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### **"Process Control Technology Application in the Manufacture of Discrete Component NC"**

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### **"Process Control in CNC Manufacturing for Discrete Components: A STEP-NC Compliant Framework"**

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# Process control technology Application in the manufacture of discrete components NC

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## Abstract

*With today's highly competitive global manufacturing marketplace, the pressure for right-first-time manufacture has never been so high. New emerging data standards combined with machine data collection methods, such as in-process verification lead the way to a complete paradigm shift from the 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, the authors provide a definition for 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 analyser to derive rules for corrective measures to control the manufacturing process. The design for the knowledge-based process analyser and the*

*various process control mechanisms conclude the paper.*

**Keywords:** Process control; CNC; Application

## 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.

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 realising 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 emphasise the need for process control in CNC manufacturing that relies on optimisation and control of the machining process.

In this regard, there is a major requirement to seek standardised methods for representation of product and process modelling information across the manufacturing life cycle. Product models are well established commercially at the design phase with information relating to geometry, tolerances, functional capability, assemblies etc. already defined in current standards such as STEP (ISO 10303[1]) and represented within CAD systems; Significant effort is now being placed on developing effective product modelling strategies for supporting process planning and CNC manufacture.

This paper outlines an intelligent process control system for CNC manufacturing based on a STEP-NC-oriented knowledge-based framework. The key contributions of the paper are the identification of the process control elements, STEP-NC compliant framework for process control and a working outline of self-learning algorithms within a knowledge-based process analyser.

## **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.

The quality of the machined parts is directly affected by the accuracy and precision of CNC machine tools. This emphasises the need to investigate the machine tool capability in terms of repeatability and accuracy along with the manufacturing errors that can be eliminated and lead towards the production of quality parts regularly. In the past, researchers have identified the machine tool errors that affect the performance of the machine tool control and the quality of the product.

These errors have been further classified into geometric error, static/loading, thermal effects, machine tool vibration, chatter, spindle vibration, spindle deflection and control error. Various studies have been conducted to investigate these errors and their compensation during machining process. These approaches include fuzzy-based techniques, neural networks, genetic algorithms, FEMbased techniques, etc. These adaptive controllers eliminate the requirement of the off-line calibration by evaluating the force process model parameters on-line. These systems exhibit quite a complex behaviour, which is difficult to develop, analyse,

implement, and maintain and thus have not been favourable with the industry for practical applications.

The design for adaptive control systems within any machine tool control architecture falls into one of the following categories:

- (I) centralised control,
- (II) decentralised control,
- (III) hierarchical control.

Estimation of machining forces and control over these forces plays a big role in achieving process control. The conventional controller having a fixed gain, fail to maintain the system performance with dynamic force changes during machining. In this regard, adaptive controllers have proved to be successful in estimating force model parameters online and adjusting the controller gain.

Adaptive control systems primarily strive

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. ACO systems have also been developed to gain the control over the machining process parameters such as feedrate, spindle speed or depth of cut for maximising the process response for attaining better quality products. The primary objective of the GAC systems is to maximise the quality of the products in terms of finishing operations. GAC systems take structural deflection and tool wear as machining constraints for optimising the finishing quality. Rule-based controllers are developed that can improve the contouring accuracy in the wake of machining errors such as friction. It has been

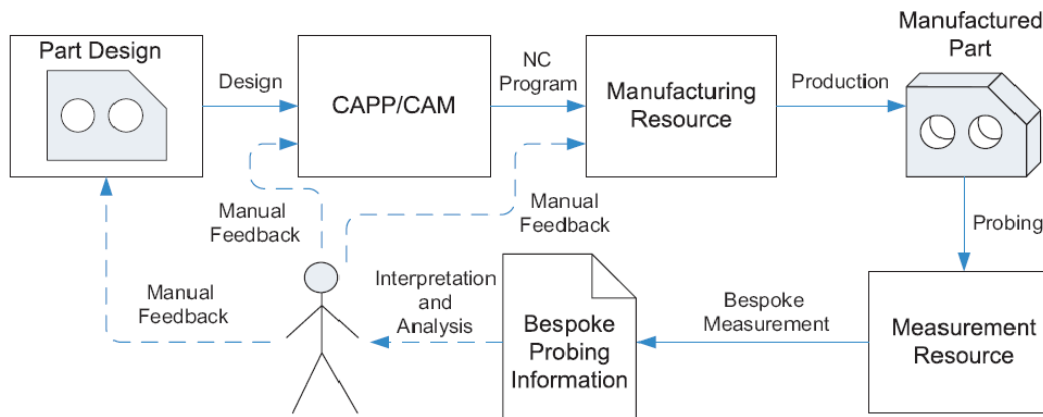


Fig. 1. Current process control loop in the CNC manufacturing.

to achieve the following two objectives:

- I. estimation of machining process parameters on-line,
- II. utilisation of estimated parameters in calculating controller gain for effectively achieving

process control in machining operations. Process control in machining has been traditionally classified into categories as: adaptive control with constraints (ACC), adaptive control with optimisation (ACO) and geometric adaptive controller (GAC). ACC systems are mainly aimed towards adjusting

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 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 emphasises 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 recognised 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 recognised as vital for achieving the process control in CNC manufacturing. It is realised 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

### 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 utilised for low level tool path NC code execution, with no access to highlevel information on the major activities of machine set-up, tooling set-up/management, inspection planning or results feedback. This is depicted in Fig. 1, which illustrates the feedback in a system

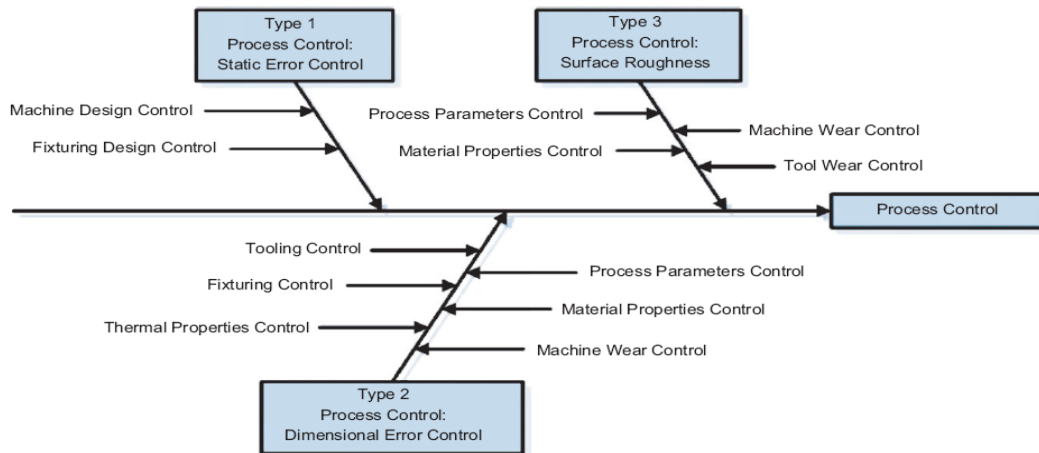


Fig. 2. Process control elements in CNC manufacturing.

this regard, recent research has been concentrated on investigating the capabilities of on-machine measurement conforming to the machine tool.

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 optimisation of machining parameters. These techniques play an important role in manufacturing data analysis.

that cannot modify the process parameters in CAPP/CAM and manufacturing resources to manufacture the parts consistently. Product models are widely used for representing design and manufacture of the components. Even where product models can use features to represent the part design, part manufacturing data are generated by CAM systems, specific to an individual machine tool, with vendor-specific interpretation of toolpath commands as well as onmachine inspection instructions. The present system therefore, lacks a standardised form of feedback that can be analysed to provide the corrective measures so that process variations can be evaluated and subsequently compensated.

In order to provide the standardised

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 analysed and fed back into the system need to be defined.

II. The different standards conforming to the inspection of a component, fixturing for the part on the machine tool and tooling requirements need to be investigated so that inspection can be achieved in a strategic and standardised manner.

III. The acquisition of the know-how pertaining to the machining process parameters will need to be represented in a formalised manner within the knowledge base.

IV. The different types of the manufacturing errors need to be analysed 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 authors 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. A view of this STEP-NC compliant process control framework is presented in Fig. 3 illustrating its major functional elements.

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 programmes 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 toolpath and inspection probe

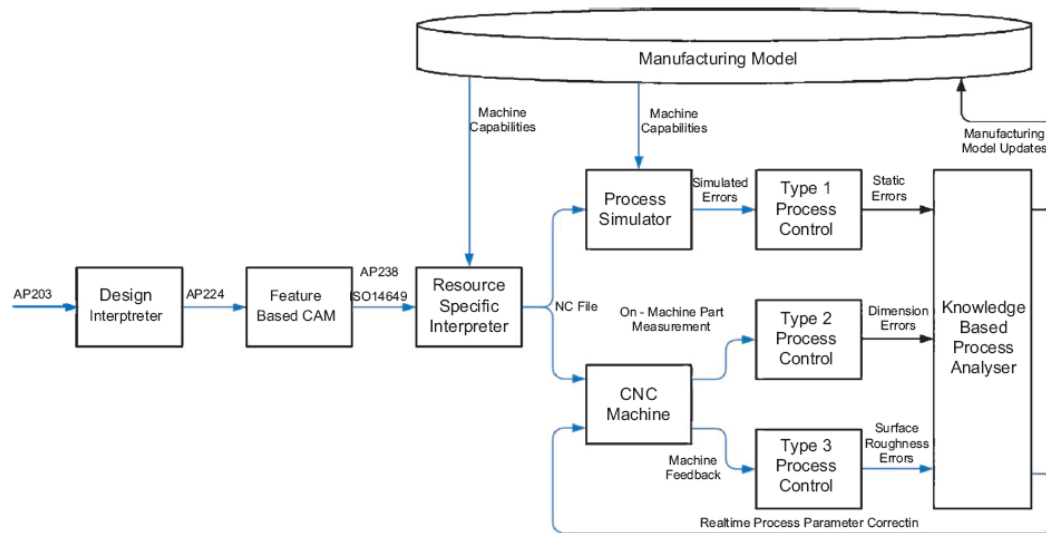


Fig. 3. STEP-NC compliant process control framework.

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 STEPNC file for the manufactured part, which could then be analysed.

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

#### **5.1. Feature-based CAPP/CAM system**

This phase carries out the process planning based on the manufacturing features. This also contains tooling, fixturing and machine model

information needed for the manufacturing of the component. A STEPNC compliant file is generated that contains the machining and measurement work plan, working steps, entities, strategies for manufacturing and inspection of the part.

#### **5.2. Resource-specific interpreter**

This interpreter generates STEP-NC like part tooling information, part fixturing information, part manufacturing information and measurement code for the component. A NC part programme 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.

#### **5.3. 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. The major

elements for the resource model have been identified as fixturing, assembly, cutting component attributes, tool assembly class, inspection process information, surface roughness, machine class and controller class. The process control simulator feeds back the compensation for the fixturing and thermal errors to the manufacturing model and the knowledgebased analyser feeds back the corrective measures for the process deviation for the production and set up data for better surface texture of the part.

#### **5.4. 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. fixturing 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 are 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 workpiece and fixture and deformation of the lift-off of workpiece are major sources of fixturing errors. The laser interferometer is typically used for machine tool accuracy testing for static errors. The fixturing set-up, contact surface between workpiece and fixture, testing instrument and thermal expansions are modelled in the manufacturing model and used by this process control simulator. Thermal profiles and fixturing

forces are to be modelled. This process control simulator makes also use of knowledgebased 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 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 modelled 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.

#### **5.5. Knowledge-based process analyser**

The knowledge-based process analyser 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 analyser uses knowledge-based tools to obtain a



certain pattern of process variation for the part that can be fed back for the corrective measures. An IDEF0 representation of information transfer within the framework is illustrated in Fig. 4.

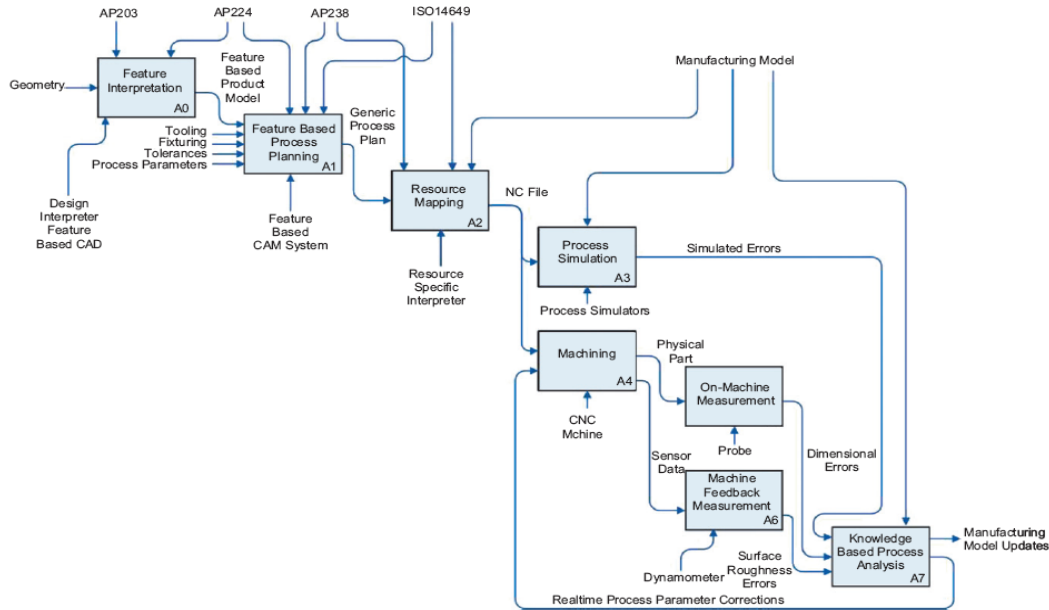


Fig. 4. IDEF0 representation of STEP-compliant process control framework

## 6. Functional framework for the knowledge-based process analyser

The role of the knowledge in the CNC manufacturing process control is to explore the feedback of the process parameters from the CNC to the CAM system. The authors have classified the knowledge requirements into four categories i.e. knowledge acquisition, updating knowledge base, knowledge representation and knowledge reproduction and utilisation. The functionalities of these elements of the knowledge-based process control system are briefly presented as follows:

I. Knowledge acquisition: To build a knowledge base on the basis of the results obtained from a set of experiments for various process parameters. The knowledge base is built

by analysing the STEP-NC file related to manufacturing information and process parameters for the part.

### II. Updating knowledge base: Mobile

agents are used to support the continuous update of the database, which helps in keeping a record of the previous parameters and subsequently analysing it.

III. Knowledge representation: This is used to represent the knowledge pertaining to features and different process control parameters. Different clustering techniques that cluster different parameters based on their similarity attribute are also to be used for representing the knowledge in the structured form.

IV. Knowledge reproduction and utilisation: Different knowledge-based tools, and data mining techniques such as rough set theory are to be applied to provide the corrective measures for the process parameters from the available knowledge base. The pattern obtained for the different process parameters are to subsequently fed back to be able to produce the products with least deviations of the required parameters for the part.

## 7. Conclusions

This paper has presented and discussed the operational structure of STEP-NC compliant process control framework for discrete components. The authors have attempted to close the manufacturing loop by incorporating three types of process control in the framework. A knowledgebased 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 STEPNC 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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