manufacturing features defined in AP 224. This also contains tooling, fixturing and machine model information needed for the manufacturing of the component. A STEP-NC compliant file (i.e. ISO14649) is generated that contains the machining and measurement work plan, working steps, entities, strategies for manufacturing and inspection of the part.

#### 5.3. Resource-specific interpreter

This interpreter generates STEP-NC like part tooling information, part featuring information, part manufacturing information and measurement code for the component. A NC part programmed is created for the

manufacture of the part. This interpreter encompasses the available resource conditions and is linked with the manufacturing model, which provides specific machine resource elements.

#### 5.4. Manufacturing model

The manufacturing model represents the process control information in CNC and includes machine model and process capability model. The primary objective of the manufacturing model is to map the resources in the machine tool for process control activities. The machine resource elements represent the information related to materials, machine tools, cutting tools and assemblies, fixtures, jigs, control devices and the communication equipment. The machine resource model for process control is being developed on the basis of standards such as AP 240, AP 219, ISO-14649 part10, 11, 16 . The major elements for the resource model have been identified as filtering, assembly, cutting component attributes, tool assembly class, inspection process information, surface roughness, machine class and controller class. The process capability model maps the manufacturing ability of the machine tool in carrying out the process control experiments. This model is aimed to develop a rule-based reasoning which act as constraints for given operations. In an initial view towards realization of the framework, surface roughness (for machining quality of surface), measuring accuracy, tool wear in terms of tool life, repeatability and

circularity are recognized as elements of process capability model. The process control simulator feeds back the compensation for the fixturing and thermal errors to the manufacturing model and the

knowledge-based analyser feeds back the corrective measures for the process deviation for the production and set up data for better surface texture of the part.

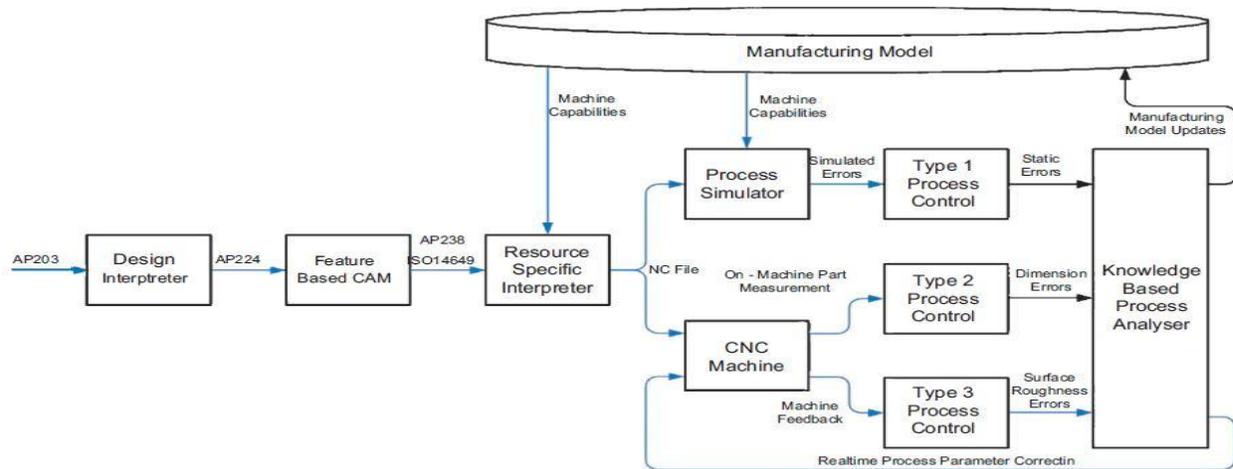


Fig. 3. STEP-NC compliant process control framework.

### 5.5. Process control

The three types of process control previously identified in Section 4 have been utilised in the framework, namely simulated process control, product control and machine control.

#### Type 1 process control:

This first type is termed as simulated process control, and is related to the compensation of static errors i.e. factoring and thermal errors which are identified as a major source of errors to the manufacturing model and feature-based CAPP/CAM. This operation is to be carried out before the machining of the part so that geometrical

inaccuracies of the machine tool can be compensated as the machine tool inaccuracies have a major impact over the final quality. These types of errors are the major source of errors in the machine tool. The important source of thermal errors is identified as heat generated by the machine tool and cutting forces during the machining of the part. Fixture set-up, clamping forces, contact surface between work piece and fixture and deformation of the lift-off of work piece are major errors. The laser sources of factoring interferometer are machine tool accuracy typically used for testing for static errors. The featuring set-up, contact surface between work piece and fixture, testing instrument and thermal



expansions are modeled in the manufacturing model and used by this process control simulator. Thermal profiles and featuring forces are to be modeled. This process control simulator makes also use of knowledge-based tools such as neural networks to provide the corrective measure for compensating the static inaccuracies of machine.

#### Type 2 process control:

The second type of feedback is identified for compensating the dimensional inaccuracies in terms of tolerances or tool offsets in the product information. This feedback is related to on-machine measurement which is recognised as an important element for achieving process control where spindle inspection probes are to be used for carrying out in-process inspection. The inspection entities for the part are defined in ISO-14649 part-16 and AP219 which is also modelled within the STEP information chain. The probing sequences and working steps to carry out the measurement are modelled in the manufacturing model. The inspection results are analysed by the knowledge-based analyser and tool offsets are fed back for compensating the tool wear to the manufacturing model and product model.

#### Type 3 process control:

The third type of process control is aimed to feedback the process parameters for the better surface finish of the part. Parts quality is also dependent on the surface roughness

which is measured using dynamometers. Machined surface condition is also modeled in the process capability model of the manufacturing model. The dynamometer provides the spindle forces which becomes the basis for calculating the roughness. The knowledge-based process analyser evaluates the different surface roughness values for various process parameters and provides the appropriate process parameters for better surface roughness and minimum tool wear. This is then fed back to the manufacturing and updated product information in the framework.

#### 5.6. Knowledge-based process analyzer

The knowledge-based process analyzer investigates the pattern of process variations from the obtained data set that relates to the process deviations for the particular component for a set of experiments. This knowledge-based analyzer uses knowledge-based tools to obtain a certain pattern of process variation for the part that can be fed back for the corrective measures.

#### Working principal of knowledge-based process analyzer

Self-learning algorithms such as data mining techniques are used to identify the potential patterns in the process parameters that control the manufacturing process. Knowledge is extracted from a large number of experimental data items for the machining operation, which are expressed in the form of decision rules to take corrective

measures for deviation in process parameters.

The different functionalities of this knowledge-based analyzer are as follows:

- (1) Knowledge acquisition: This phase builds a knowledge base on the basis of results obtained from a set of experiments pertaining to various process parameters. This is based on the results obtained from the

comparative analyser which analyses the results interpreted by the interpreter from the machine. These are based on the comparison of the obtained process parameters with the desired parameters. This helps in generating a data set of the input process parameters with their effect on those parameters that control the quality of the obtained products.

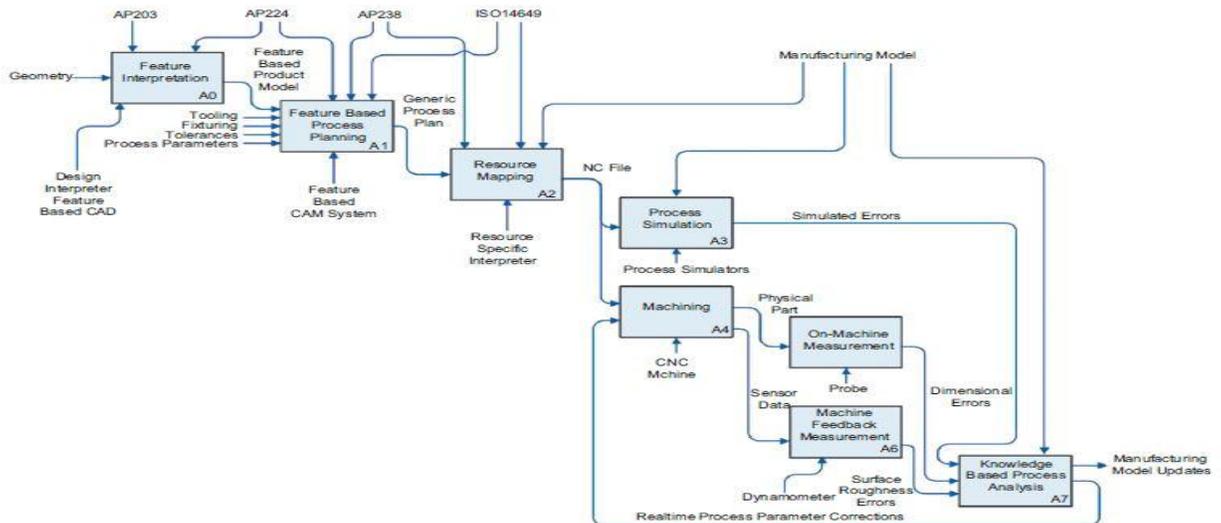


Fig. 4. IDEF0 representation of STEP-compliant process control framework.

- (2) Data set generation: Based on the knowledge acquisition of the various process results pertaining to various machining processes, a data set is generated that is analyzed by the knowledge-based tools. A comprehensive data set is generated which contains the result of experiments conducted over the desired part type. A structured form

of data set for the analysis of the process parameters is shown in (Table 1).

- (3) Knowledge analysis: A Knowledge-based tool such as rough set theory is employed to extract the knowledge from the data sets. Rough set theory is used to classify the imprecise, uncertain or knowledge expressed in terms of data acquired from



experience or historical facts. It helps in extracting rules from an available data set and determines the data regularities. The advantage of applying rough set theory for the analysis lies in the fact that it does not need any preliminary or additional information such as its probabilistic or membership values about the data set. This approach is used to reduce the size of the data set and removes the inconsistent data, which helps in establishing the dependencies between the different process parameters. In this regard, the following heuristic is to be employed.

Step 1: Set part\_ID  $i \frac{1}{4} 1$ .

Step 2: Select two process parameters (a, b) for i.

Step 3: Determine the dependency level (D) between the selected parameters for i.

Step 4: Set the threshold value t.

Step 5: For process parameters (a, b), if  $\min\{D\{(a, b), (b, a)\}\} > t$ , remove the parameters for i and check the other parameters.

Step 6: Set  $i \frac{1}{4} i+1$ , if all part\_IDs have been considered go to step 7; otherwise go to step

Step 7: Terminate the algorithm and output the reduced data set

The dependency levels of the process parameters indicate the effect of one process parameter over the other throughout the total observations and their impact over the optimized process parameters. The threshold value depends on the values obtained for the actual parameters in respect to the nominal process parameters. The threshold value is set in such a manner such that the redundant parameters in the data set can be eliminated.

Useful knowledge retrieval: Clustering algorithms such as K-mean clustering or C-mean clustering are applied to discrete process parameters of the reduced data set. This helps in clustering the parameters into different classes. Based on these classes, the decision rule generation algorithms are applied to extract the knowledge from the data set. These decision rules form a knowledge-based analysis report that will provide the corrective measures for the deviation in the process parameters that will enable the elimination of different types of errors resulting in the production of quality assured products.

Table 1  
An example format of the partial data set for the analysis of the process control parameters

Part ID	Geometrical data				Operation type (STEP-NC)	Feedrate (mm/rev)	Cutting speed (rpm)	Depth of cut (mm)	Work piece material
	Feature ID	Dimension (L/b/h) mm	Diameter (mm)	Depth (mm)					
1	Pocket_1				100 × 50 × 20 _side_rough_	0.1	1200	3	Bottom_and Al-6
	Milling				Bottom_and _side_finishing	0.08	1400	3	
2	Hole_1		5	10	Drilling	0.05	1000	5	
3									

Table 1

An example format of the partial data set for the analysis of the process control parameters

## CONCLUSIONS

This paper has presented and discussed the operational structure of STEP-NC compliant process control frame-work for discrete components. The authors have attempted to close the manufacturing loop by incorporating three types of process control in the framework. A knowledge-based analyser is proposed in the framework which analyses these process control data and provides the feed back for compensating the various types of errors such as static and dynamic errors and improving the surface quality of the parts. The paper also outlines the STEP-NC compliant information, which supports in achieving process control in CNC manufacturing. The importance of self-learning algorithms in achieving process control is recognised and a methodology is outlined for using the information from previously collected processing data to enable the feedback in framework.

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