Development of a STEP-NC-compliant feature-based inspection framework for prismatic parts

This item was submitted to Loughborough University's Institutional Repository by the/an author.

Additional Information:


Metadata Record: https://dspace.lboro.ac.uk/2134/35291

Publisher: © Ali, Liaqat

Rights: This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at: https://creativecommons.org/licenses/by-nc-nd/4.0/

Please cite the published version.
Development of a STEP-NC Compliant Feature-based Inspection Framework for Prismatic Parts

By

Ali, Liaqat

A Doctoral Thesis
Submitted in partial fulfilment of the requirements for the award of
Doctor of Philosophy of the Loughborough University

December 2005

Wolfson School of Mechanical & Manufacturing Engineering

© Loughborough University
ABSTRACT

In today’s manufacturing world there is a continuous effort to totally integrate quality control with design and manufacturing. In this context inspection and measurement of parts during manufacturing is important for process control in order to produce quality finish products. This thesis reports research into the integration of feature-based inspection of discrete components in design, manufacturing and quality cycles. Though this is recognised, the state of the art in inspection of components is still considered as a separate island of automation with no formal integration of standards and specifications.

Measurement and inspection of manufactured components is a vital element of shop-floor process control for manufacturing companies. Discrete components can be measured in-process on a CNC machine tool or on a coordinate measuring machine. This research highlights several issues regarding inspection of prismatic parts i.e. inspection planning based on measurement capabilities of the inspection equipment and accuracy of the inspection results. It also gives a comparison of different contemporary standards used for inspection e.g. comparison of DMIS with new developing standards STEP-NC and STEP, in order to recognise the need for integrating these standards into a single framework for inspection.

The major contribution of the research is a proposed inspection planning and programming framework for prismatic components based on the developing STEP-NC standard. This STEP-NC Compliant framework is supported by STEP-Compliant product and manufacturing/inspection information models and outputs a feature-based inspection plan for prismatic components that could be used to generate inspection codes for the available inspection resources. This novel framework aims to provide a capability to establish standardised measuring and inspection across the total CAx chain and will facilitate the use of inspection information downstream in the chain for inspection either on a CNC or a CMM. A STEP-NC compliant framework for inspection developed by the author provides a powerful tool for generating generic inspection plan and storing inspection results for inspection of prismatic parts. Based on this framework a prototype system using Java has been developed to demonstrate its functionality.
AKNOWLEDGEMENTS

I would like to express gratitude to my supervisors Dr S.T.Newman and Dr. J. Petzing for their encouragement and kind support through out this research. Their sincere guidance, discussions and constructive criticism helped me in achieving my research goals.

I wish to thank Mr D.W. Hurrell and Mr J Singh for their help in conducting my experimental work during this research. I would also like to thank Dr Richard Allen and Mr Aydin Nassehi for their help and support. The financial support given by Manufacturing Department Loughborough University during this research work in terms of departmental studentship is also acknowledged.

In the end I would like to thank my parents and my wife for their emotional support and prayers for my success.
# ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP</td>
<td>Application Protocol</td>
</tr>
<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
</tr>
<tr>
<td>ASAM</td>
<td>Association for Standardisation of Automation and Measuring Systems</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer Aided Design</td>
</tr>
<tr>
<td>CAPP</td>
<td>Computer Aided Process Planning</td>
</tr>
<tr>
<td>CAM</td>
<td>Computer Aided Manufacturing</td>
</tr>
<tr>
<td>CAI</td>
<td>Computer Aided Inspection</td>
</tr>
<tr>
<td>CAx</td>
<td>Computer Aided x (Variable)</td>
</tr>
<tr>
<td>CNC</td>
<td>Computerised Numerically Controlled</td>
</tr>
<tr>
<td>CMM</td>
<td>Coordinate Measuring Machine</td>
</tr>
<tr>
<td>DMIS</td>
<td>Dimensional Measuring Interface Standard</td>
</tr>
<tr>
<td>DBF</td>
<td>Design Based Features</td>
</tr>
<tr>
<td>GD&amp;T</td>
<td>Geometric Dimensioning and Tolerancing</td>
</tr>
<tr>
<td>FBICS</td>
<td>Feature Based Inspection and Control System</td>
</tr>
<tr>
<td>FRec</td>
<td>Feature Rec</td>
</tr>
<tr>
<td>IGES</td>
<td>Initial Graphics Exchange Specification</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organisation for Standardisation</td>
</tr>
<tr>
<td>NC</td>
<td>Numerically Controlled</td>
</tr>
<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology</td>
</tr>
<tr>
<td>STEP</td>
<td>Standard for the Exchange of Product Model Data</td>
</tr>
<tr>
<td>UML</td>
<td>Unified Modelling Language</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS

Abstract ................................................................. i  
Acknowledgements ..................................................... ii  
Abbreviations .......................................................... iii  

CHAPTER-1: Introduction ............................................. 1  
1.1 Background ...................................................... 1  
1.2 STEP-NC environment for manufacturing and inspection .... 2  
1.3 Aim and Objectives .............................................. 3  
1.4 Structure of Thesis .............................................. 5  

CHAPTER-2: Scope of the Research and Research Context ......... 8  
2.1 Introduction ..................................................... 8  
2.2 Research Scope .................................................. 8  
  2.2.1 State of the art component inspection ................... 9  
  2.2.2 Need of generic inspection planning at shop-floor level ... 13  
  2.2.3 Futuristic view of STEP-NC Compliant inspection process 14  
2.3 Inspection planning and programming framework for discrete components .................................................. 16  
  2.3.1 STEP-NC Compliant Product and Inspection information models 17  
  2.3.2 STEP-NC Compliant inspection framework for prismatic parts 17  
  2.3.3 Feed back of inspection results ........................... 17  
2.4 Test Cases to validate the inspection framework .............. 18  
2.5 Summary .......................................................... 19  

CHAPTER-3: Review of Automated Inspection Planning and Programming .................................................. 20  
3.1 Introduction ..................................................... 20  
3.2 Proprietary component inspection planning and programming 21  
  3.2.1 Probe path planning ......................................... 22  
  3.2.2 Knowledge-based systems ................................. 23  
  3.2.3 Probing strategies for free form surfaces ................. 25
3.2.4 Feature-based inspections
3.3 In-process measurement in manufacturing on CNC machine tools
3.4 Geometric and Dimensional Tolerancing in Manufacturing
    3.4.1 Major Tolerancing Theories
        3.4.1.1 Traditional Tolerancing theory
        3.4.1.2 Modern Tolerancing Theory
    3.4.2 Geometric dimensioning and Tolerancing
    3.4.3 Tolerance Modelling
3.5 Critique

CHAPTER 4: Review Of Inspection Standards And STEP-NC
4.1 Introduction
4.2 Introduction to standards for inspection
4.3 Dimensional Measuring Interface Standard
4.4 I++ and ASAM-ODS
4.5 STEP and STEP-NC
    4.5.1 Parts of STEP-NC Standard (ISO14649)
    4.5.2 Structure of STEP-NC
4.6 Limitation of STEP-NC standard for Inspection (ISO14649)
4.7 Limitations of DMIS as compared to STEP standards
4.8 Applications of STEP Compliant systems
4.9 Critique

CHAPTER 5: Discrete Component Inspection Planning And Programming On A CMM Or A CNC Machining Centre
5.1 Introduction
5.2 Experimentation
    5.2.1 Machining centres and CMM used for inspection
    5.2.2 Prismatic part used in experimentation
5.3 Inspection of the component on CMM (FERRANTI)
    5.3.1 Inspection Operation procedure for CMM
5.4 Inspection of the component on the CNC machining centres
    5.4.1 Inspection of component on a CNC machining centre WADKIN
5.4.2 Inspection of the component on BRIDGEPORT using touch trigger probe

5.5 Comparisons of inspection procedures
5.5.1 Comparison of inspection planning for all three machines
5.5.2 Comparison of the inspection programs used and the time of inspection
5.5.3 Comparison of the output inspection results

5.6 Critique of inspection planning and accuracy

5.7 Summary

CHAPTER-6: STEP Compliant Framework for Inspection Of Prismatic Parts

6.1 Introduction

6.2 STEP-NC Compliant Inspection framework for prismatic parts
6.2.1 Objective and function
   6.2.1.1 Definition of component
   6.2.1.2 Measurement of the component
   6.2.1.3 Method of measurement of the component

6.3 Characteristics of the STEP-compliant inspection framework
6.3.1 Defining the component using STEP-NC standard information
   6.3.1.1 Defining the part and its feature’s geometric shape
   6.3.1.2 Specifying inspection requirements

6.3.2 Generating a generic inspection Plan
   6.3.2.1 Generating a STEP NC compliant inspection file

6.3.3 Conversion of STEP-Compliant inspection file into inspection code

6.4 Generation of STEP-NC compliant inspection file for a hole-feature
6.4.1 Geometry of the hole feature
6.4.2 Inspection items defined
6.4.3 Defining Probing workingsteps in a workplan
6.4.4 Generating inspection plan and conversion into inspection code

6.5 Critique
6.6 Summary
8.3.1 Comparison with conventional approach

8.4 Summary

CHAPTER-9: Concluding Discussion

9.1 Introduction

9.2 Review of automated inspection in manufacturing and STEP-NC standard

9.3 Contemporary inspection process for part measurement in manufacturing

9.4 Use of STEP-NC for higher level generic inspection planning for a component

9.4.1 Realisation of STEP-NC Compliant framework for inspection of a part

9.4.2 Limitations of the STEP-NC Compliant framework

9.4.3 Validation of the STEP-NC Compliant framework for inspection

9.5 Future Work

CHAPTER 10: Conclusions and Future Work

10.1 Introduction

10.2 Contribution to knowledge

10.3 Conclusions

10.4 Further work

10.4.1 Extension of the STEP Compliant information models

10.4.2 Upgrading the STEP-NC compliant framework

10.4.3 Need for the development of STEP-NC interface

10.4.4 Feed back for Closing the loop in manufacturing

References

Appendix A

A.1 Part measurement on a Coordinate measuring machine (FERRANTI)

A.2 Inspection Code (ACCUDAT)

A.3 Measured inspection results
Appendix B
B.1 Part measurement on 3-axis machining centre WADKIN
B.2 NC Code (inspection)
B.3 Measured inspection results

Appendix C
C.1 Part measurement on 3-axis CNC machining centre (BRIDGEPORT)
C.2 Inspection Code
C.3 Measured inspection results

Appendix D
D.1 Graphical comparison of part measurement results
    CMM (FERRANTI) Vs CNC (WADKIN) Vs CNC (BRIDGEPORT)
D.2 Comparison of measure length of the part
D.3 Comparison of measure width of the part
D.4 Comparison of measure length of the pocket
D.5 Comparison of measure width of the pocket
D.6 Comparison of measured diameter of the hole

Appendix E
E.1 Results of part measurement on 3-axis CNC machining centre BRIDGEPORT using STEP Compliant approach
E.2 Measured inspection results

Appendix F
F.1 Machine Error on CMM(FERRANTI), CNC machine tool BRIDGEPORT and CNC machine tool WADKIN

Appendix G
Author's Publication and Conference Presentation
CHAPTER 1
INTRODUCTION

1.1 Background

Quality control is no longer considered to be a separate process to manufacture and assembly but is recognised as an integrated part of the whole design and manufacturing cycle. Inspection and measurement of manufactured parts plays a vital role in manufacture and is considered as an integral part of quality control. One of the key elements to achieve product quality is the planning of adequate measurement strategies that provides data to control the manufacturing process. Inspection results are used to determine the product’s status and reduce the variability in the manufacturing process, which is part of process control. Though this is recognised, the author still believes that the measurement and inspection processes for a manufactured part are separate islands of automation with no formal integration of standards.

Today machined parts are inspected to much tighter tolerances in order to achieve the highest quality finished products. During inspection a lot of productive time is lost as it is considered as a non-value added activity. This demand of saving precious production time in manufacturing industry has been a major factor in the introduction of Coordinate Measuring Machines. The inspection process of discrete components has been developed and automated with time and has come a long way, from the early use of gauge blocks, dial indicators, micrometers to today’s computer controlled coordinate measuring machines (CMMs) with touch trigger probes. It has automated the inspection process by reducing the time and increasing the accuracy of the inspection results (Bosch 1995).

Also in-process gauging of components on a CNC machine tool during machining is being used for process control. Touch trigger probes on the CNC machining centres that are used for setup of parts can be used for measurement of dimensions of the workpiece. Though accuracy of inspection results from in-process measurement on CNC machining centres is less and its measurement capabilities are limited as
compared to a CMM, it provides a capability of measuring the part while it is still on the CNC machining centre.

Prismatic components with features make up a significant volume of parts in manufacturing industry. Over the decades the design, process planning, machining and inspection have been significantly improved by CAPP, CAD, CAM and CAI and adopting new manufacturing standards. The new developing standards such as STEP-NC (ISO14649) and STEP (ISO10303) that are used for bidirectional flow of manufacturing data in CAx chain, are now influencing today's and future design of the inspection process.

1.2 STEP-NC environment for manufacturing and inspection

Machine tools advancements in the last five decades have resulted in today's sophisticated CNC machines with multi-axis control, adaptive control, error compensation and multi-process manufacture capabilities (Newman, 2004). This sophistication has prompted off-line software tools for CAD/CAM to ensure efficient generation and verification of NC code. However, the basic programming language i.e. based on the tool-path and machine description, has remained the same with G & M code programming (ISO 6983) (ISO 6983/1, 1982).

The new standard STEP-NC (discussed in detail in chapter 4) is being developed with a view to provide standards for automatic and consistent CNC component manufacture. STEP-NC formally known as ISO14649 is not a part programming method and is a departure from the current NC programming standard (ISO 6983) (ISO 6983/1, 1982), that only describe the tool movements for a CNC machine. ISO 14649 provides an object oriented data model for CNC machines that has detailed and structured information such as the feature to be machined, tool types used, the operations to perform, and the work plan. ISO14649 has many parts (given in chapter 4) that are responsible for providing information such as general process data, manufacturing features, machining processes (milling, turning, Wire-EDM etc.), set up and tooling, and inspection. Some of the parts are still working drafts and are in the process of being developed.
The part responsible for inspection is ISO14649-16 (ISO14649-16 WD, 2004), is still under development and discussions by ISO Committee TC184. Though it provides structured information it has limited capability to realise an integrated inspection framework at shop-floor level. These limitations of ISO14649-16 are discussed in detail in chapter 4 (section 4.7).

The main focus in this research is to overcome these limitations in ISO14649-16 to realise a STEP-NC-Compliant framework for inspection of prismatic parts at shop-floor level. The importance of having generalised inspection plans for components in manufacturing is highlighted in chapter 2. In this context STEP and STEP-NC standards are investigated to provide a generic view for feature based inspection planning and programming of individual prismatic parts. The author believes there are still some key issues regarding the inspection process for dimensional measurement of manufactured prismatic parts, which needs to be explored and properly addressed. These are as follows:

Though automation of the inspection process has progressed over previous decades, it still largely remains vendor specific. There is no generalised inspection planning, strategy and procedures for parts inspection as various bespoke inspection routines based on either standard or non-standard information exists for CMMs.

In-process gauging of parts on CNC machine centres is advantageous in the context of process control but is based on non-standard extensions of G&M canned cycles, specific to the machine. In addition there is no feedback mechanism for inspection results, which are recognised as much less accurate relative to those obtained from a CMM. Also it should be noted that the process of inspection planning, their strategies and procedures are different from those defined for a CMM.

The process planning and feature based machining of parts is quickly moving towards integration and standardization with the evolution of new standards such as STEP and STEP-NC, but for process control there is a lack of integration of standards for inspection.
1.3 Aims and Objectives

The overall aim of this research is to investigate the area of component inspection in a manufacturing environment and to explore the application of standards through the use of a STEP-NC compliant inspection process. In this research the new NC standards in the form of STEP-NC are investigated as an enabler for providing a generic structure to support the feature-based inspection and feedback of individual prismatic components.

Based on this concept a STEP-NC Compliant inspection frame-work for a prismatic part inspection is proposed supported by STEP-compliant product and manufacturing/inspection information models using STEP-NC standard. The STEP-NC compliant framework creates an interoperable inspection file, that consists of generalised inspection plan for dimensional measurement of a prismatic component and stores the inspection results. The research work provides the inspection planning and programming requirements to support the integrated STEP-NC-Compliant framework for inspection of prismatic parts.

The research scope is outlined in detail in chapter 2 and is based on the objectives summarised as follows:

i) To Review the bespoke inspection programming for prismatic parts on a CMM and at a CNC machine tool and make a comparison between them in order to establish a relation in terms of inspection strategies, procedures and accuracy of results.

ii) To review the contemporary automated inspection planning and programming in manufacturing environment, feature-based inspection process and different inspection standards and specifications like DMIS, I++, STEP and STEP-NC.

iii) Development of STEP-NC Compliant product and manufacturing/inspection information models for prismatic parts. These information models provides information about shape and geometry of
the part, features, dimension and geometric tolerances associated with part and its features, probing tool and inspection resource used. All the information will be based on standards like STEP, STEPNC and other necessary additional information to cover the limitations of STEP-NC standard.

iv) To develop an inspection framework based on STEP-NC Compliant information models that output a generalised STEP-NC compliant inspection plan for a prismatic component with features. The output in the form of work-plan, working-step, inspection-items, strategies, probing operations and tooling information etc. is interpreted into an inspection code based on the resources available (CMM or a CNC).

v) To demonstrate and evaluate the framework by inspection of example prismatic parts with simple features (hole, pocket, step, slot etc.).

1.4 Structure of Thesis

The thesis report is divided in three main sections as shown in figure1.1. The first section includes five chapters. Chapter-1 consists of a brief introduction to the research area background, overall research aim and objectives. Chapter-2 defines the scope of the research and research context. Chapter-3 reviews the automated inspection process and literature based on bespoke inspection planning and programming. Chapter-4 reviews the current inspection standards for inspection namely DMIS and I++ and the new standards in manufacturing such as STEP and STEP-NC. It identifies the extent of information provided by these standards for feature based inspection of a component. Chapter-5 highlights the relation between a CMM and a CNC machine tool for component dimensional inspection in terms of bespoke inspection strategies, procedures, execution routines and accuracy of results obtained.

The second section contains the main research work based on the defined research scope. In this section a novel framework for inspection planning and programming of discrete components is presented and validated by examples. It consists of three
chapters; in chapter-6 a generalised STEP-NC-compliant inspection framework for discrete prismatic parts is presented. Chapter-7 defines the STEP-compliant product and manufacturing/inspection information models for individual prismatic parts, which support the proposed inspection framework. Chapter-8 validates the STEP-compliant inspection framework with example prismatic parts.

The third and final section consists of two chapters. Chapter-9 discusses the overall research work in the context of the scope and the feasibility of using the STEP-NC standard for generalising and integrating inspection process in manufacturing. Chapter-10 provides the main conclusions and the further research work required in the area of inspection planning and programming of components.
**SECTION 1: RESEARCH BACKGROUND AND RESEARCH SCOPE**

**Theoretical**

<table>
<thead>
<tr>
<th>Chapter 1</th>
<th>Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 2</td>
<td>Scope of the Research and Research context</td>
</tr>
<tr>
<td>Chapter 3</td>
<td>Review of automated inspection planning and programming</td>
</tr>
<tr>
<td>Chapter 4</td>
<td>Review of inspection standards and STEP-NC</td>
</tr>
</tbody>
</table>

**Experimental**

| Chapter 5 | Discrete component inspection process on a CMM and a CNC machining center |

**SECTION 2: MAIN RESEARCH WORK**

**Theoretical**

<table>
<thead>
<tr>
<th>Chapter 6</th>
<th>STEP-NC compliant inspection framework for discrete components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 7</td>
<td>STEP-NC compliant information models for discrete components</td>
</tr>
</tbody>
</table>

**Experimental**

| Chapter 8 | Validation of the STEP-NC compliant inspection framework for discrete components |

**SECTION 3: DISCUSSION, CONCLUSIONS AND FURTHER WORK**

<table>
<thead>
<tr>
<th>Chapter 9</th>
<th>Concluding discussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 10</td>
<td>Conclusions and further work</td>
</tr>
</tbody>
</table>

Figure 1.1 Structure of Thesis
CHAPTER 2

SCOPE OF THE RESEARCH AND RESEARCH CONTEXT

2.1 Introduction

This chapter presents the scope of the research in view of a contemporary automated inspection process for discrete components. It defines the research scope based on the literature review in chapters 3, 4 and the bespoke inspection and measurement of a part illustrated by experimentation in chapter 5. It also outlines the vision of a STEP-NC compliant framework for the feature-based inspection of prismatic parts in manufacturing.

2.2 Research Scope

It is recognised that the inspection of component is vague term. In the context of this research, it is used for the automated inspection of prismatic parts either on a coordinate measuring machine or at a CNC machining centre. This research focuses on prismatic parts with features that make up the large proportion of products in manufacturing industry such as automotive parts, aircraft components, fixtures used in machined tools and so on. The purpose of the research is to generalise the inspection process plan for a prismatic component and integrate it into manufacturing as a part of process control.

The literature review in chapter 3 and 4 has highlighted two main issues among several in the area of feature based inspection of a manufactured part. First is the lack of a generalised inspection plan and secondly the use of different standards with varying limitations for interpreting an inspection plan for a component differently.

The experimentation in chapter 5 has enhanced this view where different inspection plans and bespoke routines were used for dimensional inspection of the same part across different inspection machines (Two CNC machining Centres and a CMM). The experimentation also raised several other issues while measuring a part in-process on a CNC machining centre namely its measuring capabilities and reliability of inspection results as compared to a CMM.
In this research, the STEP-NC standard is explored and its capabilities and limitations are investigated regarding inspection of parts in manufacturing. A STEP-NC Compliant framework is proposed by the author which addresses the issue of a lack of generic inspection information for dimensional inspection of a component. The framework generates a generalised inspection plan for dimensional measurement of a component upfront at the process planning stage. Before describing the STEP-NC Compliant framework, the next two sections outline:-

(i) Typical scenarios of inspection process of a prismatic part on different machines at shopfloor level
(ii) The need for an interoperable generic inspection plan for the inspection of prismatic parts at shopfloor level

2.2.1 State of the art component inspection

The contemporary automated inspection processes for a prismatic part (explained in detail in chapter 5) have been identified by the author under three scenarios as shown in Figures 2.1, 2.2 and 2.3 respectively.

(i) This initial scenario is the inspection of the components at the coordinate measuring machine where inspection code is vendor specific mostly provided by the CMM manufacturer. Some inspection programs are standardised e.g. those based on a Dimensional Measuring Interface Standard (DMIS). The inspection planning involves human effort (i.e. manual input from the human operator) and the inspection data is post processed to be analysed by the vendor specific inspection program to give meaningful results. Though the inspection is feature based there is still a need for more knowledge transfer downstream in a standardised format.

(ii) The second scenario consists of in-process inspection of components on a CNC machining centre for process control. A touch trigger probe is used in a machining centre for setup purposes before machining a part. It is
also used to perform simple inspection routines to inspect the machined component to check whether it is out of tolerance. In case of a traditional 1990s CNC machining centre, the inspection routines are based on canned cycles in G&M codes, the resulting inspection data is not in any standardised format and there is no feedback. The inspection is not feature based and another issue is the accuracy reliability of the inspection results obtained relative to that on a CMM.

Figure 2.1 First scenario of component inspection on a CMM presented by the author
(iii) In case of a new CNC machining centre with state of the art controller, the probing capabilities are more and the inspection is limited but feature based. The output inspection results are the actual dimensions of the part and its features in the form of a text file, unlike the traditional 1990s CNC machining centre where human effort is required for calculating meaningful results from raw data points.
There is a difference between the three scenarios in terms of specific inspection planning, inspection programming and reliability of the inspection results in terms of accuracy. These were highlighted in chapter 5 with the aid of an experiment in which a part was inspected on a 1990s CNC machining centre and on a latest state of the art controller.
CNC machining centre, Finally it was also inspected on a shop-floor CMM. The bespoke inspection planning in each scenario is due to three factors:

(i) Part Measuring Capability
(ii) Accuracy limit to which a dimension can be measured
(iii) Time taken to complete measurement

The next section highlights the need for a generic inspection plan for parts measurement that is independent of the inspection resource used. Such a generic interoperable inspection plan is achieved by adding additional information to the existing information about touch probing of parts in ISO14649-10 and 16.

2.2.2 Need of Generic inspection planning at shop-floor level

The CNC manufactured products are in demand globally in today’s manufacturing world. For cost effective products the trend in manufacturing companies is to have their production facilities closer to their markets and cheaper workforce. Today global companies have several CNC manufacturing venues around the world to manufacture products locally according to the local market demands (Nassehi 2005).

Total implementation of this concept is difficult due to the different configurations of the available facilities in various manufacturing centres. At shop floor level manufacturing engineers have to cope with numerous programming specifications due to the diverse nature of CNC machining resources. In manufacturing a product at a manufacturing facility CAD files are interpreted and local process plans are generated based on the configuration of the available resources. The local interpretation of CAD models for a part in different facilities can result in different process plans. Moreover for process control different local inspection plans are created based on the available inspection resources at the manufacturing facilities.

One solution for overcoming this problem is to have an interoperable process plan for each product containing the necessary manufacturing information that can be interpreted according to the machining facilities available. Though a lot of effort is put on generating interoperable process plans there is lack of focus on generating
interoperable inspection plans. Interoperable inspection plans for the measurement of parts can be a subset of an overall process plan that can be interpreted locally at any available resource. The three scenarios discussed in the previous section 2.2.1 shows the vendor specific nature of inspection and measurement at shopfloor level. Interoperable generic inspection plans for part measurement at shopfloor level are required in order to

1. Inspect the part on any available inspection resource
2. Inspect the part on more accurate machine easily if desired
3. Inspect the part on an alternative machine if other inspection machines are busy
4. Inspect the part in-process during machining for first off inspection before final inspection

The STEP standard [ISO10303] has emerged to provide a common platform for engineering and manufacturing data transfer while the STEP-NC standard [ISO14649] provides a hierarchical structure of manufacturing information to realise interoperable process plans. STEP-NC has various parts (explained in chapter 4) that provides necessary information about tool setup machining operations, inspection measurement etc. Part 16 for inspection and measurement of manufactured parts is still under development and has insufficient information in realising interoperable inspection plans. However supplementing and modifying the current information with additional information, a framework can be realised to generate interoperable generic inspection plans. These generic inspection plans can be interpreted into inspection codes for any available resource at shop-floor level.

2.2.3 Futuristic view of STEP-NC Compliant inspection process

The inspection process is an important part of the overall manufacturing process. A review of previous and contemporary inspection was provided in chapter 2. In light of the on going research in this field and the influence of the STEP-NC standard, a future view of the STEP compliant inspection process for a component is presented as shown in Figure 2.4.
The future of inspection planning for components will include much more information downstream in terms of inspection workplans, workingsteps and a feedback mechanism for the inspection results. The aim of using such standards as STEP-NC (ISO14649) along with AP219 is to provide an inspection software
platform. In this research such an idea of a STEP-NC-compliant framework for inspection of prismatic components is presented which is detailed in the next section.

2.3 Inspection planning and programming framework for discrete components

Inspection planning and programming can be considered at different levels, the strategic inspection planning at a company level of the whole production, planning for a batch of components and inspection planning for individual parts. It should be recognised that the focus of framework in this research is on inspection of individual prismatic components and its features.

The process of component inspection may be presented in several steps. The first step is the identification of the geometric shape of the part, the individual features present, and the association of tolerances with these features. Secondly, the inspection resource information e.g. a 3-axis CNC machining centre with probing capability or a coordinate measuring machine. The third step includes the inspection planning and programming of the component based on the product information and measuring capabilities of the available resources. The next step is the execution of an inspection program and then finally comes the analysis of inspection results and feedback.

The STEP-NC compliant inspection process framework is based on a product information model and a manufacturing/inspection information model, and basically covers three main aspects of component inspection, namely:-

(i) Product information which includes geometric dimensions and shape of the component, features identification, information about geometric tolerances attached to the part dimensions and individual features.

(ii) Inspection planning information that includes strategy, inspection procedures, execution of an inspection program and tooling information.

(iii) Analysis of the inspection data obtained to give meaningful results and feedback for process control.
2.3.1 STEP-NC Compliant Product and Inspection information models

The product model provides information about the shape, form and features of the part to be manufactured and inspected and the knowledge of the tolerances defined for the part dimensions and individual features. This product model is considered to be a section of both the design and manufacturing phase i.e. an overlap of manufacturing and the design cycle. The knowledge of shape, geometry, features and tolerances in the product model are provided by STEP standards and various Application protocols e.g. the information about the features in the product model is provided by AP224.

The manufacturing/inspection process model encompasses the information provided by the product model. The additional knowledge provides the machining/inspection process planning; resources; the execution of inspection programming and feedback of the inspection results.

2.3.2 STEP-NC Compliant inspection framework for prismatic parts

The STEP-NC-compliant framework to be developed consists of generalised inspection planning information that is based on the manufacturing model, inspection code generation, and inspection results analysis, (explained in detail in chapter 6). The generalised inspection plan devises a strategy for inspection based on the knowledge provided by the product data model and additional information provided by different standards (e.g. work plan by ISO14649). It is then converted into a specific inspection program, which also takes into account the tooling (e.g. a touch trigger probe on a CNC machining centre or a CMM) and the mode of inspection programming.

Generalised inspection planning will generate a STEP-NC-compliant file containing inspection items to be measured (e.g. diameter of a circle), inspection strategies, the working steps etc. The STEP-NC Compliant physical file is then interpreted to an inspection program based on the resources information.

2.3.3 Feed back of inspection results

The execution of the inspection process yields inspection data which is analysed to give meaningful results and interpreted back into a standard STEP-NC format. The
STEP-NC Compliant inspection file consists of result statements that can be updated with actual measured results after inspection on the machine such as actual diameter of a hole feature or width of a rectangular slot feature etc. Moreover the inspection results obtained at the controller can be directly used as feedback without storing it back into the STEP-NC Compliant format.

2.4 Test Cases to validate the inspection framework

The STEP-compliant inspection framework will be considered for prismatic components and be validated by a number of test cases, which includes prismatic parts with simple features such as hole features, closed pockets etc. The geometric shape of the typical example parts with features to be inspected using this framework are shown in Figure 5.5.

![Test piece1](image1)
![Test piece2](image2)
![Test piece3](image3)

Figure 5.5- Shape of example prismatic parts with regular features.
Generic inspection plans were generated based on the geometrical shape of two parts (Test piece 1 and test piece 2) using the STEP-NC compliant framework (discussed in detail in chapter 8). The third part (Test piece 3) was used as a case study to show the working of the framework and its comparison with the conventional inspection planning (the same example part that was used in the experimentation given in chapter 5).

2.5 Summary

This chapter provides the scope of research in the area of discrete component inspection. The typical scenarios of conventional inspection process for a component across a CMM and a CNC machining centre are outlined. The requirement of an interoperable generic inspection plan i.e. independent of the machine source at shopfloor level is highlighted. In addition a futuristic view of component inspection is presented which is STEP-NC Compliant and based on this view an inspection framework is defined by the author.

The framework consists of a suite of standards oriented manufacturing and product information models. The sources of information for these models are primarily parts of STEPNC (ISO14649) along with some information from STEP (ISO10303) standards, which provides the information on inspection planning and programming; and additional non-standard information for inspection process planning that includes the manufacturing resources. The inspection results in this framework are stored they can be analysed and used as a feedback to control the manufacturing process.

This STEP-NC Compliant inspection framework is used to prove the feasibility of the STEP-NC standard to generalised inspection planning for discrete components and integrate it into manufacturing for process control. The framework will be tested by selecting and inspecting different discrete parts and its features. It should be noted that the STEP-NC standard (ISO14649-part16) and the related application protocol AP219 of STEP standard for inspection are still under development.
3.1 Introduction

This chapter reviews the literature in the areas of automated inspection planning and programming in a manufacturing environment. The issues discussed are proprietary inspection planning and programming systems, feature-based inspection, in-process measurement and inspection and other related issues such as tolerancing (illustrated in the figure 3.1).

![Figure 3.1 Research areas in the literature review]
3.2 Proprietary component inspection planning and programming

Inspection planning and programming is necessary to reduce the time and effort involved in component inspection. Coordinate Measuring Machines are powerful metrological tools and are widely used for contemporary automated inspection of components in manufacturing industries. This provides improved accuracy of the inspection results and reduces overall inspection time as this speeds up the inspection execution process. The reported research in the past two decades in the area of automated inspection planning is based on inspection planning for CMMs which includes:

(i) Probe path planning
(ii) Knowledge-based systems
(iii) Probing strategies for free-form surfaces
(iv) Feature-based inspection

The research work is not strictly divided into the above mentioned four categories, rather many researchers work in these areas is overlapping as shown in the Figure 3.2.

Figure 3.2 Overlapping of the research work by different researchers in the area of inspection planning and programming in manufacturing
3.2.1 Probe path planning

A framework for computer-directed inspection was presented by Hopp (Hopp 1984). This framework outlines path planning, such as interference checking, measurement point generation, and path correction.

In 1989 Atkins and Derby defined two methods for inspection points and path generation (Atkins and Derby 1989). One was for simple features through interactive parameterisation of a set of macros and the other for more complex features where the points and path were achieved manually. The drawback in following this approach was that the sequence planning was left to the discretion of the operator.

Hong and Chia presented a dimensional inspection path planning system for inspection of dies and molds on CMMs (Hong and Chia 1995). It generates automatic probe paths free of collision which are simulated in 3-D CAD environment. Though it is regarded as an inspection planning system, it is focused only on the probing path generation and suitable mostly for sculptured surfaces.

Another generative inspection process planner IPPEX (Inspection process planning EXpert) was developed by Brown and Gyorog (Brown 1990). This rule based system linked the planner to a product modeller. The product modeller was further coupled to dimension and tolerance modellers. The functional architecture of IPPEX includes setup determination, probe configuration, inspection planning, and probe path simulation.

In 1998, Kuang and Ming presented a probing path planning method. This method uses geometric models created in AutoCad, and automatically creates probing points for inspecting a feature, a collision free probe path and then simulation of the probe path. However, this method is only used for probing path generation and probe path planning and does not provide any tolerance information associated with the part's features (Kuang and Ming 1998). They presented a CAD-directed inspection planning system for CMMs. It used algorithms for analysing and specifying uniformly distributed probing points for features like planes, cylinders and cones. Once the sequence of inspection features and their associated probing point locations have been determined the features are combined together through a collision-free path.
Another algorithm for finding a collision free probe path for inspecting parts was presented by Yueh and Prabakar, it generates a collision-free probe path between two measurement positions. Their research aim was to integrate the CMM with CAD for part inspection. Though the algorithm uses the CAD database of the part to generate the inspection path, it is still only for generating the probe paths and is yet to be developed for feature based inspection (Yueh and Prabakar 1999).

Also a methodology for determining a set of part orientations on a coordinate measuring machine (CMM) was presented by Soonki and Medeiros in 1998. In this method the concept of visibility map was used to represent accessible directions from which measurements for inspecting a tolerance can be performed (Soonki and Medeiros 1998).

3.2.2 Knowledge-based systems

A pioneering knowledge-based process planning system for rotational parts called Expert Computer Aided Planning System (EXCAP) was developed at UMIST (Tang and Davies 1990, 1995). EXCAP automatically generated process plans from its own knowledge base and the geometry obtained from a CAD file through IGES.

This work was extended with another knowledge-based inspection planner entitled INSPEX with the addition of inspection rules for the generation of in-process and post-process plans for inspection of turned components (Kalta et al 1992, Tang and Davies 1995). The initial data requirement for the INSPEX planner could be in the form of an IGES file representation of a toleranced product model from the CAD system, or the partially processed product model produced during planning execution of EXCAP.

Corrigall (Corrigall 1990) focused on automation of inspection planning and programming. He proposed an inspection plan and code generation (IPCG) within a design to manufacture environment. It covered the design phase, process planning, machine operation planning and cutter path generation and then inspection planning and code generation for CMM's. The system also generated manufacturing programming codes for NC machines and inspection code for CMM's. Although the approach is integrated, the issue of standardizing the inspection process remains unclear and
inspection planning is reduced to presenting a code specifying mostly the tool path movement on a CMM.

An intelligent interface link between a CAD system and a CMM, proposed at Brunel University (Hassan et al 1992) consisted of a distributed system where inspection task was controlled by combining several programs and the constraint modelling system RASOR (Rules And Systems Of Rules). The CAD database with additional sources constructed an extended feature file which provides all the necessary information required for part measurement on a CMM. The information data is categorised as geometric feature description, additional probing geometry, approach geometry, tolerance conditions and control parameters.

Based on feature-based design Merat and Radack (Merat et al 1991, Merat and Radack 1992) defined their automatic inspection planning system where part design is described by primitive formed features and the inspection of these features is defined by basic inspection-plan fragments.

A system of flexible vision inspection was presented in 1996 by Moi and Kok that provides information about the dimensions and location of the part to be inspected. It is a flexible system in which pre-stored models of the machined part are not required. A camera captures the image of the machined part during the inspection and a built-in ruler in the vision system measures its dimensions. Though the system is flexible, it is a non-contact inspection system which takes more time in the inspection of parts as compared to touch trigger probing and in addition also it is not feature based (Moi and Kok 1996).

Sunnho and Sungho (Sunnho and Sungho 1996) proposed an offline inspection planning system for CMMs. It consists of a data input module, the measurement planning module, and the statistical analysis module. The system however only considered positional tolerance of shallow holes. It is therefore limited to be considered as a feature based inspection planning system for a component.

The object oriented inspection planner was presented by Gu and Chan which retrieved inspection-related information from a set of generic product modelling libraries for the
inspection process and path planning. It consisted of two knowledge-based planning systems namely an Inspection Process Planner and Inspection Path Planner. These systems were developed for the integration of a STEP model with a CMM. Linear planning techniques for generating efficient inspection plans were adopted which used general inspection strategies and algorithms to enable it to be used on other CMMs. The inspection probe path had a local path (representing the probe trajectory) and a global path (representing the connections between the features). Graphical simulation software was also developed to simulate the inspection probe path (Gu and Chan 1995, 1996).

Recently Hwang (2004) proposed inspection planning for CMMs to reduce inspection times. The method is based on minimizing the setups and probe orientations required during inspection, but the level of inspection planning focuses only on part setup and probe changes and travel times (Hwang et al 2004).

3.2.3 Probing strategies for free form surfaces

Menq (Menq et al 1990, 1992) focused on an inspection planning system for sculptured surfaces consisting of three modules. A localization module that provided an algorithm to locate a more accurate orientation and location of the part without any simple datum defined. The inspection planning module which employs a statistical approach to determine the number of measuring points required on the surface and is only applicable to form tolerances. Finally, there is a comparative analysis module which compares measurement data to the specified dimensions and tolerances.

Pahk's research into automation of the inspection of dies and moulds proposed three types of sampling strategies for probing points (Pahk et al 1993, 1995). The first is a uniform distribution in which measurement points formed a grid that had a nearly square distribution which gives a uniform coverage over the sculptured surface. The second is a curvature dependent distribution where the number of sampling points increases as the degree of curvature increases. Finally a hybrid distribution in which the distribution of measuring points was determined as a combination of both the uniform and the curvature distributions and was employed to avoid too many measurement points being concentrated in regions of high curvature.
Robert and Wilhelm presented an adaptive sampling strategy for part surfaces dimensional measurement on a CMM (Robert and Wilhelm 1999). The strategy was based upon the use of surface normal measurement data to develop an interpolating curve between sample points which was used to select subsequent measurement targets iteratively. The method was particularly applicable to measurement of complex surfaces with coordinate measuring machines.

Kwan and Hyun in their research proposed algorithms for the inspection of free form shapes by laser scanning (Kwan and Hyun 2000). The algorithms included three steps

(i) All possible accessible directions at each sampled point on a part surface were generated considering constraints that satisfied the view angle, the depth of view, interference checking, and avoiding collision with the probe.

(ii) The number of scans and calculation of the most desired direction for each scan.

(iii) The scan path that gives the minimum scan time was also generated

However the algorithms did not take into account the shape of the part, tolerance information or other factors like fixtures used.

3.2.4 Feature based inspection

A lot of research work has been completed in the area of feature-based inspection. In late 1980s El-Maraghy and Gu developed an expert system for inspection planning (implemented in PROLOG) (El-Maraghy and Gu 1987). The system was developed for automated inspection plan generation for rotational components. It has a generative planner and is applied to a feature based design model. This planning system consists of a knowledge-base that identifies features, searches for reference-datums, and plans the inspection sequence.

Research work reported by Bagshaw (Bagshaw and Newman 1999, 2002) defined an integrated inspection system outlined in a Production Data Analysis framework. This
involves the creation of feature based part model geometry, an operation plan and then creating an inspection procedure, automatic feature tolerance analysis and expert system to analyse the reason for any errors. The system focuses on a feature-based approach and has a feature library (e.g. hole, billet, pocket, slot features) and as other aspects which include tolerance representation and interpretation, uniform distribution of feature probing points and the generation of a feature based probing path.

In other research some prototype inspection process planning systems have been developed. Zhang (2000) presented an idea of a prototype (Zhang et al 2000). The aim was to provide inspection process planning directly from the CAD model.

The prototype includes five integrated functional modules as shown below

(i) The tolerance feature analysis
(ii) Accessibility Analysis
(iii) Clustering Algorithm
(iv) Path Generation
(v) Inspection process simulation

The tolerance feature analysis module provides input tolerance information and establishes the relationship between the tolerance information and surface feature. The accessibility analysis module evaluates all the accessible probe orientations for every surface feature. The clustering algorithm module groups the inspection probe and surface features into an inspection group to reduce time for the inspection probe exchange and calibration. The path generation module determines the number of measurement points, their distribution and their inspection sequences. The inspection process simulation module checks for collision between the part and the probe.

These five corresponding modules were developed to reduce the inspection time, though the work focuses more on probe orientation and path generation algorithms. Kramer (2001) presented an architecture for a Feature Based Inspection and Control System (FBICS) for machining and inspection of parts (Kramer et al 2001). The characteristics of FBICS are a tightly integrated open architecture, hierarchical tasks and control, standard data representation with clearly defined modules, command
interfaces and data interfaces. A STEP based data model, which automatically generates NC code for machining and DMIS code for inspection and can be used off-line as well as for on-line planning.

This highlights a stand-alone architecture and two integrated architectures. The stand-alone architecture defines three levels i.e. cell controller that focuses on creating the part from a blank or inspecting a machined part, work controller for single set-up of the part and task controller for inspecting a single feature. It also defines two integrated architectures i.e. loosely integrated and tightly integrated FBICS, the only difference from the stand-alone architecture is that each controller is divided into two or more processes. Though this system makes use of standard defined features in AP224 for generating DMIS format files, the architecture is more elaborate on process planning for feature based machining, but it is vague on feature based inspection planning.

Off-line programming capabilities are provided by CMM vendors, many of them offer native off-line programming software. The National Institute of Standards and Technology (NIST) in Washington D.C USA presents a picture of the use of inspection programming software systems. A CAD system with design modules linked with inspection programming functions, such as collision checking and simulated data output, next is an inspection program execution module and finally a data reporting and analysis system (NIST 2001).

Figure 3.3- Meterology automation Major Systems and Hot interfaces (NIST 2001)
The approach that showed inspection planning and programming interfaces are shown in figure 3.3, which links design, programming and data measuring stages in part inspection process.

Bagshaw (Bagshaw and Newman 2002) defined a Production Engineering Productivity System Inspection Module (PEPSIM) in a Production Data Analysis framework, that involves the creation of a part model geometry, an operation plan and then creating an inspection procedure, automatic feature tolerance analysis and expert system to analyse the reason for any errors. PEPSIM focuses on a feature-based approach and has a feature library (hole, billet, pocket, slot features) and other aspects which include tolerance representation and interpretation, uniform distribution of feature probing points and the generation of feature based probing path. Production Data Analysis framework, a larger prototype manufacturing data analysis expert system provided diagnosis and elimination of manufacturing errors on a 3-axis vertical machining centre.

Barreiro (Barreiro et al 2003, 2005) proposed an information model to integrate with manufacturing and design activities that was based on methodology given in STEP standards. Integration was achieved through a common product information model where a functional information model, a reference information model and an interpreted information model were defined. To test the validity of the information model, a real work environment IFCIA (Inspection Framework for Concurrent Information Access) was developed. The IFCIA architecture consists of a product modelling system, an object-oriented central database and a tri-dimensional coordinate measuring machine. The model was implemented on an object-oriented product central database which is accessible by all the applications. The generation and transference of the information among these systems were carried out according to information model data structures. The model had been recently tested taking as reference the information objects included in the previously developed model.

Killmaier and Ramesh (Killmaier and Ramesh 2003) developed a method that uses a genetic algorithm to detect form deviations (waviness, random deviation, offset, peak, etc.) of standard geometrical features (line, circle, plane, cylinder, cone and sphere). The genetic algorithm arrives at the optimal values of these deviation types that reproduce the profile very close to the measured one. The information is stored in a knowledge-
based system to adopt a suitable measurement strategy. An interactive software assistance with graphical view was developed to effectively handle the detection procedure.

Yongqing’s research focused on studying the influences of the probe length and volume on the accessibility of inner features, such as slots and holes. These were analysed in detail for dimensional inspection on CMMs. A feasible algorithm which took the effects of the probe length and volume into account, was proposed to overcome shortcomings of abstracting the probe as an infinite half-line (Yongqing et al 2004).

Recently Yadong and Pielhua developed methods for inspection of free form surfaces using feature based approach without design datums. The approach had two major steps; first was localization of measured surface data based on the datum reference; and second was further localization based on the surface characteristics for minimizing the deviation of the measured surface data while the datum reference features were still within the design tolerance zone (Yadong and Pielhua 2005).

In 2004 Chen (Chen et al 2004) proposed a haptic virtual coordinate measuring machine (HVCMM). It is a coordinate measuring machine (CMM) inspection path planning environment that made use of the haptic modeling technique for CMM off-line programming. It simulates a CMM’s measurement operation in a virtual environment with haptic perception and it enables CMM off-line programming to take place similar to a real CMM operation. Using the HVCMM system collision-free probe paths can be easily generated as compared to other off-line inspection planning methods.

### 3.3 In-process measurement in manufacturing on CNC machine tools

In-process measurement is an important element of process control in the manufacturing environment. This section reviews the previous and ongoing research in this field and its related issues such as machine tool accuracy and deviations due to tool deflection.

Research in studying the “in-process measurement” techniques developed for controlling the accuracy of the workpiece was carried out at UMIST, UK in 1997 (Yandayan and Burdekin1997). The study had surveyed the available technology for the
"in-process control" of machined products in relation to turning, and cylindrical grinding prior to completion of the machining process. Though the research was limited to turning parts it focused mainly on non-contact methods for measurement.

Katsushi proposed an arm with passive joints having a probing system for online measurement on the machine tool that had 7 degrees of freedom (Katsushi et al 1999). The prototype shape could be automatically measured with the accuracy of the order of a micrometer. Also a numerical method of the inverse kinematics is given to calculate the optimal posture of the arm for the shape to be measured. The on-line measurement system though reasonably accurate was limited as it was tested only for measuring shape and roughness of surfaces of the solid parts.

Henke (Henke et al 1999) proposed two models representing form errors in cylindrical features to highlight the relationships between manufacturing process variables and deviations from perfect geometric forms. A method was introduced to identify deviations from a perfect shape of the cylindrical feature. One model was analytical for modeling the axial errors and angular dependencies in cylindrical features. The other model used the techniques of principal component analysis to extract properties of shapes from the measurement data directly. The research though advantageous in determining the form errors in features lacked actual consideration of many other factors e.g. force of fixtures, thermal affect on the material involved etc.

Another model to solve the deterministic metrology problem for platform-type machine tools (PTMT) was developed (Valdimir 2000). The approach was based on normal deviations of the actual points of machined surface from nominal surface points. Accuracy of cumulative errors, cyclic deviations, backlash etc., were formulated. The error modeling was achieved for determining accuracy using typical setups in milling cylinders and planes. However the research in developing this model was purely analytical and limited to simple cylindrical features and planes.

Tam and Cheung developed a genetic algorithm based defect identification system for machined-parts inspection. It was based on genetic algorithm and knowledge system techniques. The system identified defect from the mass and centre of coordinates of defective parts and a knowledge base which stored previous defects. In this system only
inertial properties are required and it is not affected by the environment (Tam and Cheung 2000).

Ramesh (Ramesh et al 2000) presented a model for error compensation in CNC machine tool elements. Finite element techniques were used to model and analyse thermal and kinematical errors due to extended usage of the machine. The usage of a machine tool produced thermal expansion in its various structural elements. The proposed model however did not give an entirely accurate picture of the total errors in the machine tool structural elements as the errors were determined through FEM techniques which gave an approximation in results.

A new interpolation method with shape functions that implicitly includes the non-rigid-body condition, was proposed to increase the CNC machine tool accuracy (Shih et al 2000). It was used to predict the total position/orientation error and deflection, due to cutting forces for on-line software compensation, which utilizes recursive iterations to compute compensation commands to the machine drives. Also a software program for automatic NC code conversion was also developed for CNC multi-axis machines.

A method for machined surface error compensation was introduced by Myeong. It was based on an inspection database which used an on-machine measurement system in profile milling. The geometric error compensation of the machining center was achieved by using a closed-loop configuration and the probing errors were also considered. A workpiece was machined and then inspected for surface error distribution. In order to efficiently analyze the surface errors, two characteristic surface error parameters Werr and Derr were defined. Various polynomial functions for determining surfaces error were used and experimentation was carried out to validate it (Myeong et al 2003).

Tsutsumi and Saito (Tsutsumi and Saito 2003) in their research work presented an algorithm to identify angular deviations linear axes relating to rotary axes in 5-axis machining centers. Three types of simultaneous three-axis control motions were designed for each rotary axis for identifying deviations. In the measurement, two translational axes and one rotary axis are simultaneously controlled keeping the distance between a tool and worktable constant. In order to determine the deviations,
mathematical modeling was used based on the results, actual deviations in 5-axis machining centers were obtained which gave precision results.

Ong and Hinds (Ong and Hinds 2003) proposed a procedure to select optimal feed rates that ensure that tolerances could be met and used in the down milling mode for demonstrating the process while machining a slot. A tolerance analysis chart was used for clarifying the results of the test in relation to the tolerance standards. Also the consideration was given to the transient errors at the exit of the cut through demonstration.

Recently Hua’s research (Hua et al. 2004) has focused on developing a measurement technique on machining centers for 3D free-form contours. During the research an autonomous measuring principle was proposed which resulted in a prototype measuring device applicable to a machining center. Experimentation was carried out using a measuring device. A laser displacement detector in a narrow range was combined with the movable part of a linear encoder on the nut of a ball screw, where its linear encoder detected the moving displacement of the screw nut. Experiments for identifying the sensing direction errors for an assembled measuring device were developed. The results of some experiments demonstrated the effectiveness of the proposed inspection method and error identification approach.

Yizhen and Yin (Yizhen and Yin 2004) recently developed an ‘enhanced virtual machining’ framework to quantitatively predict part geometry errors due to CNC machine axis motion and positional inaccuracies while machining sculptured surfaces. The combinations of error motions form a complicated pattern of part geometry errors. In this framework machine tool error models were integrated into NC machining simulation where the ideal cutter path for surface machining is divided into sub-paths. The machine tool error model predicted geometric errors for each interpolated cutter location and both solid modeling and the surface modeling approaches were used to translate machine geometric errors into part geometry errors. Though the work was novel it still is specific to sculptured surface machining.

Other research in this area included a method developed to measure thermal errors in a CNC machine tool spindle (Seung et al. 2004). It was used to predict the thermal effects
of the spindle on machine tool accuracies and was based on the use of a ball bar system instead of the conventional capacitance sensor system. It was shown that a single ball bar system is enough for the simultaneous measurement of both geometric and thermal errors.

Similar work by Yann (Yann et al 2004) was used to predict the influence of cutting forces on the machine spindle deformation or any fixture or holding deformation. Taking the positioning error into account, the inaccuracies for side milling as well as end milling were modeled from the cutting conditions used. These models were used to predict machining errors specific to the machining type and compensated for them.

Jacob (Jacob et al 2004) introduced a Reconfigurable Inspection Machine (RIM) and the Stream of Variations (SoV) methodology which was in context of defining an advanced closed loop quality control methodology for reconfigurable manufacturing systems. The aim was to perform rapid root-cause diagnostics for faster ramp-up of reconfigurable systems through integration of the Reconfigurable Inspection Machine (RIM) and the Stream of Variations (SoV) methodology. It was experimentally validated by a machining error which was introduced during machining of an engine head. The measurement data collected by the RIM was processed and used to find the root-cause of the error using the SoV methodology.

Recently a system was proposed to inspect the verticality of cylindrical workpieces by multi-vision sensors that was fast, on-line, non-contact, flexible and more accurate. The system included a “sensor-unit” that had stripe structured light sensors. The methodology was validated through experiments by setting up a real system and the results indicated the high capability for inspecting large workpieces (Zhenzhong and Guangjun 2005).

Liu’s (Liu et al 2005) research resulted in introducing a new method for measuring circular motion error of numerical control (NC) machine tools. The instrument used included a linear displacement transducer bar with two balls at each end and a high accuracy rotary encoder. The variations in the radius were detected by the transducer and the rotation angle of the bar being measured by the rotary encoder while the
machine moved in a circular path. The installation of the instrument was simple and had good repeatability and high precision of measuring circular motion trajectories.

### 3.4 Geometric and Dimensional Tolerancing in Manufacturing

This section reviews the research work regarding tolerancing of mechanical parts in manufacturing. It discusses

- (i) Major Tolerancing Theories
- (ii) Geometric Dimensioning and Tolerancing
- (iii) Tolerance Modelling

#### 3.4.1 Major Tolerancing Theories

For mechanical designed parts, geometric tolerancing theories and methods are usually categorized into two major theories i.e. the traditional plus/minus tolerancing theory and the modern tolerance zone theory.

- (i) Traditional Tolerancing theory
- (ii) Modern Tolerancing Theory

##### 3.4.1.1 Traditional Tolerancing theory

The traditional tolerancing theory provided tolerance limits on size that allow variation in the linear or angular dimension. Hillyard (Hillyard and Braid, 1978) developed a dimensioning theory that provided a scheme to specify sizes of interrelated features and to check whether a feature was over, under, or exactly defined by a set of specified dimensions on a part. The draw back of the traditional theory is that it does not specify the form or true geometrical variation e.g. flatness of a surface.

##### 3.4.1.2 Modern Tolerancing Theory

To overcome the shortcomings of the traditional tolerancing theory, modern tolerancing theory has been introduced that depends upon two principles i.e. maximum material condition and independence principle (Weill 1988). The two principle standards most commonly used are:
(i) British Standards Institution - BS308
The major parts of the standard comprises of BS 308 Pt.1 1984 (corresponds to ISO128) and BS 308 Pt.2 1985 (corresponding to ISO standards No. 129, 406 and 1302)

(ii) American National Standards Institute - ANSI Y14.5M
First introduced by ANSI in the December of 1982, it was then revised by the American Society of Mechanical Engineers (ASME) in 1994. The main objective of this standard is to integrate dimensioning and tolerancing techniques into design and manufacture.

Tolerancing standard ANSI Y14.5 is based on the MMC principle. In ANSI Y14.5M, a tolerance zone is defined as a virtual region formed around the true feature. Requicha (Requicha 983, 1986, 1990) provided mathematical formulations for tolerance zones in his research. According to him a tolerance zone is a region bounded by similar perfect geometry, offset from the nominal feature surface.

3.4.2 Geometric dimensioning and Tolerancing

Geometric dimensioning and tolerancing (GD&T) is a method for explicitly describing a geometry and the allowable variation in the size and position of its features. GD&T enables design engineers to describe part features in such a way that they can be accurately manufactured and inspected. GD&T was not effectively established and documented until early 1980s i.e. when ANSI Y14.5M-1982 (ANSI Y14.5M-1982) was published by the American National Standards Institute publication. Geometric dimensioning and tolerancing specified the shape requirements and the interrelationships between features of the part. The shape requirements include functional needs the suitability for assembly with its designed counterpart(s) manufacturability, esthetics and conformance to regulations. As manufacturing process leaves dimensional variations in parts (Hoffmann, 1982), designers have to specify a region called tolerance zone to allow dimensional variation in actual parts.

GD&T was used to convey the designer’s intent following which the process engineers could select the appropriate processes and plan the manufacturing operations. Also
inspection data comparisons with specified tolerances could be used by quality engineers to examine product's dimensional conformity.

The negative effect of omitting the use of GD&T was shown by Wearring and Karl (Wearring and Karl 1995) through computer simulation of the fabrication of five thousand simple workpieces. In this simulation each of the component was manufactured, inspected and assembled using a specialised inspection gauge. The simulated results showed 99% of the components acceptable when GD&T was followed while the acceptability dropped to 20% when GD&T was ignored and improper component positioning and feature inspection was employed.

3.4.3 Tolerance Modelling

Several techniques have been developed for computing offset surfaces. Approaches developed by Lin (Lin 1981) and Rossignac (Rossignac and Requicha 1986) are well suited for constructive solid modelling, while the method of Rogers (Rogers and Fog 1989) is based on boundary representations.

In today's manufacturing environments tolerancing is specified by the designers manually on a drawing or in a CAD system and it varies for different designers. Salomon in 1996 focused on the geometry relevant for functioning to avoid such a problem (Salomons et al 1996). A tool for functional tolerance specification was developed, which supported the user and generated semi-automatic tolerance type specification, while manual specification could also be still possible.

EPS-1 architecture comprising a geometric modeller and a dimensional and tolerancing modeller was developed at the University of Texas (Reimann and Sarkis 1993, 1994). The product model definition of a three-dimensional component was given by the geometric and tolerance models constructed by the modellers. The geometrical and tolerance information were retrieved by interrogation with the models through the IGES like applications interface and the dimensioning and tolerancing applications interface specifications respectively.
Moon considered a minimum-zone evaluation problem for flatness to determine the minimum tolerance zone enclosing all the measurement points of a surface (Moon 1997). The geometric approach called the ‘convex-hull edge method’ (CONHEM) was proposed that guaranteed the minimum zone tolerance for a given set of measurement points.

A computational scheme to represent and interpret the geometric tolerances (mainly size, orientation and position tolerances) assigned to polyhedral objects was proposed by Roy and Li which was based on a surface-based variational model. The part model was subjected to applied variations where the model variables were constrained by relations derived from tolerance zones. The issue of describing tolerance zones according to different tolerance specifications was addressed and the scheme had been implemented in an object-oriented programming environment (Roy and Li 1999).

Hong presented a CAD model-based approach for the evaluation of general form features. Non-uniform rational B-splines were used to define form tolerances by developing an algorithm (Hong 1999). Huang introduced an optimised approach to allocate planar tolerance that included dimensional and orientation geometric specifications. A special relevance graph (SRG) was to deal with the increased complexity of planar tolerance analysis and it was also applied for the geometric dimensions and tolerances. A linear optimal model was developed for solving the tolerance allocation problem (Huang et al 2002).

Tseng and Chou (Tseng and Chou 2002) worked on sensor integration, data extraction, data processing, monitoring the cutting tool, safety of the tool machinery, and quality of the components in processing. A detection method was used to extract the workload of a spindle motor from a CNC controller, and then transmit the data through a I/O card. Another framework was presented by Yaron and Leo for the systematic study of parametric variation in planar mechanical parts and for efficiently their tolerance envelopes (Yaron and Leo 2004). Position and shape of part’s features were defined explicitly as a function of parameters whose nominal values varied with tolerances. Tolerance envelopes were used for quantifying functional errors, identifying unexpected part collisions, and determining assemblability. Four efficient algorithms for computing first-order linear approximations with successive accuracy were defined.
A method based on a graphical representation of part features was introduced in recent research by Bernard and Hassen (Bernard and Hassen 2005). An iterative procedure was defined that covered datum references and workpiece setup and determined ISO specifications. The tolerances were represented in vector forms for surfaces and it was limited only to the machining process. Another adaptive sampling procedure that used manufacturing surface error patterns was presented by Affan (Affan et al 2005). The optimization search methods were used to reduce sample size, while maintaining high accuracy and demonstrated with straightness and flatness evaluation. The initial points for sampling were identified through such a characterization of the process and its affect on the workpiece. These sampled points were fitted using the least-squares method to complete the form evaluation. Using an adaptive approach, it was proposed that the number of points sampled were potentially less than that which would be expected to achieve the same level of accuracy using traditional sampling methods.

Datum target usage within Geometric Dimensioning and Tolerancing (GD&T) is commonplace in manufacturing industry, these are used primarily for manufacturing and inspection setups. Hossein analytically (and through simulation) examined the effect of variation in datum targets on part acceptance A three-dimensional mathematical model for hole position error with respect to the datum was defined and a simulation was adopted to identify the major sources of hole position error datum errors. The influence of the datum on the measured location of holes referencing those datum was significant (Hossein et al 2005).

3.5 Critique

The automation of inspection planning and process has developed significantly in the 1990s but these developments have been primarily vendor specific. Though the primary aim is to reduce the time of inspection in the manufacturing environment, the reported research has resulted in different types of native programming systems for Coordinate Measuring Machines. The inspection planning systems proposed in previous research (Atkins 1989, Hong 1995, Kuang 1998) are focused only on probe path generation for inspection of parts on CMMs and did not include aspects like the order of features to be inspected etc. Though some knowledge base systems (Corrigall 1990, Gu 1996, Merat 1992, Tang 1995, Bagshaw 1999 and 2002) were introduced the inspection plans
generated by these were specific and not in any standardised form. The recent proposed feature based inspection models (Thomas 2001, Barreiro 2003 and 2005 etc.) had tried to integrate inspection planning with over all process plan, but it these were unable to generalise feature based inspection planning. Moreover the tolerance representation according to GD&T has provided a mechanism in order to simplify tolerance modelling but it still has to overcome its complexities.

In-process measurement on the CNC machine tool is important for Process Control which is a vital element of quality control in manufacturing environment. To achieve reliable in-process measurement of parts, CNC machine tool accuracy plays a vital role. A lot of reported research (Yandayan 1997, Henke 1999, Valdimir 2000, Yizhen 2004, Liu 2005) is in the area of methodologies for detecting errors either in structural components of the CNC machines or deflection of tools due to its dynamics. There is very little research in exploring the full extent of measuring capabilities of a CNC machine tool i.e. using a contact probes for inspection of a part. For in-process inspection on a CNC machining center issues e.g. feature measuring capabilities and accuracy the resulting data compared with that of a traditional inspection on a CMM are highlighted in chapter 4.

The inspection planning systems developed are subjected to different specifications and standards rather than the effort required to standardise the whole process to a single or number of ISO standards. It is the author's belief that a need for an integrated platform towards inspection and measurement of discrete components at the machine tool and the CMM is required in order to close the loop between manufacture and quality control. To achieve this STEP-NC (which is discussed in the next chapter) can provide the basis for this integrated plate form which enables upfront generalised inspection planning in manufacturing.
CHAPTER 4

REVIEW OF INSPECTION STANDARDS AND STEP-NC

4.1 Introduction

This chapter is a review of the STEP-NC standard highlighting its capabilities and limitations and also its comparison with other standards and specifications used in manufacturing for inspection. It outlines various standards for part inspection in a manufacturing environment, limitations of DMIS standard as compared to STEP standards and also reviews the STEP-Compliant systems.

4.2 Introduction to standards for inspection

Currently a number of standards and specifications are used for the inspection process in manufacturing. These standards and specifications for component inspection typically include DMIS, and new developing standards such as AP219 (ISO10303-219), STEP-NC (ISO14649) etc. In addition specifications like I++ and ASAM-ODS are used in the automotive industry, which focuses on inspection equipment used.

4.3 Dimensional Measuring Interface Standard (DMIS)

The most prominent and contemporary of these standards used for component inspections on CMM is “DMIS” Dimensional Measuring Interface standard (DMIS 3.0 1995). It is the standard for communication of dimensional measurement program sequences and results for manufacturing inspection and is widely used with CMMs. It is for bi-directional communication of inspection data between computer systems and inspection equipment. DMIS is used either as an intermediate file format between a CAD system and the CMM’s native proprietary inspection language, or as a native programming language for direct control of the CMM.

The DMIS standard specifies the parameterization of inspection features and tolerances, the establishment of part coordinate systems and datum reference frames, sequencing for machine motion and measurement, sensor and rotary table definition and calibration, user prompting, data output, and high level language constructs.
This ANSI and ISO standard consists of two distinct but related parts, provided within two separate documents and is a standard language primarily for inspection on CMMs (NIST 1997). DMIS development began in February 1985 as the Dimensional Measuring Interface Specification Project. Users and suppliers of dimensional measuring equipment combined efforts to create a standard that would allow the communication of inspection data between automated systems. The first version, DMIS 1.0, was completed in March 1986, and DMIS 2.0 followed in September 1987. The American National Standards Institute “ANSI” accepted DMIS 2.1 as ANSI/CAM-I 101-1990 and likewise accepted DMIS 3.0 in 1995. Further development in the DMIS standard resulted in DMIS 4.0 that was accepted as an ANSI standard in 2001 and its development as an ISO standard is also currently underway (DMIS website).

DMIS provides a neutral format for inspection programs and inspection results data. The inspection program from the computer system is pre-processed into the DMIS format, the program is then executed and the inspection results data is post processed to the original format of the CAD system. DMIS is an ANSI standard and supports tolerances based on ANSI Y14.5, 1994 standard. Its version DMIS 3.0 was the standard for off-line communications of the inspection program and results. Originally it was a neutral interchange format, but it has now developed into a full inspection programming language.

DMIS interprets the inspection programs to dimensional measuring equipment and provides measurement and process data back to an analysis and collection system as shown in Figure 4.1. The interfacing equipment use DMIS vocabulary directly or through a pre-processor to convert the native data formats into the DMIS format. It also uses a postprocessor to convert the DMIS interpretation into its own data structure. Inspection programs can be created in many ways i.e. by CAD systems, non-graphical systems, automated systems, or manually and a DMIS inspection program can then be executed on dimensional measuring equipments.

DMIS provides a readable and writable vocabulary of terms, establishing a neutral format for the preparation of inspection programs and results data. This vocabulary
can also function as a programming language. A typical example of DMIS statements (DMIS 3.0 1995) for measuring a circle is:

\[
F(\text{CIRCLE}_1) = \text{FEAT/CIRCLE,INNER,CART,10,10,5,0,0,1,4} \\
\text{MEAS/CIRCLE, F(\text{CIRCLE}_1),3} \\
\text{GOTO/10,10,5} \\
\text{PTMEAS/CART,12,10,5,-1,0,0} \\
\text{PTMEAS/CART,8,10,5,1,0,0} \\
\text{PTMEAS/CART,10,12,5,0,-1,0}
\]

The explanation of the code is as follows:
In the first line \( F(\text{CIRCLE}_1) \) is the label of the feature, \text{INNER} means that it is a circle that belongs to a hole. \( \text{CART}\ 10,10,5 \) are \( x, y, z \) coordinates of its centre position with \( 0, 0, 1 \) as its axis direction while 4 indicates the diameter of the circle.

The other lines show the measurement of three points on the circle (that is the minimum required for measuring a hole).

![Figure 4.1 Inspection programming using DMIS](image-url)
4.4 I++ and ASAM-ODS

"I++" specification was developed with the help of the automobile industry (Audi, BMW, Daimler Chrysler, Volvo and VW) which provides specification for dimensional measuring equipment interface (I++ specification). Its main goal is to achieve a new programming system for inspection equipment like 3D Coordinate Measuring Machines with large multiple carriage, Form Testers, Cam shaft and crankshaft measuring machines. It is a specification that aims at connecting different application packages to all the DMEs by creating a standardised set of communication protocols.

"ASAM” stands for Association for Standardisation of Automation and Measuring Systems and was initiated by German car manufacturers in 1998. ASAM ODS (Open Data Services) is a subgroup inside ASAM standard. ASAM ODS is the specification of a data model using STEP EXPRESS as the modelling language. ASAM ODS consists of three different layers based on various specifications. These are Application Programming Interface (API) defined by using formal languages like the interface definition language, Data model defined using STEP EXPRESS language (ISO 10303-11) and the Physical Layer that is the projection of data model into a relational data base system (ASAM-ODS 2003).

4.5 STEP and STEP-NC

STEP (Standard for the Exchange of Product model data) is a common name for ISO10303 and it has many individual parts and Application Protocols (OMAC 2002) while ISO14649 known as STEP-NC is a draft ISO specification for a data model for computer numerical controllers. Part programming for NC machine tools is achieved using the standard ISO 6983 of G and M codes (ISO 6983/1 1982) which is limited in coping with the demands of modern NC technology. A part program in ISO6983 defines tool movements and switching instructions while the new object-oriented data model of STEP-NC presents a higher level of information, it has feature-based manufacturing tasks e.g. roughing of a pocket. All the necessary operations to produce a finished part from raw material can be described by such manufacturing tasks and the part program provides a higher quality of information to the shop floor. As the geometry of raw piece and finished parts are defined by STEP syntax, so a
direct information exchange between CAD/CAM and NC can be realised. The geometric data of the part can be imported directly from CAD systems and only technology information has to be added to create a part program (STEPNC newsletter issue 1, 2000).

The collaborative manufacturing environment in view of STEP-NC application protocols is shown by Figure 4.2

![Diagram showing Sources of Process and Product Data]

**Figure 4.2 STEP NC APs Enable Collaborative Manufacturing Environment (OMAC 2002)**

The new STEP-NC data models basically program in terms of manufacturing features instead of defining tool paths. It introduces the concept of working steps i.e. a combination of manufacturing features and technological information. The
working steps represent the essential building blocks of the machining process and each working step describes a single manufacturing operation using one tool and one strategy e.g. roughing of a pocket.

STEP-NC is a departure from the conventional G and M codes and CNC controllers, where post processors are required to generate unique cutter paths to suit each machine tool (shown in Figure 4.3). It depends on the specific part attributes namely features like holes, pockets etc. and processes like profiling, roughing and facing milling. It eliminates the need for post processors and establishes the collaborative manufacturing environment between design, process planning and the machine controller on shop floor.

![Bi-Directional Information Flow with STEP-NC process as compared to a conventional process](Figure 4.3)

Figure 4.3 Bi-Directional Information Flow with STEP-NC process as compared to a conventional process (Allen et al, 2003)
The following table gives an overview of the research work being carried out regarding STEP-NC in Europe, Switzerland, Korea and USA from industrial and academic perspectives.

<table>
<thead>
<tr>
<th>Region</th>
<th>Industrial partners including Siemens with users such as Daimler Chrysler, Volvo Research institutes like WZL, Aachen University and Loughborough University</th>
<th>Research covers milling, turning and inspection of the ISO14649 standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>Collabration of Agie, Starrag and CAM manufacturer CADCAMation</td>
<td>Leading development of the standard for wire-cut and die-sink EDM</td>
</tr>
<tr>
<td>Switzerland</td>
<td>National Research Laboratory (NRL), Pohang University and ERC-ACI-Seoul National University</td>
<td>Research developments in milling and turning architectures for ISO14649 compliant controllers</td>
</tr>
<tr>
<td>Korea</td>
<td>Super Model project involving industrial partners including STEP Tools Inc., Boeing, Lockheed Martin, General Electric and General Motors, together with recognised CAM vendors such as Gibbs Associates and MasterCAM</td>
<td>Research Focus on full automations of CAD to CNC manufacturing process through the use of STEP standards</td>
</tr>
</tbody>
</table>

Table 4.1 Academic and Industrial Research work based on STEP NC around the globe

The STEP-NC research work around the world is largely focused on integration of Design, Process Planning and Manufacturing with little attention to the inspection and measurement of the parts for process control. The research work by the author is focused on applying the STEP-NC standard to the inspection process by proposing a framework for the dimensional measurement of prismatic parts as outlined previously in chapter 2.
4.5.1 Parts of STEP-NC Standard (ISO14649)

STEP-NC is formally known as ISO14649, it is divided into several parts that are shown in table 4.2. Some of these parts are working drafts still in development stages.

| ISO14649-1 | It gives an overview of the standard and its fundamental principles |
| ISO14649-10 | It provides general process data needed for NC-Programming within |
| ISO14649-11 | It provides process data for milling |
| ISO14649-111 | It provides information about tools for milling machines |
| ISO14649-12 | It provides process data for turning |
| ISO14649-121 | It provides tool for turning machines |
| ISO14649-13 | It provides information about Wire-EDM |
| ISO14649-14 | For contour cutting of wood and glass |
| ISO14649-16 | Data for touch probing based inspection |

Table 4.2 Parts of STEP NC (ISO14649) standard

Many of the ISO14649 parts that include general process data, machining (milling and turning) and its tooling are fully developed. The part responsible for inspection and measurement using touch probes ISO14649-16 is still under development and its limitations are given in section 4.7. Most of the features in STEP-NC (ISO14649) closely resembles with that of AP224 (ISO10303-224). Also AP219 (ISO10303-219)
specifies planning and executing dimensional inspection results. AP219 however does not specify the inspection and measurement tasks for features such as “probing workingsteps” that are defined in ISO14649-16.

4.5.2 Structure of STEP-NC

The STEP-NC data model provides geometric description based on STEP (ISO10303) and technological information integrated together in a structured program. The structure consists of a Header and Data section. A Project entity serves as an explicit reference for the starting point of the manufacturing tasks (STEP-NC newsletter, issue2 2000).

The header section consists of general information and comments concerning the part program which is described in a Physical File Format according to the ISO10303 Part21 (ISO10303-21 1994) e.g. filename, author, date, organization, etc. The data section is the main section and includes all information about manufacturing tasks and geometries. This section is categorized in three parts which are:

(i) Workplan and executables
(ii) Technology description
(iii) Geometry description.

The work plan has a combination of several executables that are of three types i.e. working step, NC function, and program structure. To make any change to the sequence of operations, only this part of the program needs to be changed while the definitions relating to the geometry description and technology information are unchanged.

The technology description provides complete definition of all working steps given in the work plan and contains tool data, machine functions, strategies and other process data. It also defines the work piece and all surfaces, regions and features of the finished part. A complete technology description consists of not only cutting width and depth, spindle speed, feed, finishing allowance, and tool used but also the
tool dimensions, tool type, and other data for identifying the usage and conditions of the tool.

All geometrical data for the work pieces, the manufacturing features referred to in the working steps and the setups are described using the ISO 10303 data format. The working steps are manufacturing tasks that is subdivided into “machining working steps” and “probing working steps”. The machining working steps are for the machining tasks while the probing working steps are for probing tasks. STEP-NC standard is divided into various parts e.g. ISO14649 part1 (ISO14649-1) gives fundamental information, part 10 deals with general process data where part 11 deals with milling, part 12 turning etc. Some of these parts are still working drafts and yet to be finalized which is the case of ISO14649 part 16 (ISO14649-16) which deals with inspection and measurement data.

4.6 Limitations of STEP-NC standard for inspection (ISO14649-16)

ISO14649-16 provides information about inspection activities, inspection items, tolerances, reference datum for inspection, inspection result storage and probing stylii. It extends ISO14649-10 which contains general process data and other information like project, workplan, workpiece etc. all this information is for inspection using a touch trigger probe.

The inspection activities define a probing working step which is an inspection task. It has its probing operation and a set of inspection items. The inspection items are entities to be measured, these being either dimensions with tolerances or tolerances for shape entities such as circularity of a circle. The tolerances definition and the reference with respect to which the inspection item is measured are also provided.

Though information about inspection is provided by ISO14649-16, it has limitations regarding feature-based inspection of a part. These limitations are as follows:

(i) No inspection features are defined
(ii) No relation between inspection items and features exists
(iii) No direct link between the manufacturing features in ISO14649-10 and the probing workingsteps defined in ISO14649-16

(iv) The inspection result statements doesn’t specify what result to store

(v) The feasibility of ISO14649-16 has not been practically proven yet

4.7 Limitations of DMIS as compared to STEP standards

DMIS as previously explained in section 4.3 is a standard for bi-directional communication of inspection information between computer systems and equipment. The CAD system specifies the geometric information and is pre-processed to generate a DMIS language file, which is post-processed into a probe path at the CMM. For tolerance information it makes use of related standards such as ANSI Y14.5.

The features in DMIS are simple geometric elements and the DMIS program does not give complete description of the part to be inspected. It also does not provide a general geometric modelling capability. Moreover the DMIS specification does not state that a single nominal feature may correspond to more than one actual feature, but seems to assume that the correspondence is one to one (NIST 1998). Currently the features defined in DMIS are primitive as compared to those defined in STEP standards. It is believed to progress and maintain compatibility with the developing STEP standards and is moving towards becoming an ISO standard. The features represented in DMIS outlined in Table 4.3 are mostly geometric primitives compared to those defined in STEP standards (e.g holes, pockets, slots etc.).

The manufacturing features in STEP-NC are similar to those in AP224 (ISO10303-224), which are divided mainly into four groups

(i) machining features
(ii) transition features
(iii) replicate features and
(iv) compound features
A typical example of comparison between STEP-NC and DMIS features could be the representation of a pocket feature. It is defined as a pocket feature in STEP-NC, divided into subclasses like closed pocket, open pocket while in DMIS the closed pocket feature is represented as four side planes and a bottom plane i.e. a combination of five primitive features.

In fact all the features given in DMIS are included in STEP-NC features in one form or another, e.g. plane feature, circle, point, arc, pattern, cylinder, cone etc. On the other hand STEP-NC features include many features like pocket, protrusion, circular cut out that are not given in DMIS and are defined using the other primitive features. In spite of defining primitive features DMIS provides appropriate language for inspection programs that are passed on to the measuring equipment and then passed back the measurement data for analysis.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARC</td>
<td>Arc</td>
</tr>
<tr>
<td>CIRCLE</td>
<td>Circle</td>
</tr>
<tr>
<td>CONE</td>
<td>Cone</td>
</tr>
<tr>
<td>CPARLN</td>
<td>Parallel Line</td>
</tr>
<tr>
<td>CLYNDR</td>
<td>Cylinder</td>
</tr>
<tr>
<td>ELLIPS</td>
<td>Ellipse</td>
</tr>
<tr>
<td>GCURVE</td>
<td>3d Curve</td>
</tr>
<tr>
<td>GSURF</td>
<td>3d Surface</td>
</tr>
<tr>
<td>LINE</td>
<td>Line</td>
</tr>
<tr>
<td>OBJECT</td>
<td>User Defined Feature</td>
</tr>
<tr>
<td>PARPLN</td>
<td>Parallel Plane</td>
</tr>
<tr>
<td>PATTERN</td>
<td>Pattern</td>
</tr>
<tr>
<td>PLANE</td>
<td>Plane</td>
</tr>
<tr>
<td>POINT</td>
<td>Point</td>
</tr>
<tr>
<td>PTDATA</td>
<td>Output Point Data</td>
</tr>
<tr>
<td>RCTNGL</td>
<td>Rectangle</td>
</tr>
<tr>
<td>SPHERE</td>
<td>Sphere</td>
</tr>
</tbody>
</table>

Table 4.3 Features defined in DMIS (DMIS3.0 1995)
4.8 Application of STEP Compliant systems

STEP NC presents a higher level of information compared to traditional G & M code CNC programming. Research work at Loughborough University in 2002 had identified three implementation frameworks for incorporating STEP NC data structures within CAD/CAM systems (Newman et al 2002).

The first framework implies a CAD/CAM system that generates a STEP-NC (ISO14649) output and can be further subdivided into two groups. One has the ability only to export STEP NC code and the other has both import and export capabilities as shown in Figure 4.4. The major issue involved with this kind of framework is the ability of post processor for converting the manufacturing data into ISO14649 format, which is totally different to low level G&M code programming.

The second framework (as shown in Figure 4.5), provides a CAD/CAM system either with an external or an internal STEP-NC data support structure. The CAD/CAM system is independent in the external data support structure while for internal STEP-NC data support structure, geometric and manufacturing data is duplicated both in native format and ISO14649 format.

The third framework presents a higher level of compliance that uses ISO14649 and ISO10303-224 for both the geometric and manufacturing data models. This framework is supposed to be the basis of new developments for CAD/CAM vendors with one of the options as the need to post process the STEP data into ISO 6983 G/M code output for conventional CNC controllers (shown in figure 4.6).
Figure 4.4 First Framework, (a) Framework that exports STEP-C-NC data (b) Variant framework that imports/exports STEP-C-NC data (Rosso et al 2002)
Figure 4.5 Second Framework, (a) An external STEP-C-NC interfaced CAD/CAM environment (b) Internally shared STEP-C-NC CAD/CAM environment (Rosso et al 2002)
Research at Loughborough University resulted in application of STEP-NC to asymmetrical turned components in which the major challenges in implementing STEP-compliant CAD/CAM systems for manufacturing asymmetric rotational parts were presented. Roberto in 2004 highlighted the problem of feature positioning and operation for turn components and overcame it through the use of STEP-NC i.e. ISO14649 part 10 and 11. It was shown that the features in STEP-NC (e.g. a hole or a pocket) could be used in both the face and the revolution surface of a turning part by translation and rotation of their own coordinate system (Roberto et al 2004).

Other STEP-NC publications relate to the STEP-NC project in Korea. Suh presented STEP-NC compliant shop floor programming “SFP” (Suh et al 2002). The key features in the architecture design for Shop Floor Programming system involves a STEP-AP physical file interpretation, part program based on ISO14649, geometrical data provided by ISO10303 AP224, feature recognition, process plan generation and
the working steps required, output in ISO14649 format or conversion into G codes
based on the type of CNC controller (conventional control, new control or intelligent
control). A conceptual framework called ANSC was also presented by Suh for an
intelligent STEP-compliant CNC which had ISO 14649 as an input and performed
manufacturing tasks in an intelligent and autonomous way. This framework was
derived from the analysis of information in ISO 14649, CNC on the shop floor of an
intelligent manufacturing system (Suh and Cheon 2002).

Wonseok and Young's research focused on the development and testing of a STEP-
NC milling machine where ISO14649 could provide information in generating tool
paths instead of directly giving the tool path to CNC machines. The tool path
generator in the system was made using Visual C++. The STEP-NC arranged in
XML was used as an input file and also example 1, included in ISO14649-11 was
machined to test the manufactured STEP-NC milling system (Wonseok and Young
2003).

During Research work by Liu and Zhang at Shandong University (China) a
framework for a STEP-NC interpreter was proposed and a prototype was
implemented with STEP application tool where the milling schema was converted
into C++ classes using the EXPRESS compiler. The interpreter based on STEP-NC
based machining was also implemented in the ST-Developer environments and was
used to read the STEP-NC file and then extract and organize object-oriented
manufacturing information. A basic STEP-NC based controller was proposed with
interpreter, decision maker and an executer. The interpreter framework though useful
has still to be validated for developing a STEP-NC compliant controller for NC
machines (Liu and Zhang 2004).

In terms of application of STEP-NC, Suh in 2002 presented the virtual gears model
for measuring geometric errors in manufactured spiral bevel gears. Different errors
such as tooth profile error were measured by comparison of the VGM with CAD
model (soft-master model). The algorithms developed were experimentally validated
with test gear manufactured by CNC milling. It was suggested that the model-based
method could be incorporated on a new intelligent CNC controller based a STEP-NC
interface as an on-line inspection module (Suh et al 2002).
Xu and He presented an overview of the STEP-NC and highlighted the benefits of ISO14649 in integrating CAD, CAM and NC data in a single database, to which each CAx system or NC controller could have access for information retrieval, modification and appending (Xu and He 2003).

4.9 Critique

The standards and specifications used in manufacturing inspections are DMIS, I++, ASAM-ODS, STEP and STEP-NC standards. I++ and ASAM are specifications specifically developed by a different groups of automotive industries concerned with dimensional measuring equipment and automation of measuring systems. DMIS and STEP standards are used for inspection of discrete components in a manufacturing environment.

Though DMIS acts as an inspection programming language between CAD system and measuring equipment and provides complete information regarding inspection procedure and feedback of measured data for analysis, it only defines primitive features e.g. it specifies a closed pocket feature as combination of five plane surfaces.

STEP and STEP-NC on the other hand describe features in detail and cover many aspects of analysis of measured data in AP219, but the inspection execution phase i.e. inspection work plan and working steps etc, have still to be defined in detail. The part of STEP-NC standard for inspection is ISO14649-16 that contains information about inspection activities, inspection items and inspection datum. However the information provided by ISO14649-16 doesn’t specify any relation between its inspection activities and items with the features defined in ISO14649-10. The application of STEP-NC standard to propose various STEP-compliant systems had been mainly focused on process planning and machining etc. There is still a need for overcoming the limitations and developing a STEP-NC-Compliant inspection framework which is an important part of the process control. The ISO14649 part 16, though a working draft provides information about inspection of a part and its relevant tolerance information in a structured way.
CHAPTER 5
DISCRETE COMPONENT INSPECTION PLANNING AND
PROGRAMMING ON A CMM OR A CNC MACHINING CENTRE

5.1 Introduction

This chapter focuses on the in-process measurement of a part on a CNC machining centre relative to the contemporary inspection of the part on a coordinate measuring machine. In-process gauging of the part is advantageous while it is still on the CNC machine. Several issues i.e. bespoke inspection planning specific to the machine, and other related issues such as measuring capabilities, and accuracy of results are exemplified by experimentation in this chapter.

The experimentation was performed in order to show the need of a generalised inspection plan for inspecting a part either on a CNC machining centre or a CMM. Currently inspection planning is very specific for a part's inspection and is mostly completed for CMMs. For the in-process measurement of a part on CNC machining centres, the planning is primitive, the measuring capabilities limited and accuracy of the inspection results less reliable than that of a CMM.

5.2 Experimentation

This section outlines the experimentation illustrating the differences between inspection and measurement of a machined part on two different CNC machining centres and a CMM. It highlights three aspects, firstly to demonstrate the limitations of 3-axis CNC machining centres regarding measuring capabilities in comparison to a coordinate measuring machine. Secondly to show the bespoke inspection plans specific to each machine on which the part is inspected. Finally to show the repeatability and accuracy of inspection results obtained from inspection on CNC machining centres compared with that of a CMM. A comparison was made between the inspection procedures and results; highlighting the difference in inspection planning and programming, measuring capabilities and reliability of the inspection results in terms of accuracy.
A work-piece was machined and its dimensions inspected on two CNC machining centres and then on a CMM using touch trigger probe. The focus in this experiment was on inspection planning and accuracy of measured results, to illustrate the limitations of inspection at the CNC machine tool in comparison with the more accurate coordinate measuring machines.

The main objectives of the experimentation were:

(i) To analyse the capabilities of a 1990s 3-axis CNC machining centre for inspection of a prismatic part.

(ii) To analyse the capabilities of a state of the art 3-axis CNC machining centre for inspection of a prismatic part.

(iii) To compare the machined part's inspection plan and inspection results between a 1990s CNC machining centre and a state of the art CNC machining centre.

(iv) To compare the machined part's inspection plan and inspection results obtained by inspection at the two machining centres with that of a shop-floor coordinate measuring machine.

5.2.1 Machining centres and CMM used for inspection

The two CNC machining centres and the Coordinate Measuring Machine used in the experimentation are given as follows:

(i) 1990s 3-axis CNC machining centre “WADKIN”

(ii) State of the art 3-axis CNC machining centre “BRIDGEPORT”

(iii) Bridge type coordinate measuring machine “CMM (FERRANTI)”
The probing equipment used on a CNC machining centre is different to that used on a CMM. The specification of each machine along with their probing equipment used in the experimentation is given in Table 5.1.

<table>
<thead>
<tr>
<th>WADKIN V 4-6</th>
<th>1990s 3-axis CNC machining centre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table size</td>
<td>X-750mm Y-500mm</td>
</tr>
<tr>
<td>Axis Capacities</td>
<td>X-600mm Y-460mm</td>
</tr>
<tr>
<td>Axis feed rates</td>
<td>upto 1000mm/min</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.013mm</td>
</tr>
<tr>
<td>RENISHAW Probe Head</td>
<td>MPS1 - sense directions ±X, ±Y, +Z</td>
</tr>
<tr>
<td>and Probe stylus</td>
<td>stylus over-travel X and Y ±17.5° and</td>
</tr>
<tr>
<td></td>
<td>Z 8mm</td>
</tr>
<tr>
<td></td>
<td>Ruby ball stylus (Ceramic stem) PS33R</td>
</tr>
<tr>
<td></td>
<td>Length 50 mm ball dia 5mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BRIDGEPORT VMC 610XP²</th>
<th>(state of the art 3-axis CNC machining centre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table size</td>
<td>X-840mm Y-470mm</td>
</tr>
<tr>
<td>Axis Capacities</td>
<td>X-610mm Y-510mm</td>
</tr>
<tr>
<td>Axis feed rates</td>
<td>Upto 43000mm/min</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.004mm</td>
</tr>
<tr>
<td>RENISHAW T- T- probe</td>
<td>OMP40- sense directions ±X, ±Y, +Z</td>
</tr>
<tr>
<td>Probe Head</td>
<td>stylus over-travel X and Y ±12.5° and</td>
</tr>
<tr>
<td>and Probe stylus</td>
<td>Z 6mm</td>
</tr>
<tr>
<td></td>
<td>Ruby ball stylus (Ceramic stem) PS33R</td>
</tr>
<tr>
<td></td>
<td>Length 50 mm ball dia 5mm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FERRANTI Metrology systems</th>
<th>(3-axis Bridge type CMM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring Range</td>
<td>X-750mm Y-7500mm</td>
</tr>
<tr>
<td>Output Resolution</td>
<td>Z-500mm</td>
</tr>
<tr>
<td></td>
<td>0.0001</td>
</tr>
<tr>
<td>Axis feed rates</td>
<td>Upto 1000mm/min</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.0005mm</td>
</tr>
<tr>
<td>RENISHAW Probe Head</td>
<td>PI19</td>
</tr>
<tr>
<td>and Probe stylus</td>
<td>Total Angular Movement</td>
</tr>
<tr>
<td></td>
<td>A-axis ±105°-0°-in 7.5° steps</td>
</tr>
<tr>
<td></td>
<td>B-axis ±180° in 7.5° steps</td>
</tr>
<tr>
<td></td>
<td>Ruby ball stylus (Ceramic stem) PS33R</td>
</tr>
<tr>
<td></td>
<td>Length 50 mm ball dia 5mm</td>
</tr>
</tbody>
</table>

Table 5.1 Specification of the two CNC machine tools and the CMM used in the experimentation
5.2.2 Prismatic part used in experimentation

The geometry of the part used in the experimentation is from an example part in the STEP-NC standard (ISO14649-11) as shown in figure 5.1. The material of the component is polymer and its material properties are given in Table 5.2.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m$^3$)</td>
<td>700 – 750</td>
</tr>
<tr>
<td>Co-efficient of thermal expansion (10$^{-6}$ K$^{-1}$)</td>
<td>50 - 55</td>
</tr>
<tr>
<td>Compressive strength (N/mm$^2$)</td>
<td>25 - 30</td>
</tr>
<tr>
<td>Flexural strength (N/mm$^2$)</td>
<td>20 - 25</td>
</tr>
<tr>
<td>Shore D hardness ISO868</td>
<td>60 - 65</td>
</tr>
<tr>
<td>Colour</td>
<td>Brown</td>
</tr>
</tbody>
</table>

Table 5.2 Material properties of the component

Figure 5.1- Example component (ISO14649-11) for inspection
5.3 Inspection of the component on CMM (FERRANTI)

The standard part from the standard ISO14649-11 (Figure 5.1) was inspected on a coordinate measuring machine and the inspection operation procedure is as follows:-

5.3.1 Inspection Operation procedure for CMM

Automated inspection of the component was carried out, using ACCUDAT (measuring software). The sequence of inspection operation on the coordinate measuring machine is given in figure 5.2 and is as follows:-

(i) A top datum plane was established at the surface of the component, by touching the probe at 4- points on the component surface.

(ii) Two more points were probed on the side face along the length to establish the x-axis, and then one point probed on the face along the width to establish the y-axis. The software aligned the x-axis along the length and y-axis along the width respectively.

(iii) The end faces of the part were probed (4 points each) and the length and width of the component were given by the 3-D length measure in the inspection software.

(iv) The inner faces of the pocket were probed (4 points each) and the length and width of the component and the pocket were given by the 3-D length measure.

(v) The inner surface of the hole was probed at 4 points in order to measure the diameter

(vi) To obtain the depth of the pocket and blind hole, planes at the bottom surfaces of the pocket and the hole were established by touching the probe at 4 points on each surface. The depth of each feature was given as a 3-D distance measurement between their bottom surface planes and top datum plane.
Figure 5.2 Sequence of probing the part on CMM (FEERANTI)
5.4 Inspection of the component on the CNC machining centres

The measurement of main dimensions of the part and its features after machining on a 3-axis CNC machining centre was carried out, using a touch trigger probe. The Touch trigger probe on a CNC machining centre is mainly used for setting up of a part that is to be machined. The probe is also used to check the dimensions of the main features of the part after machining, depending on the measuring capabilities.

For the purpose of demonstrating the measuring capabilities, the example part (shown in the previous section) was inspected and measured on two different 3-axis CNC machining centres (described in section 5.2.1); one was WADKIN with FANUC controller and the other a “BRIDGEPORT” with Siemens 840D controller.

5.4.1 Inspection of the component on a CNC machining centre WADKIN

The inspection procedure on “WADKIN” using a touch trigger probe is given as follows:-

(i) The top surface of the part was probed in order to locate it and establish the z-coordinate of the surface in reference to the machine-zero. This was achieved by touching the top surface of the part with the probe at a single point.

(ii) Three points, two each on the side-faces along with the width and length of the part and one on the top surface were probed to set the origin at the corner by setting x, y, z coordinates to zero and also establish x-axis and y-axis.

(iii) The parallelism of the end faces along the length (X-direction) and width (Y-direction) were checked first. The datum was set at one of the corner point of the part and then the end faces in X-direction were probed to find the parallelism in the x-direction. Similarly the end faces of the component in the Y-direction were probed to find the parallelism in y-direction.

(iv) For measuring the length of the part and the pocket, bespoke probing routines (based on ISO6983) in the positive X-direction and negative X-
direction were used. The x-coordinates were noted from the controller screen and the lengths of the component and pocket were then calculated by taking difference of the coordinates.

(v) The width of the part and the pocket were obtained in the same manner by probing along Y-axis (-Y and +Y probing for measuring the width of the part and the pocket).

(vi) To measure the diameter of the hole, the probe was moved just above the centre of the hole (approximately) and the inner surface was then touched at four different points to obtain the centre of the hole. The probing routine was then started and the inner surface was probed at four points (two opposite points each in X and Y directions) to give us the radii in reference to the datum centre of the hole. The diameter was then calculated by taking the average of the diameters in X and Y directions respectively.

(vii) To measure the depth of the pocket and depth of the hole, the surface of the component was probed at one point with the z coordinate being noted in reference to the machine coordinate system, the bottom of the pocket was then probed for its z-coordinate. The depth was obtained from the difference of z-coordinate at the top surface of the part and bottom surface of the pocket. The probe was again used for measuring the bottom surface of the blind hole (single point) for the z-coordinate and the depth was calculated by taking its difference from the z-coordinate at the top surface.

The inspection program for the part measurements in G&M codes (ISO6983) and the calculated inspection results from the measured data are given in appendix B. The sequence of probing operation of the CNC machine tool WADKIN is illustrated in Figure 5.3.
Figure 5.3 Sequence of probing the part at CNC machine tool (WADKIN)
5.4.2 Inspection of the component on BRIDGEPORT using touch trigger probe

Feature-Based inspection of the part on the BRIDGEPORT CNC machining centre was carried out using built-in probing cycles provided by Renishaw for the 840D Siemens' NC controller.

The sequence of measurement operation (given in Figure 5.4) was as follows:

(i) The z-datum was established on the top surface of the part by touching the probe at a single point.

(ii) The origin was defined at one of the corner of the part by setting the x, y and z coordinates equal to zero. The x and y axis were established by probing two points at the front face (yz-plane) and the side face (xz-plane) of the part in x and y directions respectively.

(iii) Length and width of the part were measured by using built-in measuring probing cycle for web measurement by probing two points in x direction and two in y direction i.e. one point each at the opposite faces of the part.

(iv) Location of the centre of the hole feature and its diameter measurement were carried out using built-in bore measurement routine (four points probed at inner surface of the hole).

(v) The probe was moved to centre position of the pocket feature and its length and width were measured using built-in pocket measurement routine (probing one point each at the inner faces of the pocket.

Once the datum corner was established each of the probing operations were repeated ten times. The inspection code for inspection and measured inspection results from the Bridgeport CNC machining centre is given in appendix C.
5.5 Comparisons of inspection procedures:

A comparison between component inspection at the CNC machining centre and inspection on a CMM (FERRANTI) was completed. There was also a comparison of inspection procedures and results between the two CNC machining centres. This comparison is as follows:

(i) Comparison of inspection planning for all three machines

(ii) Comparison of the inspection programs used and time taken to complete the inspection operations

(iii) Comparison of the output inspection results.
5.5.1 Comparison of inspection planning for all three machines

The component’s inspection plans for the CMM and both CNC machining centres, given in Table 5.3, Table 5.4 and Table 5.5 respectively, are as follows:

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Items</th>
<th>Measurement</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Part orientation relative to CMM</td>
<td>Alignment and datum</td>
<td>Measure Plane-1 on Top surface of the part (4 pts.) and Two lines (2pts. Each)</td>
</tr>
<tr>
<td>2.</td>
<td>Length of the part</td>
<td>Length dimension</td>
<td>Measure Plane-2 &amp; Plane-3 at either end along the length (4pts. each)</td>
</tr>
<tr>
<td>3.</td>
<td>Width of the part</td>
<td>Length dimension</td>
<td>Measure Plane-4 &amp; Plane-5 at either end along the width (4pts. each)</td>
</tr>
<tr>
<td>4.</td>
<td>Length of the pocket feature</td>
<td>Length dimension</td>
<td>Measure Plane-6 &amp; Plane-7 at (4 pts. each)</td>
</tr>
<tr>
<td>5.</td>
<td>Width of the pocket feature</td>
<td>Length dimension</td>
<td>Measure Plane-8 &amp; Plane-9 at (4 pts. each)</td>
</tr>
<tr>
<td>6.</td>
<td>Depth of the pocket</td>
<td>Length dimension</td>
<td>Measure Plane-10 on bottom surface of the pocket (4 pts.) in reference to the top surface of the part</td>
</tr>
<tr>
<td>7.</td>
<td>Depth of the hole</td>
<td>Length dimension</td>
<td>Measure Plane-11 (3 pts.) bottom surface of the hole in reference to the datum surface</td>
</tr>
<tr>
<td>8.</td>
<td>Diameter of the blind hole feature</td>
<td>Diameter and position</td>
<td>Measure circle (4pts.)</td>
</tr>
<tr>
<td>9.</td>
<td>Fillet radii of the pocket corners</td>
<td>Radius and Position</td>
<td>Measure circle (4pts.)</td>
</tr>
</tbody>
</table>

Table 5.3 Plan for part inspection on a CMM (FERRANTI)
### Plan for part inspection on “WADKIN”

**Stylus Selection:** Diameter of stylus 5 mm  
Length of stylus 50 mm

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Items</th>
<th>Measurement</th>
<th>Operation</th>
</tr>
</thead>
</table>
| 1.        | Part orientation relative to machine tool | Datum Establishing coordinate system at the corner of the part Alignment | Establishing datum surface (probing 10 points on the surface-1).  
Coordinate system (probing 3 points on the three faces[1,2, 5] of the part at the corner).  
Checking X parallelism  
Checking X parallelism |
| 2.        | Length of the part             | Length dimension                         | Probing two points in the X-direction—one at each end face[2,3]  
(Taking x coordinates on the end-faces along the length and calculating the difference)                                                                                                                   |
| 3.        | Width of the part              | Length dimension                         | Probing two points in the Y-direction—one at each end face[4,5]  
(Taking Y coordinates on the end-faces along the length and calculating the difference)                                                                                                                   |
| 4.        | Length of the pocket feature   | Length dimension                         | Probing two points in the X-direction—one at each inner-face[6,7] of the pocket.  
(Taking x coordinates on the inner-faces along the length and calculating the difference)                                                                                                                   |
| 5.        | Length of the pocket feature   | Length dimension                         | Probing two points in the Y-direction—one at each inner-face[8,9] of the pocket.  
(Taking Y coordinates on the inner-faces along the length and calculating the difference)                                                                                                                   |
| 6.        | Depth of the Pocket            | Length dimension                         | Probing a single point in the -Z-direction.  
(Z-coordinate on the bottom-face[10] of the pocket and calculating the difference with top datum surface[1] of the part)                                                                                             |
| 7.        | Depth of the blind hole        | Length dimension                         | Probing a single point in the -Z-direction.  
(Z-coordinate on the bottom-face[11] of the hole and calculating the difference with top datum surface[1] of the part)                                                                                             |
| 8.        | Diameter of the blind hole feature | Diameter and position                    | Position:  
Locating centre of the hole w.r.to the machine tool coordinate reference (by probing 4 points on inner surface[12] of the blind hole two points each in X and Y directions respectively)  
Diameter:  
Probing 4 points on the inner surface[12] of the blind hole, two each along X and Y respectively and taking average of the diameters in X and Y directions                                                                 |

Table 5.4 Plan for part inspection on WADKIN
Plan for part inspection on a “BRIDGEPORT”

<table>
<thead>
<tr>
<th>Serial No.</th>
<th>Items</th>
<th>Measurement</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Part orientation</td>
<td>Inspection datum</td>
<td>z-surface measure on top surface using built-in subroutine L9811 for single surface measurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Establishing z-datum and coordinate system at the centre of the part</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Dimensions of the block:</td>
<td>Length dimension</td>
<td>Length measurements using built-in routine L9812 for web measurement</td>
</tr>
<tr>
<td></td>
<td>Length of the part and width of the part</td>
<td>Width dimension</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Diameter of the blind hole feature.</td>
<td>Length dimension</td>
<td>Length measurements using built-in routine L9814 for bore measurement</td>
</tr>
<tr>
<td></td>
<td>Centre of the hole feature w.r.to inspection datum</td>
<td>X and y position of the hole centre w.r.to inspection datum</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Dimensions of closed pocket feature:</td>
<td>Length dimension</td>
<td>Length measurements using built-in routine L9812 for pocket measurement</td>
</tr>
<tr>
<td></td>
<td>Length of the closed pocket and width of the pocket</td>
<td>Width dimension</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Width of the pocket feature</td>
<td>Length dimension</td>
<td>Measure Plane-8 &amp; Plane-9 at (4 pts. each)</td>
</tr>
</tbody>
</table>

Table 5.5 Plan for part inspection on BRIDGEPORT

The inspection plans both for the CNC machining centres and the CMM were written manually, with the plans generated for the CNC machining centres being very different to each other, and also different to the inspection plan for the CMM. A few differences are clearly visible in the inspection plans. For example the establishment of datum plane on the top surface and planes (pocket inner faces and end faces of the part) is easily achieved in the CMM program. The CMM plan also includes measurement of the fillet radii, which is not possible on the WADKIN or BRIDGEPORT CNC machining centres. However in terms of measuring capabilities BRIDGEPORT is more capable than the WADKIN, as it can measure the feature as a whole e.g. measurement of the closed pocket using probing cycle L9812.

5.5.2 Comparison of the inspection programs used and the time of inspection

The inspection routine used on the WADKIN CNC machining centre is very primitive based on ISO6983 (G codes), which only recorded the x and y positions during probing. For example the diameter of a hole-feature is probed in the x-direction and then in y-
direction and is calculated manually by taking the average value (The bespoke inspection program in ISO6983 is given in the appendix). On the other hand there are built-in probing cycles for inspection of simple features on the Seimen’s NC controller (SHOPMILL) on the BRIDGEPORT machining centre. The CMM (FERRANTI) has a user friendly inspection software interfaced with its controller that generates automated inspection routines and is feature based.

The time taken to inspect the features of the component (example part in ISO14649-11) by the WADKIN CNC machining centre was 2.5 hours, nearly 5 times the time for inspection of the same features on a CMM. It is actually more for the CNC machining centre if the time of manually calculating the dimensions from the inspection data is considered. The dimensional measurement time taken on the Bridgeport was approximately equal to that of the CMM inspection time.

5.5.3 Comparison of the output inspection results

The most important issue in comparison between inspection on a CNC machining centre and a CMM is that of reliability and accuracy of the resulting data. The accuracy of the CNC machining centres and the CMM are different as the machine error on each is different. The errors obtained by running a dynamic test (ISO230-4) on the WADKIN and BRIDGEPORT machining centres was ±17µm and ±6µm respectively while on the CMM Ferranti the machine error (ISO10360-2) is ±5µm (see appendix F). A typical comparison between dimensions obtained from inspections on the two CNC machining centres and a CMM is elaborated by the graph shown in figure 5.4. The graph shows consistency of the results (hole diameter measurement) for the CMM in comparison with the inspection results on the two CNC machining centres.

The data from the measurement of the hole diameter on the CMM and the two machining centres is given in table 5.6. Though repeatability of the measured results data from the two CNC machine tools over 10 measurements is less than that for the CMM, it is still within a reasonable range of ±5-6µm. The real difference however is the level of confidence in the measured data, because the error budget for the CNC machining centres and the CMM is different. The reliability of the measured results data
from the CMM (FERRANTI) is more due to the small error bars (±5μm) as compared to the two machining centres.

![Graphical comparison of measured diameter data from CMM, WADKIN and BRIDGEPORT](image)

Figure 5.5 Graphical comparison of measured diameter data from CMM, WADKIN and BRIDGEPORT

<table>
<thead>
<tr>
<th>Diameter of the hole feature (mm)</th>
<th>CMM</th>
<th>BRIDGEPORT</th>
<th>WADKIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.972</td>
<td>21.959</td>
<td>21.950</td>
<td></td>
</tr>
<tr>
<td>21.971</td>
<td>21.959</td>
<td>21.952</td>
<td></td>
</tr>
<tr>
<td>21.972</td>
<td>21.958</td>
<td>21.950</td>
<td></td>
</tr>
<tr>
<td>21.972</td>
<td>21.958</td>
<td>21.948</td>
<td></td>
</tr>
<tr>
<td>21.972</td>
<td>21.958</td>
<td>21.950</td>
<td></td>
</tr>
<tr>
<td>21.973</td>
<td>21.961</td>
<td>21.952</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean Value “A”</th>
<th>21.972</th>
<th>21.9602</th>
<th>21.951</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std Dev “σ”</td>
<td>0.00078</td>
<td>0.00157</td>
<td>0.00134</td>
</tr>
<tr>
<td>Mean Dev</td>
<td>0.00058</td>
<td>0.00140</td>
<td>0.0011</td>
</tr>
<tr>
<td>Repeatability “R”</td>
<td>0.0029</td>
<td>0.0061</td>
<td>0.0051</td>
</tr>
</tbody>
</table>

Table 5.6 Comparison of measurement data from diameter measurement CMM (FERRANTI), WADKIN and (BRIDGEPORT)
However the measured data from the BRIDGE PORT CNC machine tool also has small error bars (±6μm) and is more reliable than the measured data obtained from WADKIN CNC machine tool having larger error bars (±17μm) as shown in Figure 5.6 and figure 5.7(a, b). There is also a difference in the mean value of the data measured between the CMM and the two machining centres where the values from the BRIGEPORT are closer to that of the CMM (FERRANTI).

![Graphical for measurement results showing error bars on each point for CMM (FERRANTI)](image)

Figure 5.6 Graphical for measurement results showing error bars on each point for CMM (FERRANTI)
Figure 5.7 Graphical for measurement results showing error bars on each point for CNC machine tools (a) BRIDGEPORT and (b) WADKIN
Similar graphical trends regarding the variation of the measured inspection results exist between the three machines for other features. Table 4.7 shows the average values, standard deviations, mean deviations and repeatability of the measured data for the part and its dimensions across the three machines while the graphical comparisons and measured results data for the part and its features are given in appendix D.

<table>
<thead>
<tr>
<th>DIMENSION</th>
<th>CMM</th>
<th>BRIDGEPORT</th>
<th>WADKIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the part (mm)</td>
<td>Mean Value “A”</td>
<td>120.030</td>
<td>120.047</td>
</tr>
<tr>
<td></td>
<td>Std Dev “σ”</td>
<td>0.0006</td>
<td>0.0009</td>
</tr>
<tr>
<td></td>
<td>Mean Dev</td>
<td>0.0004</td>
<td>0.0007</td>
</tr>
<tr>
<td></td>
<td>Repeatability “R”</td>
<td>0.0021</td>
<td>0.0034</td>
</tr>
<tr>
<td>Width of the part (mm)</td>
<td>Mean Value “A”</td>
<td>100.036</td>
<td>100.026</td>
</tr>
<tr>
<td></td>
<td>Std Dev “σ”</td>
<td>0.0016</td>
<td>0.00061</td>
</tr>
<tr>
<td></td>
<td>Mean Dev</td>
<td>0.00091</td>
<td>0.00049</td>
</tr>
<tr>
<td></td>
<td>Repeatability “R”</td>
<td>0.0058</td>
<td>0.0023</td>
</tr>
<tr>
<td>Length of the pocket feature (mm)</td>
<td>Mean Value “A”</td>
<td>79.966</td>
<td>79.993</td>
</tr>
<tr>
<td></td>
<td>Std Dev “σ”</td>
<td>0.00107</td>
<td>0.00010</td>
</tr>
<tr>
<td></td>
<td>Mean Dev</td>
<td>0.00087</td>
<td>0.00064</td>
</tr>
<tr>
<td></td>
<td>Repeatability “R”</td>
<td>0.004</td>
<td>0.001</td>
</tr>
<tr>
<td>Width of the pocket feature (mm)</td>
<td>Mean Value “A”</td>
<td>49.995</td>
<td>49.959</td>
</tr>
<tr>
<td></td>
<td>Std Dev “σ”</td>
<td>0.0020</td>
<td>0.0005</td>
</tr>
<tr>
<td></td>
<td>Mean Dev</td>
<td>0.0017</td>
<td>0.00030</td>
</tr>
<tr>
<td></td>
<td>Repeatability “R”</td>
<td>0.0077</td>
<td>0.0017</td>
</tr>
<tr>
<td>Diameter of the hole feature (mm)</td>
<td>Mean Value “A”</td>
<td>21.972</td>
<td>21.960</td>
</tr>
<tr>
<td></td>
<td>Std Dev “σ”</td>
<td>0.0008</td>
<td>0.0016</td>
</tr>
<tr>
<td></td>
<td>Mean Dev</td>
<td>0.0006</td>
<td>0.0014</td>
</tr>
<tr>
<td></td>
<td>Repeatability “R”</td>
<td>0.0029</td>
<td>0.0061</td>
</tr>
</tbody>
</table>

Table 5.7 Comparison of measurement data from part and its features inspection on CMM (FERRANTI), WADKIN and (BRIDGEPORT)

5.6 Critique of inspection planning and accuracy

A part from example 1 in ISO14649-11 was inspected on two different CNC machine tools and it was then taken to a CMM and inspected there. Comparison of inspection process plans, inspection program, time of inspection, capabilities, accuracy of the
inspection resulting data between a CNC machine tool and a CMM were made. Based on these comparisons the following conclusions were reached.

i) The probing on the 1990’s CNC machining centre WADKIN for inspection only gives x, y, z coordinates position and does not give an output in the form of feature dimensions. The resulting dimensions are obtained by manual calculations which take time and are prone to errors.

ii) The measurement capabilities of BRIDGEPORT were more than WADKIN, also a direct output of the dimensional inspection result is available. However the measuring capabilities are limited when compared to that of the CMM e.g. the inner-fillet radii feature on the pocket corners or circularity of the hole feature on the part couldn’t be measured on the CNC machine tools (WADKIN or BRIDGEPORT).

iii) The inspection plans for the CNC machine tools and CMM’s were manually written and not generated by either the bespoke routines on a CNC machine tool and CMM or any standard based inspection program on the CMM.

iv) Analysis of the measured results showed that the results from BRIDGEPORT were closer to CMM results and more reliable than the results obtained from WADKIN. In case of WADKIN the inspection results are obtained by manual calculations hence the possibility of getting more erroneous results due to human error was more.

5.7 Summary

The bespoke inspection planning and procedures for a component were illustrated in this chapter by experimentation. This experimentation showed the different inspection plans used for dimensional inspection of the same component when inspected on different inspection machines (CNC machining centres or CMM).

Two different CNC machining centres and a CMM placed in the same environment were used in the experimentation. The issues highlighted were firstly the lack of
automation in the upfront inspection planning for dimensional inspection of a prismatic part. Also the inspection planning was bespoke and specific to each of the machine. Secondly it was shown that the measuring capabilities of the CNC machining centres are improving with time, as the state of the art CNC machining centre was more capable then the 1990s CNC machine tool. Thirdly the inspection results from the three machines were analysed and it was observed that though CNC machining centres have limited measuring capabilities, the BRIDGEPORT have improved accuracy and the dimensional results are more reliable.

Along the literature review in chapter 2 and 3, the issues highlighted by the experiment in this chapter supported the research scope defined in chapter 5.
Chapter 6

STEP-NC-COMPLIANT INSPECTION FRAMEWORK FOR DISCRETE COMPONENTS

6.1 Introduction

Based on the research scope outlined previously, this chapter presents an inspection framework for individual prismatic components that is STEP-NC compliant. It includes the concept of a framework which gives a generalised feature-based inspection and measurement plan for a prismatic part. This generalised STEP-NC compliant inspection plan could be a direct input to an intelligent controller of a CNC machining centre through an interface or can be interpreted into an inspection code for a CMM. The author in this research work has mapped the STEP-NC Compliant inspection plan manually on to inspection codes for CNC machining centres and a shop-floor CMM. The main parts of this framework include a Product information model and a Manufacturing/Inspection information model based on STEP and STEP-NC standards.

6.2 STEP-NC Compliant inspection framework for prismatic parts

Inspection planning for measuring a component on different measuring machines is currently different based on the measuring capabilities the bespoke inspection routines used in each case. Three scenarios were presented in the previous chapter for the current situation of component inspection as given below

(i) Inspection and measurement of a component on a state of the art coordinate measuring machine using vendor-specific inspection software.

(ii) Component inspection at a state of the art CNC machining centre using G and M codes for measuring part with a touch trigger probe.

(iii) Component inspection at a CNC machining centre with a state of the art CNC controller using built-in probing cycles for feature measurement.
The inspection planning of an individual component is different when measured on different machines. The basic purpose of the STEP-compliant inspection planning framework is to provide a generalised automated inspection plan. A major feature of this STEP-NC compliant framework for inspection planning of components is the inclusion of high-level and detailed information in terms of an inspection workplan, working-steps and a mechanism to feedback inspection results across the total CAx process chain. This has been achieved through the use of STEP-NC (ISO14649 part 10 & 16) and AP219 as the basis for representation of product and manufacturing/inspection models for the component (Ali et al 2005).

6.2.1 Objective and Function

The objective of the framework is to eliminate the need for a component’s inspection planning specific to the machine tool and generate a generalised interoperable inspection plan file. The functioning of the framework is illustrated by figure 6.1. This inspection plan generated is independent of the machine tool used for inspection of the part and the information included is:-

(i) Definition of the component
(ii) Measurement of the component
(iii) Method of measurement of the component

6.2.1.1 Definition of the component

A prismatic component to be inspected is first defined in terms of its geometry and main dimensions e.g. a raw material with its main dimensions (length, width etc.). The features present in the part are then specified using the definition of the manufacturing features in the STEPNC standard (ISO14649-10). The next step is to add geometric and dimensional tolerances to the main part as well as the individual features present in it.

6.2.1.2 Measurement of the component

The geometric elements to be inspected are specified as inspection items which include dimensions along with its dimensional tolerances, shape along with applied shape tolerances and reference dimensions from the inspection datum along with
position tolerances. The entity "inspection items" according to the STEP-NC standard definition

Figure 6.1 STEP-NC compliant framework for inspection of discrete components

provide storage for nominal data. It is divided into three categories namely tolerated dimension items, tolerated spanning dimension items and tolerated shape items.

The inspection items defined for the prismatic block describe the part's geometry including tolerated dimension items (its main dimensions along with dimensional tolerances), tolerated shape items (e.g. flatness of top surface) and tolerated pose
items (parallelism in x and y directions). Similarly inspection items in each individual feature are defined. All this information is provided by the STEP-compliant product information model (described in chapter 7).

6.2.1.3 Method of measurement of component

The STEP-compliant manufacturing and inspection information model utilise the inspection items information and define the inspection requirements for the part. It provides set up of the inspection datum which serves as a reference datum coordinate system for the feature’s inspection. It also provides the probing tool information e.g. touch trigger probe and separate probing workingsteps for the main part and each of the features present in it. These probing workingsteps include information on probing operations and the inspection items to be inspected. A number of probing workingsteps (depending on the number of features to be inspected) are combined together to define a workplan that includes probing workingsteps as executables.

A STEP-NC Compliant inspection plan is defined using the information from these two STEP-NC Compliant models and a generalised inspection plan file is generated. The inspection plan file follows the format of ISO10303-21, and includes statements defining nominal geometry, workplan, workingsteps etc. This file can be fed directly into an intelligent controller of a CNC machining centre having a STEP-NC interface for inspecting the part. It can also be interpreted into bespoke inspection code for a CNC machining centre or a Coordinate Measuring Machine.

The inspection process execution generates inspection results in the form of actual dimensions of the part and its features. The results are analysed for deviations from the nominal and can be fed back through a STEP-NC interface to update the STEP-NC compliant inspection file. In addition a separate results analysis report can be fed back for process control without using the STEP-NC format.

6.3 Characteristics of the STEP-NC Compliant inspection framework

The STEP-NC compliant inspection framework uses the object oriented data structure of ISO14649 for defining its entities and generating an inspection plan file. The activities of the framework are illustrated by figure 6.2. The main characteristics of the STEP-NC compliant inspection framework are as follows:
6.3.1 Defining the component using the STEP-NC standard information

The component to be inspected is defined by the Product information model (explained in detail in chapter 7) which defines the geometrical shape and dimensions.
of the part and its features, the geometric and dimensional tolerances, the items to be inspected and the reference datum for inspection. The main sources of the product information are ISO14649 part10 and ISO14649 part 16 with additional information that specifies feature-based inspection requirements.

### 6.3.1.1 Defining the part and its feature's geometric shape

The part is specified as an object using the definition of the workpiece as given in ISO14649-10 that has six attributes (four of which are optional) which defines:

(i) The workpiece identity namely its unique identification
(ii) The material of the workpiece
(iii) Its global tolerance which is valid when no other tolerances are specified
(iv) Its geometry i.e. an exact description of the final workpiece geometry according to ISO 10303-514
(v) Its bounding geometry might be defined as a box, a cylinder (as defined in ISO10303-42) or a geometry according to the definition of the entity advanced_brep_shape_representation (ISO10303-514).
(vi) Positions of the clamping device on the workpiece's surface.

For the purpose of inspection only three attributes are needed i.e. the identity of the workpiece, its global tolerance and its bounding geometry. For example a rectangular block with dimensions of length, width and depth. The features present in the part are also defined using the 2.5D manufacturing and transition features present in ISO14649-10, the maximum attributes required for inspection are:

(i) The feature identity as its unique identifier,
(ii) The parent workpiece to which the feature belongs, and
(iii) The shape characteristics of the feature

### 6.3.1.2 Specifying inspection requirements

The inspection requirements that include inspection items to be inspected associated with the part as well as its features, establishing a reference datum for inspection and the probing tool information are specified for the component.
(i) Defining STEP compliant inspection items:

Geometric and Dimension Tolerances as specified in ISO14649-16 are added to the main part such as plus/minus tolerances added to the main length of the block or parallelism in the x-direction to define its inspection items. Also Geometric and Dimension tolerances are added to each feature present in the part to define its inspection items e.g. plus/minus tolerance added to the diameter as a dimensional tolerance and the circularity of a round hole-feature. The tolerances specified in ISO14649-16 have three categories i.e. dimensional tolerance, applied shape tolerance and pose tolerance.

The dimension tolerance defines length measure or angle measure with upper and lower limits. The applied shape tolerance is given as straightness, flatness, circularity, cylindricity, shape of line or shape of the surface. The tolerances that come under the category of pose tolerance are angularity tolerance, circular runout tolerance, concentricity tolerance, parallelism tolerance, perpendicularity tolerance, position tolerance, symmetry tolerance, total runout tolerance.

The items for inspection associated with the part and each feature are specified according to the definitions provided for inspection items in ISO14649-16. The inspection items there are defined as toleranced dimension items or toleranced shape items with shape and dimensional tolerances e.g. length of the part with plus minus tolerance is the toleranced dimension item.

(ii) Establishing inspection datum and defining probing tool:

The inspection datum is the datum to which position of each feature to be inspected is referenced. The inspection datum axes and datum plane are established on the part for inspection according to the definition provided in ISO14649. It could be either of the two given below.

(a) Three orthogonal planes on three faces of the prismatic part defining an origin where these planes meet

(b) A plane e.g. top surface of the part, a line and a point.
The probing tool is a touch trigger probe having the length of its stylus and diameter of its spherical tip defined.

6.3.2 Generating a generic inspection plan

Based on the geometrical information of the part, its features and the specified inspection requirements are defined. In the STEP-NC standard (ISO14649-10 and 16) insufficient information is available for feature-based inspection, the missing information includes:-

(i) No separate inspection features defined
(ii) The number of inspection items for a feature to be inspected
(iii) Inability to specify that the probing workingstep is for a single feature or for a number of separate inspection items
(iv) No linkage is present between the inspection items and probing workingsteps in ISO14649-16 with the features defined in ISO14649-10

In the STEP-NC compliant inspection framework, there is a single probing workingstep for each of the feature present in the component and one additional probing workingstep for the main dimensions of the work piece. ISO14649-16 defines the inspection items but it does not specify the number of inspection items required for a single feature. Also in ISO14649-10 manufacturing features are defined which do not have inspection attributes with it. To remedy this the number of inspection items for each feature is determined by identifying the entities required to measure that feature e.g. to measure a rectangular closed pocket, the entities required are its length, width, depth and cornered fillet radii that are considered as its inspection items.

An inspection workplan is generated which contains executables i.e. probing workingsteps for the main part dimension and for each feature present in the part. The probing working step includes the probing operation and a list of inspection items where the number of inspection items depends on the feature to be inspected. The probing operation is user defined and has the probing tool e.g. touch probe
information, the probing strategy and reference datum information. Each inspection item refers to a result statement where the actual measured result is to be stored. An inspection workplan for a workpiece having "n" number of features is shown in Figure 6.3.

Figure 6.3 Inspection Workplan for workpiece having "n" number of features
6.3.2.1 Generating a STEP-NC compliant inspection file

All this information about workpiece and its features geometry and the inspection activities (workplan, probing workingsteps etc.) is combined to generate a STEP-NC Compliant inspection file for the component. The STEP-Compliant inspection file contains a "Header Section" and a "Data Section". The Header Section consists of the Project statement while the data section includes statements having information about the workpiece geometry, its features geometry, inspection items, tolerances, workplan, probing workingsteps, inspection reference datum, probing tool used etc. It also contains result statements which are updated with actual results after execution of the inspection operation at the machine tool. The STEP-NC Compliant inspection file for a hole feature inspection is explained in section 6.4.4.

6.3.3 Conversion of the STEP-Compliant inspection file into inspection code

The STEP-NC Compliant inspection file for a component can be converted into a specific inspection routine for a CNC machining centre for in-process measurement or a coordinate measuring machine ideally through a STEP-NC interface. The inspection results obtained at the end of the inspection process are analysed and can be fed back to update the STEP-NC Compliant inspection file. In this framework the direct mapping of a STEP-NC inspection file on a machine specific inspection code has been manually achieved. The principle of mapping is shown in figure 6.4, and is explained below:

The Workplan in STEP-NC inspection file has number of Probing workingsteps depending on the number of features to be measured. Each Probing workingstep in the STEP-NC file has a set of inspection items with an associated probing operation. The probing operation has its probing tool and refers to a reference datum setup. Each probing tool can be directly mapped on to each parameter for the touch trigger probe on measuring machine while the reference datum setup mapped onto the machine specific probing routine for setting up the datum coordinate system. The set of inspection items gives the parameters for the entities to be measured via machine specific inspection code. The probing operation can be directly mapped on to the machine specific probing routine for measuring the feature.
6.4 Generation a STEP-NC-compliant inspection file for a hole-feature

The working of the framework is demonstrated by generating a STEP-NC-compliant inspection plan file for an example feature such as a round hole and then converting it into a bespoke inspection code for a CNC machining centre. The round hole in a prismatic part with diameter D and tolerance t is to be inspected as shown in the
Figure 6.5. The hole feature is first defined by the STEP compliant product information model as follows:

6.4.1 Geometry of the hole feature

The hole feature is defined as an object with the following attributes

Its id: Hole feature 1

Its parent workpiece as a prismatic block (a rectangular block as shown in figure 6.5)

Its diameter as “D” and its centre axis as A1

![Diagram of hole feature]

Figure-6.5 Hole feature’s description

Let the workpiece in which the hole-feature lies is called as “workpiece 1” which belongs to a certain project “project 1”.

6.4.2 Inspection items defined

The tolerance “t” which specifies the tolerance zone is added to the diameter, So $D \pm t$ is the tolerated dimension item to be measured. $2t$ is the Tolerance zone having upper and lower of the hole diameter “D” as shown in figure 6.6. To simplify the example let the diameter of the hole feature $D = 22\text{mm}$ and the tolerance $t = 20\mu\text{m}$. 
An inspection datum is set-up which serves as a reference for the location of the hole feature. The datum plane P1 is established at top surface of the part and the datum coordinate system at one of its top corner as shown in Figure 6.7.

6.4.3 Defining probing workingsteps in a workplan

Interacting with the product information model, the manufacturing/inspection information model defines probing workingsteps. The probing workingstep for the inspecting the hole feature is defined having the following attributes:

- Its id: probingworkigstep1
- Its operation: probing operation1
- Its items: toleranced dimension item1
The probing operation refers to the reference inspection datum and it is user defined. A number of probing workingsteps are combined in a work plan and in this case there is only one probing workingstep i.e. probing workingstep 1 to inspect the hole-feature.

6.4.4 Generating inspection plan and conversion into inspection code

All these statements of hole-feature, its workpiece, inspection items inspection datum, workplan, workingsteps and probing tool information are combined in a structured way to produce a generic STEP-NC compliant inspection file as shown in Figure 6.8.

Figure 6.8 A STEP-NC-compliant inspection plan for a hole-feature generated by a prototype system developed by the author
The STEP-Compliant inspection file contains a list of statements beginning with a project statement as its header where each "# number" indicates another object and the $ sign stands for optional attribute or reference. The statements in the STEP-NC Compliant inspection file for the hole feature (shown in figure 6.7) contains a project statement, feature information, inspection requirement and planning data and inspection result statement. These statements are explained as follows:

(v) Project statement

The file starts with a project statement "#1" with project1 as its identification and contains the workplan and a list of workpieces (one in this example) denoted by "#11" and "#7" respectively.

(vi) Feature information data

The line statements #2, #3, #4, #5, #6 contains the information about the feature. "#2" defines the feature as a "ROUND HOLE" feature with 'Round hole 1 as its identification. #5 refers to the diameter of the hole, #3 indicates to the surface of the workpiece where the hole exists, #4 is the position of the axis of the hole, "#6" specify the bottom condition and #7 is the parent workpiece for the feature. #8, #9 and #10 specify the x, y and z coordinates, direction and reference direction of the hole axis position with identification as "A1" defined by #4. The tolerance applied to the diameter is a plus minus tolerance given by line #17 that refers to #5 which specifies the diameter as a tolerance length measure.

(vii) Inspection requirement and planning data for round hole

Workplan is defined by the statement in #11. Its id is given as "inspection of hole1" and it contains a list of working steps which in this case its only one probing working step for "hole1". #12 defines the probing working step with its identification as "inspect hole 1". It contains the security plane, the probing operation and the inspection items denoted by #13, #18 and #15 respectively. The probing operation has the identification as "measurement operation 1" and it refers to inspection datum #21, probing strategy (i.e. user defined) and probing tool used.
(viii) Inspection Results

#28 defines the inspection result statement which relates back to the probing working step. It contains the information about measured diameter value as a toleranced length measure. The tolerance length measure has optional attributes in #30, that can be updated with actual measured results.

A prototype system based on a Java platform is developed to generate the STEP-NC compliant inspection plan files for prismatic parts with regular features (discussed in chapter 8). It is object oriented and uses a library of classes based on ISO14649 schema.

The STEP-NC inspection file is interpreted into inspection code through manual mapping (shown in fig 6.9, 6.10 and 6.11) for hole-feature inspection on a three different machines i.e Bridgeport, Wadkin and CMM (the three machines are already described in chapter 5). Table 6.1 shows the manual mappings of the STEP-NC inspection file on to the machine specific code according to the principles given previously (section 6.3.3). The statements from the STEP-NC compliant inspection plan file that controls the inspection code is shown in Figure 6.9. The inspection results obtained are stored and interpreted back into the STEP-NC compliant format with actual inspection results.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>#20 to #27</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reference datum setup and Probing tool</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N10 T= Probe</td>
<td>N05 T= Set datum at corner</td>
<td>10 Rot_chr</td>
<td></td>
</tr>
<tr>
<td>N15 M19</td>
<td>N10 P87 =079 ! Y coordinate</td>
<td>20 Sel_tip(0.0)</td>
<td></td>
</tr>
<tr>
<td>N20 G0534X0Y0</td>
<td>N15 P86 =106 ! X coordinate</td>
<td>30 Speed(125.0000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N20 P85 =1 ! Corner type</td>
<td>40 Prbspd(10.0000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N25 P84 =15 ! Fixture offset number</td>
<td>50 Pos(2.5000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N30 (GSUB,TWDCOR)</td>
<td>60 Wkg_pln(&quot;XY&quot;)</td>
<td></td>
</tr>
<tr>
<td>#12 to #19</td>
<td>N0035(ID,PROG,TWDBOR,BORE-PROVEN,3D)</td>
<td>70 Seq(1)</td>
<td></td>
</tr>
<tr>
<td>Probing routine for measurement of the inspection items of hole-feature</td>
<td>N0040 ! Sets a datum to the centre-point of a bore and then N0045 ! probes the quadrant points to calculate their radii. N0050 P93 = 30 ! Safe rapid height N0055 P92 = 30 ! Probing length N0060 T01 M06 N0070 P91 =5 ! Z coordinate N0080 P87 =156 ! Y coordinate N0090 P85 =165 ! X coordinate N0100 P84 =11 ! Radius N0110 P84 =15 ! Fixture offset number N0120 (GSUB,TWDBOR) N0130 E(P84) N0140 P92=P85+10 !Reassign probing length N0150 ! Probe first radius N0160 P90 = 0 ! Y coordinate N0170 P89 = 0 ! X coordinate N0180 P88 = -1 ! -X direction N0190 (GSUB,TWDPX) N0200 P70 = P89 +X result N0210 ! Probe second radius N0220 P90 = 0 ! Y coordinate</td>
<td>80 Locate 180 Meas(&quot;Circle 1&quot;,&quot;HOLE&quot;)</td>
<td></td>
</tr>
<tr>
<td>N35 R26= 10 R9=3000</td>
<td>N0230 P90 = 0 ! X coordinate N0240 P88 = 1 ! +X direction N0250 (GSUB,TWDPX) N0260 P71 = P89 -X result N0270 ! Probe third radius N0280 P90=0 ! Y coordinate N0290 P89 = 0 ! X coordinate N0300 P88 = -1 ! -Y direction N0310 (GSUB,TWDPY) N0320 P72 = P90 +Y result N0330 ! Probe fourth radius N0340 P90 = 0 ! Y coordinate N0350 P89 = 0 ! X coordinate N0360 P88 = 1 ! +Y direction N0370 (GSUB,TWDPY) N0380 P73 = P90 +Y result N0390 (DSP,8.25,THE RADII OF THIS BORE ARE : ) N0400 (DSP,10.32,+X : (P70)8.3mm N0410 (DSP,11.32,-X : (P71)8.3mm N0420 (DSP,12.32,+Y : (P72)8.3mm N0430 (DSP,13.32,-Y : (P73)8.3mm N0440 (DSP,14.32,THE : (P74)8.3mm) N0450 M30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N40 L9810</td>
<td>N0230 P90 = 0 ! X coordinate</td>
<td>110 Level(&quot;P 1&quot;)</td>
<td></td>
</tr>
<tr>
<td>N45 L9800</td>
<td>N0240 P88 = 1 ! +X direction N0250 (GSUB,TWDPX) N0260 P71 = P89 -X result</td>
<td>120 Master(&quot;Z&quot;)</td>
<td></td>
</tr>
<tr>
<td>N50 R7=22 R11=0.02 R23=1</td>
<td>N0270 ! Probe third radius N0280 P90=0 ! Y coordinate N0290 P89 = 0 ! X coordinate</td>
<td>130 Meas(&quot;Line&quot;)</td>
<td></td>
</tr>
<tr>
<td>N55 L9814</td>
<td>N0300 P88 = -1 ! -Y direction N0310 (GSUB,TWDPY) N0320 P72 = P90 +Y result</td>
<td>140 Align(0,&quot;L 1&quot;)</td>
<td></td>
</tr>
<tr>
<td>N60 L9800</td>
<td>N0330 ! Probe fourth radius N0340 P90 = 0 ! Y coordinate N0350 P89 = 0 ! X coordinate</td>
<td>150 Master(&quot;Y&quot;)</td>
<td></td>
</tr>
<tr>
<td>N65 R26=20</td>
<td>N0360 P88 = 1 ! +Y direction N0370 (GSUB,TWDPY) N0380 P73 = P90 +Y result</td>
<td>160 Meas(&quot;Line&quot;)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0390 (DSP,8.25,THE RADII OF THIS BORE ARE : ) N0400 (DSP,10.32,+X : (P70)8.3mm N0410 (DSP,11.32,-X : (P71)8.3mm N0420 (DSP,12.32,+Y : (P72)8.3mm N0430 (DSP,13.32,-Y : (P73)8.3mm N0440 (DSP,14.32,THE : (P74)8.3mm)</td>
<td>170 Master(&quot;X&quot;)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0450 M30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0060 T01 M06</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0070 P91 =5 ! Z coordinate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0080 P87 =156 ! Y coordinate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0090 P85 =165 ! X coordinate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0100 P84 =11 ! Radius</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0110 P84 =15 ! Fixture offset number</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0120 (GSUB,TWDBOR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0130 E(P84)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0140 P92=P85+10 !Reassign probing length</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0150 ! Probe first radius</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0160 P90 = 0 ! Y coordinate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0170 P89 = 0 ! X coordinate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0180 P88 = -1 ! -X direction</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0190 (GSUB,TWDPX)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0200 P70 = P89 +X result</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0210 ! Probe second radius</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>N0220 P90 = 0 ! Y coordinate</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6.1 Manual mapping of the STEP-NC-compliant inspection plan onto the inspection code for two CNC machining centres and a CMM
Figure 6.9 Manual mapping of the STEP-NC-compliant inspection plan onto the inspection code for 3-axis CNC machining centre (Bridgeport with Siemens controller having SHOPMILL interface)
Diameter of the Hole
N0035(ID,PROG,TWDBOR,BORE-PROVEN,3D)
N0040 ! Sets a datum to the centrepoint of a bore and then
N0045 ! probes the quadrant points to calculate their radii.
N0050 P93 = 30 ! Safe rapid height
N0055 P92 = 30 ! Probing length
I
N0060 TO1 M06
NOO70 P91 = 5 ! Z coordinate
N0080 P87 = 079 ! Y coordinate
N0090 P86 = 106 ! X coordinate
N100 P85 = 11 ! Radius
N101 P84 = 15 ! Fixture offset number
N110 (GSUB,TWDBOR)
N120 E(P84)
N130 P92 = P85 + 10 ! Reassign probing length
N140 P87 = 079 ! Y coordinate
N150 P86 = 106 ! X coordinate
N160 P85 = 11 ! Fixture offset number
N170 (GSUB,TWDBOR)
N180 P70 = P89 ! + X result
N190 P88 = -1 ! -X direction
N200 (GSUB,TWDPX)
N210 P71 = P89 ! + Y result
N220 P87 = 156 ! Y coordinate
N230 P86 = 165 ! X coordinate
N240 P85 = 1 ! Corner type
N250 P84 = 15 ! Fixture offset number
N260 (GSUB,TWDPY)
N270 P90 = 0 ! Y coordinate
N280 P90 = 0 ! Y coordinate
N290 P88 = 1 ! + Y direction
N300 (GSUB,TWDPY)
N310 P90 = 8.3 mm
N320 (DSP,10,32,-Y: P72) 8.3 mm
N330 (DSP,11,32,+Y: P71) 8.3 mm
N340 (DSP,12,32,+X: P70) 8.3 mm
N350 (DSP,13,32,-X: P73) 8.3 mm
N360 DO M06
N370 M30
N9999 (END,PROG)

Figure 6.10 Manual mapping of the STEP-NC-compliant inspection plan onto the inspection code for 3-axis CNC machining centre (WADKIN with FANUC controller)
Figure 6.11 Manual mapping of the STEP-NC-compliant inspection plan onto the inspection code for a Shop-floor CMM (Ferrantti)
6.5 Critique

The STEP-NC Compliant inspection framework provides inspection information for individual prismatic parts i.e. generic and interoperable. However it has a few limitations these are:-

(i) Firstly it is only feasible for prismatic parts with simple features having regular geometry e.g. cylindrical, conical, rectangular or angular blocks etc. The reason being that for regular features general measuring entities can be defined

(ii) Secondly it is developed using basic information in ISO14649-16, therefore is useful only for inspection of touch trigger probes and is not applicable to non-contact probes. As in Part 16 all the measuring operations for feature-based inspection are defined with respect to touch trigger probes

(iii) Thirdly the inspection items for profiled features or complex sculptured surfaces are not defined in this framework. The reason is that defining general measuring entities for a profile feature or a 3-D complex surface is difficult. For example a profile feature will have measuring entities specific to its shape.

(iv) The output inspection file generated by this framework consists of empty result statements which are later updated with actual results. However, the nature of actual measured results is not defined, e.g. it can be mean values of the entity measured (as shown in chapter 8).

6.6 Summary

In this chapter the concept and functionality of the STEP-compliant inspection framework were discussed. The main objective of the framework is to prove the feasibility of STEPNC standard in generating a generic inspection plan for inspection of discrete components. The main characteristics of the framework include defining of the component and features, inspection requirements, generating a generalised inspection plan and interpreting it into an inspection code.
The component information is provided by the product information model. Interacting with this model the manufacturing and inspection model describes inspection items, inspection datum information, probing workingsteps that combines in a workplan and probing tool information. A STEP-NC compliant file for generalised inspection planning of the component is generated. This file is then interpreted by manually mapping it into an inspection code for a CNC machine or a CMM with the measurements of inspection items the results being added to the file.

The functioning of the framework was demonstrated by inspecting the diameter of a hole feature with plus minus tolerance. The sources of information used were based on ISO14649 (part 10 and 16) with additional information (to overcome its limitations) such as defining one probing workingstep for each feature and the list of inspection items for each feature were defined to realise this framework. The major limitations of this framework is that it is applicable to 2 1/2 D prismatic components and not for parts having sculptured or profile features.
Chapter 7

STEP-NC COMPLIANT INFORMATION MODELS FOR INSPECTION OF DISCRETE PARTS

7.1 Introduction

This chapter describes the two information models that support STEP-NC compliant framework for inspection of prismatic parts. The information models i.e. the product information model and the manufacturing/inspection information model are based on the STEP-NC (ISO14649 part 10&16) and additional information from ISO10303.

7.2 Product and manufacturing information modelling

Product and Manufacturing information models have been previously presented by many researchers. The work most related to this research includes a feature-based modeller proposed by Patel where the FBM captures the geometrical knowledge of prismatic part and features and the related process planning for the CNC machine is generated by an automated process planner (Patel and Pande, 2002). Other such work consists of the information modelling by Amaitik (Amaitik and Kilic 2005) to integrate design with manufacturing and by Molina at enterprise level (Molina and Bell, 2002) or the information models using combination of IDEFO and UML methodologies presented by Dorador (Dorador and Young, 2000).

Though the UML methodology has been used, the difference between the author’s information models and the previously presented models is that it only focuses on product data and its inspection requirements for an individual component. The product information model provides the geometric and tolerance information about the part and interacting with it the inspection knowledge is provided by the manufacturing/inspection information model. The object oriented UML approach has been used by the author to model the product information and its related inspection requirements.

7.3 STEP-NC Compliant information models for prismatic parts

STEP-NC provides a source of standard structured information regarding product, general manufacturing process, machining and measurement data etc. In this context
the author has proposed a product information model for a component and an inspection information model based on ISO14649-10 and ISO14649-16 as shown in figure 7.1. The STEP-compliant product model for a component defines the following:

(i) Geometric information of the part and its features
(ii) Tolerances information
(iii) Inspection items associated with the part and its features

Figure 7.1 STEP-Compliant Product Information Model for a prismatic component
7.3.1 Geometric information of the part and its features

The geometric information of the part includes its shape and its dimensions where the definitions and terminology are provided in ISO10303 that is used in ISO14649 part 10 e.g. to specify a block shape "block" is used in ISO14649 part 10 referenced from ISO10303-42. The features in this model are specified using the 2½ D manufacturing features and the transition features in ISO14649-10 that closely resembles the features provided in ISO10303-224.

The tolerances are specified according to the definitions in ISO14649-16 and are categorised as

(i) dimension tolerances that include a tolerance zone with upper and lower limits for length measure and angle measure

(ii) Applied shape tolerances that include straightness, flatness, circularity, cylindricity

(iii) Pose tolerances that include parallelism tolerance, perpendicularity tolerance

7.3.2 Inspection items

The inspection item are entities defined in ISO14649-16 that acts as a container to attach tolerances to geometric elements and store the inspection results. These tolerated elements can be attributes of features (e.g. diameter of a round hole), relations within one feature (e.g. distance between two sides of a pocket) or relations between two different items (e.g. distance of the centerline of two holes, perpendicularly of a hole towards a plane).

In this information model the part is specified as the workpiece along with its attribute defining its shape that is adapted from ISO14649 part 10. For measurement tolerances are added to its main dimensions to specify the inspection items associated with it which are given as follows:-
(i) toleranced _dimension_items:
This includes length, width, depth of the workpiece with dimensional
tolerances having upper and lower limits

(ii) toleranced_pose_items:
This includes parallelism in x-direction and parallelism in y direction

The 2½ D manufacturing features are divided into machining features, replicate
features and compound features. The features defined in the product information
model are machining features defined in ISO14649-10. Though these are used for
feature based 2½ D machining, the same are used in this model for inspection. The
reason is that for inspection the inspection items are associated with the necessary
attributes of the machining features already defined. It includes the following
features:-

(i) Pocket
(ii) Round hole
(iii) Slot
(iv) Step

The transition features include:-
(i) Edge round
(ii) Chamfer

7.3.2.1 Pocket feature

The general pocket feature of ISO14649-10 is a sub-type of machining feature that is
further subdivided into closed pockets and open pockets. For machining purposes it
is defined by its contour on the outer face of the workpiece and its depth. It may
have one or two bosses and is defined as a class with the following attributes:

(i) Its_bosses: This indicates the optional list of bosses that is not cut during
the machining of the pocket.
(ii) Its slope: its an optional attribute that specify the slope of the pocket i.e. angle of its border with respect to the local z-axis

(iii) Bottom condition: shows a number of bottom conditions e.g. a flat bottom or a spherical bottom surface.

(iv) planar_radius and orthogonal radius: optional attributes that specify the fillet radii if it exists in the pocket

(v) Its feature boundary: For close pockets the feature boundary is a close profile while for an open pocket its an open profile. The profile in each case lies in the local xy plane and is not self intersecting.

The only attributes required for the purpose of inspection of the closed pocket is its bottom condition with other optional attributes of slope and fillet radii. The geometric elements to be measured for a general pocket feature are, its length, its width, its depth, radii of the fillet (if fillet corners exist), slope angle (if slope exists), flatness of the bottom surface and parallelisms in x-axis and y-axis. The tolerance information is added to each of these elements in order to define the inspection items are given in ISO14649-16 and are as follows:

(i) toleranced_dimension_items:
   a. Length, width, depth of the pocket with dimensional tolerances having upper and lower limits
   b. Radii of the fillet (if exists) corners dimensional tolerance having upper and lower limits
   c. Slope angle (if exists) with dimensional tolerance having upper and lower limits

(ii) toleranced_shape_items:
   a. flatness of the bottom surface

(iii) toleranced_pose_items:
   a. parallelism in x-direction
b. parallelism in y direction

7.3.2.2 Round hole feature

This entity defines both holes and threaded holes in ISO14649-10. The product information model only represents holes, the feature_placement of the hole is its center in the local xy plane and its depth is in -ve z direction. Its a subtype of machining feature and its attributes include:

(i) its diameter  
(ii) feature_placement  
(iii) Change in diameter that is optional and used for tapered holes 
(iv) Bottom_condition for blind holes.

The geometric elements to be measured for a round hole feature are its diameter, its circularity, the cylindricity of its internal surface, its depth (for blind holes) and its taper angle for tapered holes or change in diameter . The tolerance information is added to each these items in order to define the inspection items as given in ISO14649-16 and are as follows:

(i) tolerated_dimension_items:
   a. Diameter of the hole with dimensional tolerances having upper and lower limits  
   b. Depth of the hole (for blind holes) with dimensional tolerance having upper and lower limits 
   c. Taper angle (for tapered holes) or change in diameter with dimensional tolerance having upper and lower limits 

(ii) tolerated_shape_items:
   a. Circularity of the round hole 
   b. Cylindricity of the round hole 

7.3.2.3 Slot feature

Slot is a subtype of machining feature with the attributes that include:
(i) its course_of_travel that describes the location and extension of the slot
(ii) its swept_shape to define its cross-section area
(iii) its end conditions.

The geometric elements be measured for a slot feature its width, its depth, angle measure, radii etc. Its associated inspection items include

(i) tolerated_dimension_items:
   a. width of the slot with dimensional tolerances having upper and lower limits
   b. corner radii (flat slot end type) with dimensional tolerances having upper and lower limits
   c. End radius (end radius type) with dimensional tolerance having upper and lower limits
   d. End bottom radius (Woodruff slot end type) with dimensional tolerance having upper and lower limits

7.3.2.4 Step feature

A step feature is subtype of machining feature and is created by machining a volume from top and sides of the workpiece. Like an open pocket, its contour is open to its sides and its attributes for machining include:

(i) its open boundary
(ii) its set of bosses if present

The geometric elements to be measured in a step feature are its depth and the angle between the two surfaces defining it. Its associated inspection items include:-

(i) tolerated_dimension_items:
   a. Depth of the step with dimensional tolerance having upper and lower limits
   b. Angle between its two surfaces with dimensional tolerance having upper and lower limits

108
7.3.2.5 Transition features

A transition feature consists of an edge round or a chamfer, both of these are defined as entities edge_round and chamfer in ISO14649 that maps on to the definition provided in AP219. Chamfer is a transition between to corresponding edges and its attributes include:

(i) the angle to one of the plane
(ii) its offset distance.

The inspection items associated with the chamfer feature are:

(i) tolerated_dimension items
   a. angle to one of the face with upper and lower tolerance limits
   b. offset from one plane with upper and lower tolerance limits

The edge round is an outer fillet specified by attributes that include:

(i) its radius
(ii) its two offsets.

The inspection items associated with the edge_round are

(i) tolerated_dimension items
   a. radius with upper and lower tolerance limits
   b. offset from first face with upper and lower tolerance limits
   c. offset from second face with upper and lower limits

7.4 STEP-compliant manufacturing and inspection information model

The manufacturing & inspection model includes set-up information, Machining and tooling information and Inspection information for individual components. This model is concerned with the inspection information and describes the part of information which can be added to the component which already has the setup and machining information as shown in figure 7.2 and it includes
(i) Inspection process information
   a. Inspection datum setup
   b. Probing working steps

(ii) Probing tool information
   a. Touch probe
   b. Tool probe

Figure 7.2 STEP-Compliant Manufacturing / Inspection information Model
7.4.1 Inspection process and tooling information

The inspection items from the product model are used in the manufacturing/inspection model to add inspection process information which includes

(i) Inspection datum setup
(ii) Inspection activities
(iii) Probing tool

7.4.1.1 Inspection datum setup

An inspection datum is setup on the part to which the all the inspection measurement of the part and its feature can be related. ISO14649-16 defines an entity as reference_datum_setup for inspection related activities. This entity is further subdivided into two classes

(i) plane_line_point_reference_datum_setup is specified by its origin, a datum plane a line and a point to establish the datum coordinate system

(ii) reference_datum_setup_3planes is specified by its origin and three orthogonal planes that meet at the origin to establish the datum coordinate system

7.4.1.2 Inspection activities

Separate probing workingsteps are defined for the inspection of the work piece and each of the features present within it. The entity probing workingstep is an executable given in ISO14649-16 that defines a probing activity. It is a subtype of touch_probing which in turn is a subtype of workingstep (referred from ISO14649-10). Its attributes include a set of inspection items, its security plane and its probing operation. For example the Probing workingstep for a round hole feature has the following inspection items:

(i) its diameter with tolerance as its tolerance dimension item
(ii) its circularity as tolerated shape item and
(iii) its cylindricity as its tolerated shape item.

7.4.1.3 Probing tool

The probing tool used for probing operation is a touch trigger probe either on a CNC machining center or a CMM. It is defined as entity probing_tool in ISO14649 and is a subtype of another entity touch probe. Its attribute includes its fixture dimensions, its body dimensions and its stylus dimension.

7.5 UML Representation of the product and inspection information models

UML class diagrams have been used in Object store i.e. a database management system to represent the structure of the product information model and manufacturing/inspection model as shown in figure 7.3. The data structure is primarily based on ISO14649 part10 and part 16 standards where the entities are defined as classes with attributes. The newly added information in the authors UML model is the link between feature and its associated items, as the probing workingsteps for a particular feature contains its associated items. In figure 7.3 Project is defined as a parent class (ISO14649-10) which contains the information about the workpieces, main work plan (that include machining workplans and inspection workplans).

The product model is defined by classes using the definitions for part and its geometry in ISO14649-10 and ISO10303. Separate class for inspection items is created in the product model related to the geometric elements of the part and each of the feature. The inspection activities are defined in the manufacturing information model. Probing workingsteps for inspection are defined based on ISO14649-16 information. Each probing workingstep has inspection items related to the work piece and every feature present within it. It also specifies the probing operation for measurement of the inspection items. The probing operation refers to an inspection datum which is defined as a class. All these probing workingsteps are combined in the workplan for inspection. Inspection result entities are defined as classes (ISO14649-16), these classes relates to the probing workingsteps and acts as storage of actual results. For example Inspection Result has additional attribute like length_measure, that can be the actual measured length of the part.
Figure 7.3 UML representation of the STEP-Compliant information models in the inspection framework for prismatic parts
7.6 Summary

The STEP-compliant information models that support the inspection framework for prismatic parts were presented in this chapter. The STEP-compliant product information model provided the geometric information of the individual part and its features and the tolerances information. The features were specified according to the definitions provided by the ISO14649 for 2¾ D manufacturing and transition features. These include features such as round hole, general pocket, slot, step, edge round and chamfer. The tolerances information (dimensional, applied shape and pose) is added to the geometric elements to define inspection items as specified in ISO14649-10 associated with the part and each of its features.

Based on the inspection items defined the manufacturing/information model provides the inspection process information. It includes defining separate probing workingsteps for the part and each of its features that are combined in a workplan as executables and the probing tool information (using ISO14649-10 & 16).
CHAPTER 8
VALIDATION OF THE STEP-COMPLIANT INSPECTION FRAMEWORK
FOR DISCRETE COMPONENTS

8.1 Introduction
This chapter presents the validation of the STEP-NC Compliant inspection framework discussed in chapter 6 with three test cases. A prototype system based on Java is developed that automatically generates STEP-NC-Compliant inspection file for feature-based inspection. For two of the test cases generic inspection plans were generated showing the functioning of the prototype system for STEP-NC compliant inspection. The third test piece is an example part from ISO14649-11 (used in experimentation in chapter 4), it is used as a case study to compare the STEP-NC compliant inspection planning and programming with the conventional approach (given in chapter 5).

8.2 Prototype IT system for generating STEP-NC-Compliant inspection plan
To implement the STEP-compliant framework for inspection a prototype system is developed using Java platform to generate STEP-NC-compliant inspection plan files for prismatic parts with simple features. The java platform provides an object oriented environment that contains a library of classes based on ISO14649 schema. The input to the system is the dimensions and tolerances information of the part and its features and the output is a STEP-NC-compliant inspection plan file as shown in Figure 8.1.

This file is in ISO10303-21 format and consists of statements containing part and its features geometric information, geometrical and dimensional tolerance information, workplan, probing workingsteps for part and each of the features present and inspection results statement. This STEP-NC compliant inspection plan file is mapped on to an inspection code for part measurements or could be automatically interpreted into inspection code for the machine using a STEP-NC interface. The inspection results after the inspection operation are analysed and are used to update the STEP-NC file with inspection result statements containing actual measured dimensions.
Figure 8.1 Output STEP-NC inspection plan generated by the prototype inspection system
8.2.1 Defining the header statement in the inspection plan

The inspection file generated starts with defining a project in the header statement as shown in Figure 8.2. This project statement includes the information about the main workplan, the set of workpieces and other optional attributes such as the date of the project, the name of the person etc. (As defined in ISO14649 part10). The statement refers to a PROJECT entity that has its identifier defined as a STRING and it includes the inspection WORKPLAN and the WORKPIECE classes.

```
#1=PROJECT('Project1',#6,(#2),$,,$);
```

![Diagram showing the definition of a project](image)

Figure 8.2 Dialog in the prototype system showing the input parameters i.e. project ID, workplan ID and workpiece information

8.2.2 Defining the Workpiece and its features

The geometric shape of the workpiece is prismatic i.e a rectangular block shape. It is defined as a ‘WORKPIECE’ class and its shape is defined by another “BLOCK” class
with its attributes of length, width and depth dimensions. The name of the workpiece is given as "its id" and this associates the workpiece with the attributes of the rectangular block. Geometric shape of each feature, its dimension description and its placement with reference to the inspection datum plane is given by the statement showing the feature class for example the rectangular closed pocket feature. Each of the feature is defined as a separate class in the ISO14649 library. Tolerance information is added to define the inspection items for the workpiece as well as the feature to be inspected as shown in Figure 8.3.

![Figure 8.3 Adding dimensional tolerance to the workpiece dimensions](image)

The inspection items are divided into toleranced dimension item, toleranced shape item and toleranced pose item. The inspection items associated with the workpiece are defined as follows:

(i) Nominal length of the workpiece with dimensional tolerance is specified as an entity that belong to a class called “toleranced dimension item”.

(ii) Nominal width of the workpiece with dimensional tolerance is also defined as another toleranced dimension item entity
In a similar manner the inspection items associated with each feature are defined e.g.
the inspection items with a round hole feature are as follows:-

(i) Nominal diameter of the round hole is specified as an entity that belongs to
toleranced dimension item class

(ii) Circularity of the hole defines the form of the hole with entity belonging to
the toleranced shape item class

(iii) Cylindricity of the hole defines the cylindrical form of the hole feature and
the entity belongs to the toleranced shape item

8.2.3 Generating inspection plan

An inspection datum is setup at the part and the position of each feature is defined
relative to this reference datum. This datum is defined by the entity reference datum
setup. The inspection plan file that contains the project in the header statement,
specification of the part and its features, its inspection items, workplan, probing
workingsteps etc. is generated as shown in Figure 8.4
The STEP-compliant inspection plan is generalised and the prototype system can generate inspection plan file for any size workpiece and any size features present in it (Currently it is implemented for closed pocket and round hole features). Inspection file generation for two example test parts are given as follows:

8.2.3.1 Test case 1

The first test case is an example part that is a rectangular block (120x100x50) with a closed pocket feature (80x50x30) shown in figure 8.5. A reference coordinate system is established at the bottom right corner that serves as the inspection datum. The tolerances specified on the part are dimensional tolerances (all the values of the tolerances are supposed).

![Figure 8.5 Test piece 1: Prismatic component for Test case1](image-url)
The input to the prototype system is the project name, workpiece id, workplan plan id, dimensions and dimensional tolerances of the workpiece, closed pocket feature dimensions along with its tolerances and its position relative to the reference coordinate system as shown in Figure 8.6.

![Figure 8.6 Input parameters to the prototype system for the workpiece and the closed pocket feature.](image)
The output generated is a STEP-NC-Compliant inspection file in ISO10303-21 format.

The inspection file is shown in figure 8.7 and is described as follows:

```
#1=PROJECT('Project1',#5,(#2),($,$,$));
#2=WORKPIECE('workpiece1',#3,($,$,$));
#3=BLOCK('Rectangular block',#1,120.0,100.0,50.0);
#4=CLOSED_POCKET('closed pocket feature',#5,(#6),($,$,$));
#5=WORKPLAN('workplan1',(#7,#6),($,$,$));
#6=PROBING_WORKINGSTEP('closed pocket',#40,#23,(#10,#11,#12,#13,#14));
#7=PROBING_WORKINGSTEP('workpiece block',#40,#23,(#8,#9,#$,$));
#8=TOLERANCED_DIMENSION_ITEM(Length of workpiece,#38,#32,#3,$);
#9=TOLERANCED_DIMENSION_ITEM(Workpiece width,#45,#33,#3,$);
#10=TOLERANCED_DIMENSION_ITEM(Length of pocket,#46,#15,#4,$);
#11=TOLERANCED_DIMENSION_ITEM(Width of pocket,#47,#16,#4,$);
#12=TOLERANCED_DIMENSION_ITEM(Depth of pocket,#48,#17,#4,$);
#13=TOLERANCED_POSE_ITEM(parallelism x,#49,#21);
#14=TOLERANCED_POSE_ITEM(parallelism y,#50,#4,$);
#15=TOLERANCED_LENGTH_MEASURE(80.0,#18);
#16=TOLERANCED_LENGTH_MEASURE(50.0,#19);
#17=TOLERANCED_LENGTH_MEASURE(30.0,#20);
#18=PLUS_MINUS_VALUE(80.01,79.99,4);
#19=PLUS_MINUS_VALUE(50.01,49.99,4);
#20=PLUS_MINUS_VALUE(30.01,29.99,4);
#21=PARALLELISM_TOLERANCE(0.0050,#28,#$);
#22=PARALLELISM_TOLERANCE(0.0050,#28,#$);
#23=PROBING_OPERATION('probe closed pocket',#24,#25,#26);
#24=REFERENCE_DATUM_SETUP(#27);
#25=PROBING_STRATEGY('user defined');
#26=TOUCH_PROBE('touch trigger probe');
#27=AXIS2_ORIENTATION_3D('ref datum origin',#29,#30,#31);
#28=PLANE('z axis');
#29=CARTESIAN_POINT('ref datum origin location',#31,#32,#33,#34,#35,#36,#37,#38,#39,#40,#41,#42,#43,#44,#45,#46,#47,#48,#49,#50,#51)
```

Figure 8.7 STEP-NC compliant inspection file for Test piece1
The file starts with a header statement that shows the project name i.e. project1 and includes the inspection workplan and single workpiece. Each number in the line refers to another object e.g. #5 refers to workplan and #2 to the workpiece while the $ sign shows optional attributes. The workplan consists of the executables which are two probing workingsteps i.e. one for measuring the workpiece main dimensions and other for the closed pocket feature as given in line #7 and #6.

These probing workingsteps have their id defined as a STRING and contains the security plane and the list of inspection items e.g. in the closed pocket probing workingstep #23 refers to the security plane defined and (#10,#11,#12,#13,#14) refers to the list of inspection items. The inspection items show the nominal values with tolerances.

The probing workingsteps refers to the probing operation line that has the reference datum setup and the probing tool information. The result statements at the end refer to the respective probing workingstep act as storage for the actual measured results that update the file.

8.2.3.2 Test case 2

The second test case include an example part that is a rectangular block (120x100x50) with a hole feature of diameter 22mm shown in figure 8.8. A reference coordinate system is established at the bottom left corner that as the inspection datum. All the dimensions are in millimetres and and all the dimension tolerances specified have supposed values. The input to the prototype system is the project name, workpiece id, workplan plan id, workpiece dimensions, dimension tolerances of the workpiece, round hole feature dimensions and tolerances and its position relative to the reference coordinate system as shown in Figure 8.9.

The output generated is a STEP-NC-Compliant inspection file in ISO10303-21 format for the workpiece2 that is similar to the one shown for test case 1. Though it has different inspection items and shape tolerances defined for the hole feature and is given as Figure 8.10
A case study in the next section shows the functioning of the STEP-Compliant inspection framework from automated generalised inspection plan, its translation into an inspection code for a CNC machine tool and execution of the code to obtain inspection results.

Figure 8.8 Test piece 1: Prismatic component for Test case 1
Figure 8.9 Input parameters to the prototype system for the workpiece and the hole pocket feature.
The file contains a STEP-NC compliant inspection file for Test piece2, as shown in Figure 8.11. All dimensions are in millimetres and dimensional tolerances of ±0.01mm (supposed value) are specified.

8.3 Case study

This case study involves the inspection of an example part from ISO14649-11 (used in experimentation in chapter 4) as shown in Figure 8.11. All the dimensions are in millimetres and dimensional tolerances of ±0.01mm (supposed value) are specified.
Figure 8.11 Test piece 3: Example part from (ISO14649-11)

A STEP-Compliant inspection plan was generated for test part. The file was interpreted into inspection code for a 3-axis CNC machine tool (Bridgeport machining centre with new intelligent controller) where it was inspected. The entities measured in the part included

(i) Length of the workpiece  
(ii) Width of the workpiece  
(iii) Length of the pocket  
(iv) Width of the pocket  
(v) Diameter of the hole  
(vi) Position of the hole

All the nominal dimension values were input to the prototype system along with the associated tolerance limits as shown in Figure 8.12.
The STEP-NC compliant file generated (shown in Figure 8.13) was interpreted by manually mapping it onto an inspection code for the controller on the CNC machining centre (BRIGEPORT). The measured results (given in Appendix E) after the inspection execution were stored as a text file.
Figure 8.13 STEP-NC-Compliant inspection file generated for the example part
8.3.1 Comparison with conventional approach:

The same part has been inspected using contemporary inspection procedures on three
different machines (previously explained in detail in chapter 5) and different bespoke
inspection planning was used to inspect the part in each case. The same inspection code
for the Bridgeport was created using primitive inspection planning manually as shown
in Table 8.1.

### Plan for part inspection on a 3-axis CNC machining Centre Bridgeport

(840D Seimen's controller with SHPMILL)

<table>
<thead>
<tr>
<th>Stylus Selection (touch trigger probe)</th>
<th>Environment (machine table)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of stylus 6mm</td>
<td>Temperature of the part: Room Temperature</td>
</tr>
<tr>
<td>Length of stylus 30mm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>S-No.</th>
<th>Items</th>
<th>Measurement</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Part orientation</td>
<td>Inspection datum</td>
<td>Establishing z-datum and coordinate system at the centre of the part z-surface measure on top surface using built-in subroutine L9811 for single surface measurement</td>
</tr>
<tr>
<td>2.</td>
<td>Dimensions of the block: Length of the part and width of the part</td>
<td>Length dimension</td>
<td>Length measurements using built-in routine L9812 for web measurement</td>
</tr>
<tr>
<td>3.</td>
<td>Diameter of the blind hole feature, Centre of the hole feature w.r.to inspection datum</td>
<td>Length dimension X and y position of the hole centre w.r.to inspection datum</td>
<td>Length measurements using built-in routine L9814 for bore measurement</td>
</tr>
<tr>
<td>4.</td>
<td>Dimensions of closed pocket feature: Length of the closed pocket and width of the pocket</td>
<td>Length dimension</td>
<td>Length measurements using built-in routine L9812 for pocket measurement</td>
</tr>
<tr>
<td>5.</td>
<td>Width of the pocket feature</td>
<td>Length dimension</td>
<td>Measure Plane-8 &amp; Plane-9 at (4 pts. each)</td>
</tr>
</tbody>
</table>

Table 8.1 Manually written inspection plan for dimensional measurement of Test Piece 3 on BRIDGEPORT

The disadvantage of such bespoke and specific inspection plan is that if the location or
dimensions of the feature are changed then a new bespoke plan from scratch is needed.
The case study proved that inspection of the part using the STEP-NC compliant framework has five main advantages as compared to the conventional approach:-
(i) The inspection plan it generates contains higher level information
(ii) It is generated automatically using the prototype system based on the STEP-Compliant framework
(iii) It is more generalised i.e. independent of the machine tool used for inspection
(iv) Any change in part or feature dimensions are easily adapted
(v) The STEP-NC-compliant inspection file can be easily added as extended data to the machining information that already exists for the same workpiece.

8.4 Summary

This chapter has described a prototype system to validate the functioning of the STEP-NC-Compliant inspection framework introduced in chapter 6. The prototype system aims to automatically generate generalised and interoperable inspection plans for prismatic parts with simple features. The prototype system is developed using an object oriented programming approach in Java that uses a class library based on “ISO14649” schema. The input to the prototype system is the geometrical parameters and tolerance information of the workpiece and its features. The output is a STEP-NC-compliant inspection file containing features and workpiece information, workplan, probing workingsteps etc. in this regard the working of the prototype system is explained by showing generalised inspection plan generation for two test parts. A case study was carried out in the end to validate the functionality of the STEP-NC Compliant inspection framework. It highlighted its advantages over the conventional approach of inspection planning discussed in chapter 5.
Chapter 9

CONCLUDING DISCUSSION

9.1 Introduction

There has always been a focus in the manufacturing industry to produce high quality finished components. The dimensional inspection and measurement of the part plays a key role as the inspection results are used to control the manufacturing process and reduce variations in the component. Though efforts have been made in the last decade to automate the inspection process and integrate it into the manufacturing process, there is still no fully generic approach to inspection planning. The recent development of the ISO14649 Part 16 (STEP-NC) has provided the opportunity to support such a generic approach using a data structure which enables inspection process to be integrated with manufacturing.

During this research work, and with respect to the original objectives defined in chapter 1 and scope of the research defined in chapter 2, the author has achieved the following:

- Highlighted typical machine dependent bespoke inspection planning methods for dimensional inspection of prismatic parts.
- In the context of in-process measurement, the measuring capabilities and inspection results accuracy of the CNC machining centre have been investigated, with comparison made to coordinate measuring machines.
- The novel feasibility of the STEP-NC standard as an enabler to generalise the feature-based inspection planning for a component has been established.
- A unique STEP-NC-Compliant framework has been established supported by two information models to provide a higher level inspection plan for prismatic parts.
- A novel prototype system has been developed to validate the functionality of the proposed inspection framework.
This chapter discusses the research work carried out by the author in more detail, highlighting the novel aspects of the work, and contributions to the global body of knowledge.

9.2 Review of automated inspection in manufacturing and STEP-NC standards

The literature review by the author in chapter-2 mainly covered automated inspection planning and programming in manufacturing. It also reviewed in-process measurements and error detection in CNC machine tools and other related issues such as tolerancing. The investigation in the area of inspection planning revealed that in most cases it is limited to probe path planning and probing strategies for CMMs. Though some feature based systems used a higher level inspection planning, it still remained specific to the machine tool used for inspection. The recent research work has focused on integrating inspection process with overall process planning in manufacturing. Though this has resulted in inspection planning at an early stage in manufacturing, the author still believes there is a lack of generalised inspection planning.

In chapter 3 an overview of the STEP-NC standard is given along with brief introduction to other standards (DMIS and I++ etc.). The advantage of STEP-NC in supplying higher level manufacturing information was highlighted by the author. “DMIS” provides a standard for inspection of parts generally for CMMs, but its features are primitive as compared to STEP-NC features. Moreover the attributes of features defined in STEP-NC carries inspection as well as manufacturing knowledge with it.

9.3 Contemporary inspection process for part measurement in manufacturing

Currently measurement of parts is mostly performed on CMMs where the inspection plans are suited to the vendor specific inspection programs. In addition to the inspection on CMMs, in-process inspection of a part on CNC machining centres is very important as it gives the information about critical dimensions while it is still on a CNC machine and the errors can be corrected. Machine parts can be measured in-process on CNC machine tools for first off inspection and then on more accurate CMMs according to their measuring capabilities.
The probing capabilities of a CNC machining centre for part measurement and its comparison with the measuring capabilities of a CMM was shown in chapter 4. Several issues were highlighted by the author in the experimentation in chapter 4. The foremost was the bespoke inspection planning specific to the inspection machine, which in the case of in-process measurement on the CNC machine was primitive in nature. Other issues concerned the accuracy of in-process measurement results with respect to the results obtained from the CMM. It was important as the reliable metrology tools for inspection of a part are CMMs, and for in-process inspection on a CNC machining centre its measuring limitations with respect to a CMM should be known.

In this context the author has recognised a requirement for generic inspection planning for measurement of a component that is independent of the machine used. The data structure of STEP-NC has provided an opportunity to achieve this generic inspection planning of components where the inspection knowledge is integrated with the machining knowledge. The experimentation strengthened the author’s view of having a generic higher level inspection plan for component’s inspection independent of the inspection equipment. This helped to define the research scope in chapter 5 where the STEP-NC data structure enabled the author to propose an inspection framework for such a generic inspection plan. A comparison between the conventional approach and the STEP-NC Compliant approach for inspection process of individual components is shown in figure 9.1.
9.4 Use of STEP-NC for higher level generic inspection planning for component

The development of the STEP-NC data structure has provided an opportunity to directly transfer higher level manufacturing information to the machine controller. Several of its parts are responsible for general process data, and information about milling, turning and WEDM etc. It has also influenced the future direction of inspection process and has made possible integration of dimensional inspection process in manufacturing. Though the part of the standard responsible for inspection (ISO14649-16) is still a working draft and yet to be finalised, it enables the
inspection planning of a part at the process planning stage. The author has investigated the STEP-NC standard and has uniquely realised the development of a STEP-NC Compliant framework primarily using information provided by ISO14649 (part 10 and part 16).

However ISO14649 (part 10 and 16) insufficient information for feature-based inspection i.e. it has no inspection features or any inspection attributes for the manufacturing features defined within it. Though ISO14649-16 provides inspection task such as probing workingsteps it fails to establish that the probing workingstep is for an individual feature. Though inspection items are defined in ISO14649-16, its link with the manufacturing features is still required for inspection such as the number of items associated with each feature.

9.4.1 Realisation of a STEP-NC Compliant framework for inspection of a part

The STEP-NC-Compliant inspection framework was realised in this research through the development of two information models based on the concept of STEP-NC (described in chapter 6). The product information model provided the information about component and its features while its inspection requirements were provided by the author's manufacturing and inspection information model. By using 2.5 D manufacturing features as inspection features (that already are defined for machining in ISO14649-10) in the product information model has the advantage of integrating inspection within manufacturing.

For inspection purpose inspection items are defined in ISO14649-16, the author has uniquely established a link of these items with the manufacturing features such as hole, rectangular pockets, slots etc. to be inspected. The number of inspection items for each feature is defined and it becomes the list of items for the probing workingstep for that feature. The developed framework focuses on features with regular geometry like holes pockets, slots circular boss etc. The investigation by the author into the STEP-NC standard has revealed that such regular features defined for manufacturing can be used as inspection features. However for features having complex geometries like profile features or others such as compound features, additional attributes are needed for defining inspection features. The proposed
manufacturing/inspection information model by the author provides inspection knowledge for generating a generalised inspection plan. The generalised inspection plan is independent of the specific machine source used for inspection of a part and its features.

9.4.2 Limitations of the STEP-NC Compliant framework

The STEP-NC-Compliant inspection framework has the advantage of providing generalised and interoperable inspection information for inspection of individual prismatic parts. However there are certain limitations in using this framework such as:

- It can only generate interoperable inspection information for prismatic parts having simple features based on regular geometry such as straight holes, rectangular pockets or slots etc.

- This framework cannot be used for parts with features like a pocket having irregular profiles or a complex 3-D surface. The reason is that no generic set of inspection items can be defined for a profile feature or a sculptured surface e.g. for a profile feature the number of inspection items depends on the specific shape of the profile.

- All the inspection information provided by the STEP-NC Compliant inspection framework is for inspection machines having touch probes and is not applicable to non-contact probes.

9.4.3 Validation the STEP-NC-Compliant framework for inspection

A novel prototype system has been developed by the author based on the concept of the STEP-NC-Compliant inspection framework and is presented in chapter-8. It has demonstrated the use of STEP-NC data structure for automatic generation of inspection file for a component with test cases. The prototype system uses a Java language platform, where a library of the STEP-NC compliant classes is defined based standards such as ISO14649, AP224.
The inspection plan generated is generic and independent of the inspection machine used, it is applicable to any size of the workpiece or its features. The advantage is that it can be added as an extension to the STEP-NC-Compliant machining information already given for a part, so any change in the part or feature is easily adapted. Moreover as it is generic, the tolerances specified determines which features or dimensions can be inspected according to the accuracy limit and measuring capabilities of the machine used for inspection.

The inspection results obtained after the execution of inspection process are used to update the STEP-NC compliant file with inspection result statements. One of the issues with this approach is that a large number of data can be accumulated in the updated STEP-NC compliant file. Second is the analysis of results, the author in his case study in chapter 8 has analysed the inspection results for a prismatic part. The mean values of 10 repeated measurements of part and its feature dimensions were used to update the STEP-NC inspection file (see inspection results in appendix E). The updated STEP-NC file could be updated with the mean values of measured results for each dimension. The other approach is to statistically analyse the inspection results report and find out the best possible measured values from the inspection results data and either update the STEP-NC Compliant file or use it without the STEP-NC format. Decisions can be taken based on the inspection results report to control the manufacturing process.

9.5 Future Work

The challenge of this research has been to take a draft inspection standard (ISO14649 part 16) and attempt to demonstrate its true applicability to the inspection process. Inevitably, this work has also identified the weaknesses in the standard, which in reality can be considered as being incomplete, because of its inability to truly cater for non-prismatic and free-form surfaces.

Whilst much progress has been made in the research reported in the thesis, it is important to recognise and summarise where subsequent work should concentrate, to maximise the benefit of the feature based inspection embodied within STEP-NC. The following points provide template for the future research:
• The STEP-NC standard currently provides routes for prismatic component inspection, but does not provide any solution for irregular surfaces for freeform surfaces. Consequently the standard needs to be developed to provide this capability.

• The standard represents a vision of the future in terms of feature based inspection, yet is not being actively considered by the CMM community which has invested in the DMIS protocols and standards. The challenge here will be to demonstrate the benefits of the STEP-NC approach to the CMM community, over and above that provided by DMIS.

• Whilst STEP-NC can be implemented on the new machine tool systems as part of the software/firmware, the more significant issue is that of the backward compatibility with all of the existing machine tool systems. Whilst it has been possible to demonstrate translation between inspection plans and CNC/CMM code, this has been completed on manual basis. What will be needed for the future is automatic translation capability for any type of controller (CNC and CMM).

• STEP-NC provides a vehicle for generic inspection planning, but does not recognise the actual inspection capabilities of the machine being used to inspect. This is important when considering CNC machine tool systems and their inspection capabilities, which have significantly larger error/uncertainty budgets than the coordinate measuring machines. The challenge here will be to investigate the integrity of inspection data from different measurement centres as a function of feature based inspection.
Chapter 10

CONCLUSIONS AND FURTHER WORK

10.1 Introduction

This chapter summarizes the conclusions drawn from the research work and the further work in future that is envisaged.

10.2 Contribution to Knowledge

The main contribution in this research is the application of STEP-NC standards to define a data structure for higher level generic inspection plan for feature-based inspection of prismatic parts. Though the information in the STEP-NC standard for inspection process (ISO14649-16 working draft) is structured, it needed to be linked with each of the feature in the part. The author has accomplished that by linking the inspection items and activities to the part and each of its features.

The author has also illustrated the comparison of measuring capabilities and accuracy of part inspection results between a CNC machining centre and a CMM. This comparison provided the available measuring capabilities for part measurement while interpreting the STEP-NC Compliant inspection plan into an inspection program.

10.3 Conclusions

The conclusions are as follows:

(i) The review of the contemporary inspection planning and programming of parts in manufacturing in this research has identified the requirements of generic inspection plan at the shop-floor level.

(ii) The research has also identified the requirement of generalised information for the inspection process through the review of contemporary inspection standards such as DMIS and its comparison with the STEP standards.
(iii) The research work through experimentation has demonstrated the advantages and the limitations of in-process measurement on a CNC machining centre, in terms of measuring capabilities and accuracy of results in comparison with the more accurate CMM. This comparison establishes the fact that which of the feature dimensions in the inspection plan can be inspected on a CNC machining centre according to its measuring capability.

(iv) Investigation of the STEP-NC standard in this research has shown it to be a powerful data structure that has the potential of integrating the inspection process within the overall manufacturing process by augmenting it with necessary additional information.

(v) The object oriented environment of the STEP-NC data structures provides the strong capability in realising product and manufacturing/inspection information models to facilitate the upfront inspection planning in manufacturing.

(vi) The research has shown the integration of inspection process with manufacturing through a STEP-NC Compliant inspection framework. A STEP-NC compliant framework for inspection has demonstrated the addition of inspection information to machining and setup information for a part.

(vii) The development of STEP-NC compliant framework for inspection of individual parts in the research work has achieved the goal of providing higher level generic information independent of the machine used for inspection.

(viii) The STEP-NC compliant inspection framework has been demonstrated by the development of a prototype system that provides a strong tool for automatically generating inspection plans.
(ix) The STEP-NC compliant inspection process provides the bi-directional flow of information that has been shown by the ability of STEP-NC compliant inspection file to update by storing inspection results within it.

10.4 Further Work

The further work envisage by the author is as follows:-

(i) Extension of the STEP-compliant information models
(ii) Upgrading the STEP-Compliant framework
(iii) Need for the development of STEP-NC interface
(iv) Feed back for Closing the loop in manufacturing

10.4.1 Extension of the STEP Compliant information models

The research work carried out by the author focuses on individual prismatic parts with simple features such as pockets, slot etc. The step-compliant product information needs to be extended to include complex features like 3D surfaces and compound features. Moreover the STEP-compliant information models are based on milling parts which can be upgraded to include turning components and turn mill parts. The manufacturing information model can be extended to provide information for tool probe qualification and probing strategy and in addition the use of non contact probes.

10.4.2 Upgrading the STEP-NC Compliant framework

The STEP-Compliant inspection framework has been developed for individual prismatic components. It can be further upgraded for the inspection of assemblies and even batches of components. The information from other standard sources such as ISO10303 part 240 which is for process planning needs to be fully explored to linking the integration of the inspection process in manufacturing at an upper level.
10.4.3 Need for the development of STEP-NC interface

There is a need for development of STEP-NC interface that can automatically read the STEP-NC compliant inspection plan for machined components, add information such as machine tool used and output a complete code (machining & inspection). Moreover it should have the ability to read back inspection results after the execution of inspection in STEP-NC format.

10.4.4 Closing the loop in manufacturing

The ability of STEP-NC standards to provide bidirectional flow of manufacturing information allows us to feed back the results of inspection for process control. A new mechanism needs to be defined to use the inspection results obtained by the STEP-Compliant inspection framework to reduce the errors in the manufacturing process. Currently the approach given by the author is to update the inspection result statements in STEP-NC compliant file with actual dimensions (average measured values of the dimensions) that can be used for local feedback.

The inspection results data can be statistically analysed to get the best data which can be used as a feedback with or without using the STEP-NC format to control the process. One approach can be to have a centralised database to store the variations in the inspection results that can be analysed to determine the cause of the variation. A simple example can be determining the variation in a machined hole after roughing and storing it. Based on these store inspection results decision can be taken, for example adjusting the tolerance in the finishing cut or changing the tool for next similar feature to be machined.
REFERENCES


ANSI Y14.5M-1982, Dimensioning and Tolerancing, American Society of Mechanical Engineers, New York, NY

ANSI Y14.5M-1994, Dimensioning and Tolerancing, American Society of Mechanical Engineers, New York, NY


I++ DME Version 1.4.2,
http://www.isd.mel.nist.gov/projects/metrology_interoperability/specs/


NIST 2001, “Analysis of Dimensional Metrology Standards”, National Institute of Standards and Technology, Manufacturing Engineering Laboratory, NISTIR 6847, p17


Yaron O. B.; Leo J., 2004 “Tolerance envelopes of planar mechanical parts with parametric tolerances”, Computer-Aided Design Received 30 March 2004; received in revised form 21 June 2004; accepted 29 July 2004


Appendix A

A.1 Part measurement on a Coordinate measuring machine (FERRANTI)

Measurement Operation:
1. Establishing datum coordinate axes and datum plane
2. Length and width of the part, length and width of the pocket feature, hole diameter are measured by measurement program using inspection software ACCUDAT for the CMM.

A.2 Inspection Code (ACCUDAT):
The inspection code was generated automatically by the ACCUDAT software and is given as follows:

5 Part: SUB Part

10 ! INTERNATIONAL METROLOGY SYSTEMS (SCOTLAND) LTD.
15 ! ACCUDAT PART PROGRAM
20 ! Program Name.....FERINS
25 !
30 COM /C2/X,Y,Z,R,A,D,D2,Tptn,Form,Pts(*),Dcs(*),N
35 COM /C5/ Par(*),Tp(*),Pf(*)
40 COM /C6/ Pdi,Prb_tip(*),Tip
45 COM /C8/ Ln(*),Cir(*),Pln(*),Cyl(*),Sph(*)
50 COM /C11/Op$,Op1$,Op2$,Op3$,Printer,Prntr$,Pflg_1
55 COM /C14/R_3d(*),R_2d(*),W(*)
60 COM /G_res/ Trace(*),Invol(*),Eccen(*),Cumul(*),Adjac(*),Thick(*),B_fp(*)
65 COM /Res/Hdr$(*)$,Sn
70 Prntr$="ON"$ !For Geom Tol printout
75 !
80 Start_1: ! ******************************************
85 !
90 Manual
95 RotClr
100 Sel_tip(0.0)
105 Display("CTR OF HOLE 2MM ABOVE SURFACE")
110 Beep
115 Wait
120 Ts=TIMEDATE
125 !
130 Units("MM,ANGDEC")
135 !
140 Start_2: ! ******************************************
145 !
150 Rot_clr
155 Sel_tip(0.0)
160 Speed(125.0000)
165 Prbspd(10.0000)
170 Ptol(.2500)
175 Prof_clear(.5000)
180 Wkg_pln("XY")
185 Seq(I)
190 Locate
195 Master("XYZ")
200!
205!******************************************************************************
210!
211 MASS STORAGE IS "C:\PROGRAMS"
212 Fred$="FERRANT"
213 CREATE Fred$,1
214 ASSIGN@lo TO Fred$;FORMAT ON
215 Meas("Plane 1",4,"TOP FACE")
220 Level("P 1")
225 Master("Z")
230 Meas("Line 1",2,"FRONT EDGE")
235 Align(0,"L 1")
240 Master("Y")
245 Meas("Line 2",2,"LH EDGE")
250 Master("X")
251! FOR I=1 TO 10
255 Meas("Point ",1,"LH EDGE")
260 Output("HSP 4;X")
261 OUTPUT@lo;"PT1";
262 OUTPUT@lo;VAL$(X)
265 Meas("Point ",1,"RH EDGE")
266 OUTPUT@lo;"PT2";
267 OUTPUT@lo;VAL$(X)
270 Output("HSP 4;X")
275 Meas("Point ",1,"FRONT EDGE")
276 OUTPUT@lo;"PT3";
277 OUTPUT@lo;VAL$(Y)
280 Output("HSP 4;Y")
285 Meas("Point ",1,"BACK EDGE")
286 OUTPUT@lo;"PT4";
287 OUTPUT@lo;VAL$(Y)
290 Output("HSP 4;Y")
295 Meas("Point ",1,"RECFTEDGE")
296 OUTPUT@lo;"PT5";
297 OUTPUT@lo;VAL$(Y)
300 Output("HSP 4;Y")
305 Meas("Point ",1,"RECEBACKEDGE")
306 OUTPUT@lo;"PT6";
307 OUTPUT@lo;VAL$(Y)
310 Output("HSP 4;Y")
315 Meas("Point ",1,"RECLHEDGE")
A.3 Measured inspection results:

The measured data from dimensional inspection of the part is given in table A.1

L=Length of the part
W=Width of the part
D= diameter of the hole
L_p = Length of the pocket
W_p = Length of the pocket
Z= Z-coordinate of the datum surface (Top surface of the part)

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>W</th>
<th>D</th>
<th>L_p</th>
<th>W_p</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120.0312</td>
<td>100.032</td>
<td>21.9724</td>
<td>79.994</td>
<td>49.993</td>
<td>0.0007</td>
</tr>
<tr>
<td>2</td>
<td>120.0303</td>
<td>100.0385</td>
<td>21.9712</td>
<td>79.995</td>
<td>49.994</td>
<td>0.0006</td>
</tr>
<tr>
<td>3</td>
<td>120.0301</td>
<td>100.0367</td>
<td>21.9721</td>
<td>79.991</td>
<td>49.995</td>
<td>0.0004</td>
</tr>
<tr>
<td>4</td>
<td>120.0311</td>
<td>100.0362</td>
<td>21.9725</td>
<td>79.993</td>
<td>49.996</td>
<td>0.0008</td>
</tr>
<tr>
<td>5</td>
<td>120.0398</td>
<td>100.0368</td>
<td>21.9728</td>
<td>79.9936</td>
<td>49.9965</td>
<td>0.0006</td>
</tr>
<tr>
<td>6</td>
<td>120.0304</td>
<td>100.0368</td>
<td>21.9732</td>
<td>79.9931</td>
<td>49.998</td>
<td>0.0005</td>
</tr>
<tr>
<td>7</td>
<td>120.0304</td>
<td>100.0364</td>
<td>21.973</td>
<td>79.993</td>
<td>49.998</td>
<td>0.0003</td>
</tr>
<tr>
<td>8</td>
<td>120.0304</td>
<td>100.0367</td>
<td>21.9741</td>
<td>79.9935</td>
<td>49.997</td>
<td>0.0004</td>
</tr>
<tr>
<td>9</td>
<td>120.0288</td>
<td>100.0362</td>
<td>21.973</td>
<td>79.993</td>
<td>49.9981</td>
<td>0.0006</td>
</tr>
<tr>
<td>10</td>
<td>120.0304</td>
<td>100.0367</td>
<td>21.9731</td>
<td>79.9931</td>
<td>49.993</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Table A.1 Measured data from dimensional inspection on CMM (Ferranti)
APPENDIX B

B.1 Detail of part measurement on 3-axis CNC machining centre WADKIN (FANUC CONTROLLER)

Measurement operation:
1. Checking the X and Y parallelism
2. +X and -X probing for measuring length of the part and the pocket feature
3. +Y and -Y probing for measuring width of the part and the pocket feature
5. Measuring depth of the pocket and the hole.

B.2 NC code (Inspection):

(Parallelism X)
N0010 (ID,PROG,TWDXPA,XPARALLEL-PROVEN,3D)
N0020 ! Probes two supposedly parallel faces (two points on each)
N0030 ! and calculates the angle between them
N0040 P93 = 28 ! Safe rapid height
N0050 P92 = 30 ! Probing length
N0060 T01 M06
N0070 ! Set datum at corner
N0080 P87 =079 ! Y coordinate
N0090 P86 =106 ! X coordinate
N0100 P85 =1 ! Corner type
N0110 P84 =15 ! Fixture offset number
N0120 (GSUB,TWDCOR)
N0130 E(P84 )
N0140 ! Probe orientation of first face
N0150 P91= -5 ! Z coordinate
N0160 P90 =10 ! Y1 coordinate
N0170 P89 =-10 ! X1 coordinate
N0180 P88 =+1 ! Direction indicator
N0190 P87 =87 ! Y2 coordinate
N0200 P86 =-10 ! X2 coordinate
N0210 (GSUB,TWDXAN)
N0220 P82 = P89 ! First result
N0230 ! Probe orientation of second face
N0240 P90 =87 ! Y1 coordinate
N0250 P89 =125 ! X1 coordinate
N0260 P88 = - ( P88 ) ! Change direction
N0270 P87 =10 ! Y2 coordinate
N0280 P86 =125 ! X2 coordinate
N0290 (GSUB,TWDXAN)
N0300 (DSP,10,5,THE ERROR IS \(P89-P82)8.3\) DEGREES)
N0310 T30 M06
N0320 M30

161
N9999 (END,PROG)
(Parallellism Y)
N0010 (ID,PROG,TWDYPA,YPARALLEL-PROVEN,3D)
N0020 ! Probes two supposedly parallel faces (two points on each)
N0030 ! and calculates the angle between them
N0040 P93 = 10 ! Safe rapid height
N0050 P92 = 30 ! Probing length
N0060 T01 M06
N0070 ! Set datum at corner
N0080 P87 =079 ! Y coordinate
N0090 P86 =106 ! X coordinate
N0100 P85 =1 ! Corner type
N0110 P84 =14 ! Fixture offset number
N0120 (GSUB,TWDCOR)
N0130 E(P84)
N0140 ! Probe orientation of first face
N0150 P91 =-10 ! Z coordinate
N0160 P90 =-10 ! Y1 coordinate
N0170 P89 =10 ! X1 coordinate
N0180 P88 =+1 ! Direction indicator
N0190 P87 =-10 ! Y2 coordinate
N0200 P86 =87 ! X2 coordinate
N0210 (GSUB,TWDYAN)
N0220 P82 = P90 ! First result
N0230 ! Probe orientation of second face
N0240 P90 =115 ! Y1 coordinate
N0250 P89 =87 ! X1 coordinate
N0260 P88 = - (P88) ! Direction changed
N0270 P87 =115 ! Y2 coordinate
N0280 P86 =10 ! X2 coordinate
N0290 (GSUB,TWDYAN)
N0300 (DSP,10,5,THE ERROR IS \(P90-P82)S.3\ DEGREES)
N0310 T30 M06
N0320 M30
N9999 (END,PROG)

(Size of the blank and pocket)
( +X Probing)
N0010 (ID,PROG,TWDX1,PROBE-X-POS,3D)
N0020 P84=16 !FIXTURE OFFSET
N0040 M19 M5 Q0
N0045 G1 U0 F999
N0060 G51 U(P92) P1=20 P2=1 P4=250
N0080 P89= (PRBPSN(X)+P97+P99)
N0090 (STO,(P84),FOV(X),(P89))
N0100 (DSP,10,25,X \(TBLVAL((P84),FOV(X))8.2))
N0120 M30
N9999 (END,PROG)
( -X Probing)
N0010 (ID,PROG,TWDX2,PROBE-X-NEG,3D)
N0020 P84=16 !FIXTURE OFFSET
N0040 M19 M5 Q0
N0045 G1 U0 F999
N0060 G51 U(-P92) P1=20 P2=1 P4=250
N0080 P89= (PRBPSN(X)-P96+P99)
N0090 (STO,(P84),FOV(X),(P89))
N0100 (DSP,10,25,X \(TBLVAL«(P84),FOV(X))8.2)\)
N0120 M30
N9999 (END,PROG)
( +Y Probing)
N0010 (ID,PROG,TWDY1,PROBE-Y-POS,3D)
N0020 P84=16 !FIXTURE OFFSET
N0040 M19 M5 Q0
N0045 G1 V0 F999
N0060 G51 V(P92) P1=20 P2=1 P4=250
N0080 P90= (PRBPSN(Y)+P95+P98)
N0090 (STO,(P84),FOV(Y),(P90))
N0100 (DSP,10,25,Y \(TBLVAL((P84),FOV(Y))8.2)\)
N0120 M30
N9999 (END,PROG)
(-Y Probing)
N0010 (ID,PROG,TWDY2,PROBE-Y-NEG,3D)
N0020 P84=16 !FIXTURE OFFSET
N0040 M19 M5 Q0
N0045 G1 V0 F999
N0060 G51 V(-P92) P1=20 P2=1 P4=250
N0080 P90= (PRBPSN(Y)-P94+P98)
N0090 (STO,(P84),FOV(Y),(P90))
N0100 (DSP,10,25,Y \(TBLVAL((P84),FOV(Y))8.2)\)
N0120 M30
N9999 (END,PROG)

Diameter of the Hole
N0010 (ID,PROG,TWDBOR,BORE-PROVEN,3D)
N0020 ! Sets a datum to the centre-point of a bore and then
N0030 ! probes the quadrant points to calculate their radii.
N0040 P93 = 30 ! Safe rapid height
N0050 P92 = 30 ! Probing length
/ N0060 T01 M06
N0070 P91 =-5 ! Z coordinate
N0080 P87 =156 ! Y coordinate
N0090 P86 =165 ! X coordinate
N0100 P85 =11 ! Radius
N0110 P84 =15 ! Fixture offset number
N0120 (GSUB,TWDBOR)
N0130 E(P84 )
N0140 P92= P85+10 !Reassign probing length
N0150 ! Probe first radius
N0160 P90 = 0 ! Y coordinate
N0170 P89 = 0 ! X coordinate
N0180 P88 = -1 ! -X direction
N0190 (GSUB,TWDPX)
N0200 P70 = P89 ! +X result
N0210 ! Probe second radius
N0220 P90 = 0 ! Y coordinate
N0230 P89 = 0 ! X coordinate
N0240 P88 = 1 ! +X direction
N0250 (GSUB,TWDPX)
N0260 P71 = P89 ! -X result
N0270 ! Probe third radius
N0280 P90=0 ! Y coordinate
N0290 P89 = 0 ! X coordinate
N0300 P88 = -1 ! -Y direction
N0310 (GSUB,TWDPY)
N0320 P72 = P90 ! +Y result
N0330 ! Probe fourth radius
N0340 P90 = 0 ! Y coordinate
N0350 P89 = 0 ! X coordinate
N0360 P88 = 1 ! +Y direction
N0370 (GSUB,TWDPY)
N0380 P73 = P90 ! -Y result
N0390 (DSP,8,25,THE RADII OF THIS BORE ARE : )
N0400 (DSP,10,32,+X : \(P70)8.3\text{mm})
N0410 (DSP,11,32,-X : \(P71)8.3\text{mm})
N0420 (DSP,12,32,+Y : \(P72)8.3\text{mm})
N0430 (DSP,13,32,-Y : \(P73)8.3\text{mm})
/ N0440 T30 M06
N0450 M30
N9999 (END,PROG)
B.3 Measured Inspection results

L = length of the part,  W = width of the part,  \( L_p = L_{x2} - L_{x1} \) = Length of Pocket,  
\( W_p = W_{x2} - W_{x1} \) = Width of Pocket,  D = Diameter of the hole

Probing on the Machine tool (Wadkin 3-axis Machining center)

<table>
<thead>
<tr>
<th>No.</th>
<th>( X_1 )</th>
<th>( X_2 )</th>
<th>( Y_1 )</th>
<th>( Y_2 )</th>
<th>L</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>198.201</td>
<td>318.276</td>
<td>66.892</td>
<td>166.906</td>
<td>120.075</td>
<td>100.014</td>
</tr>
<tr>
<td>2</td>
<td>198.199</td>
<td>318.276</td>
<td>66.89</td>
<td>166.91</td>
<td>120.077</td>
<td>100.02</td>
</tr>
<tr>
<td>3</td>
<td>198.201</td>
<td>318.275</td>
<td>66.894</td>
<td>166.908</td>
<td>120.074</td>
<td>100.014</td>
</tr>
<tr>
<td>4</td>
<td>198.2</td>
<td>318.277</td>
<td>66.891</td>
<td>166.91</td>
<td>120.077</td>
<td>100.019</td>
</tr>
<tr>
<td>5</td>
<td>198.202</td>
<td>318.277</td>
<td>66.893</td>
<td>166.91</td>
<td>120.075</td>
<td>100.017</td>
</tr>
<tr>
<td>6</td>
<td>198.201</td>
<td>318.276</td>
<td>66.892</td>
<td>166.909</td>
<td>120.075</td>
<td>100.017</td>
</tr>
<tr>
<td>7</td>
<td>198.2</td>
<td>318.276</td>
<td>66.893</td>
<td>166.908</td>
<td>120.076</td>
<td>100.015</td>
</tr>
<tr>
<td>8</td>
<td>198.202</td>
<td>318.277</td>
<td>66.892</td>
<td>166.906</td>
<td>120.075</td>
<td>100.014</td>
</tr>
<tr>
<td>9</td>
<td>198.202</td>
<td>318.276</td>
<td>66.895</td>
<td>166.91</td>
<td>120.074</td>
<td>100.015</td>
</tr>
<tr>
<td>10</td>
<td>198.2</td>
<td>318.277</td>
<td>66.895</td>
<td>166.909</td>
<td>120.077</td>
<td>100.014</td>
</tr>
</tbody>
</table>

Table B.1 Measured data for length and width of part from dimensional inspection on WADKIN

<table>
<thead>
<tr>
<th>No.</th>
<th>( X_{x1} )</th>
<th>( X_{x2} )</th>
<th>( Y_{x1} )</th>
<th>( Y_{x2} )</th>
<th>( L_0 )</th>
<th>( W_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>228.22</td>
<td>308.251</td>
<td>71.903</td>
<td>121.893</td>
<td>80.031</td>
<td>49.99</td>
</tr>
<tr>
<td>2</td>
<td>228.22</td>
<td>308.25</td>
<td>71.907</td>
<td>121.896</td>
<td>80.03</td>
<td>49.989</td>
</tr>
<tr>
<td>3</td>
<td>228.219</td>
<td>308.249</td>
<td>71.903</td>
<td>121.894</td>
<td>80.03</td>
<td>49.991</td>
</tr>
<tr>
<td>4</td>
<td>228.219</td>
<td>308.252</td>
<td>71.906</td>
<td>121.894</td>
<td>80.033</td>
<td>49.988</td>
</tr>
<tr>
<td>5</td>
<td>228.219</td>
<td>308.251</td>
<td>71.906</td>
<td>121.894</td>
<td>80.032</td>
<td>49.988</td>
</tr>
<tr>
<td>6</td>
<td>228.219</td>
<td>308.25</td>
<td>71.905</td>
<td>121.895</td>
<td>80.033</td>
<td>49.99</td>
</tr>
<tr>
<td>7</td>
<td>228.219</td>
<td>308.251</td>
<td>71.905</td>
<td>121.895</td>
<td>80.031</td>
<td>49.989</td>
</tr>
<tr>
<td>8</td>
<td>228.22</td>
<td>308.251</td>
<td>71.905</td>
<td>121.896</td>
<td>80.032</td>
<td>49.991</td>
</tr>
<tr>
<td>9</td>
<td>228.219</td>
<td>308.251</td>
<td>71.905</td>
<td>121.896</td>
<td>80.033</td>
<td>49.99</td>
</tr>
<tr>
<td>10</td>
<td>228.219</td>
<td>308.251</td>
<td>71.905</td>
<td>121.895</td>
<td>80.031</td>
<td>49.99</td>
</tr>
</tbody>
</table>

Table B.2 Measured data for length and width of pocket feature from dimensional inspection on WADKIN

<table>
<thead>
<tr>
<th>No.</th>
<th>( R_{x1} )</th>
<th>( R_{x2} )</th>
<th>( R_{y1} )</th>
<th>( R_{y2} )</th>
<th>( D_x )</th>
<th>( D_y )</th>
<th>( D )</th>
</tr>
</thead>
</table>

Table B.3 Measured data for diameter of hole feature from dimensional inspection on WADKIN
APPENDIX C

C.1 Detail of part measurement on 3-axis CNC machining centre BRIDGEPORT (SEIMENS CONTROLLER with SHOPMILL)

Measurement operation:

i) Establishment of z-datum at the top surface

ii) Origin at middle of the top surface of the part and establishing x and y axis.

iii) Measuring length and width of the part using built-in measuring probing cycle.

iv) Locating centre of hole feature and measurement of diameter using bore measurement cycle.

v) Locating centre of the closed pocket feature and measuring its length and with

C.2 Inspection Code (840D controller with SHOPMILL)

N10 T= Probe
N15 M6
N20 G0G54X0Y0
N25 Z100
N30 L9800
N35 R26=-10 R9=3000
N40 L9810
N45 L9800
N50 R7=22 R11=0.25 R23=1
N55 L9814
N60 L9800
N65 R26=20
N70 R24=120 R25=100 R11=0.2 R23=1
N75 L9812
N80 L9800
N85 L9810
N90 Z=100
N95 L9800
C.3 Measured inspection results:

L = Length of the part  
W = Width of the part  
D = Diameter of the hole  
L_p = Length of the pocket  
W_p = Width of the pocket  
Z = Z-coordinate of the datum surface (Top surface of the part)

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>W</th>
<th>D</th>
<th>Lp</th>
<th>Wp</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120.0468</td>
<td>100.0275</td>
<td>21.9591</td>
<td>79.9674</td>
<td>49.9608</td>
<td>0.0007</td>
</tr>
<tr>
<td>2</td>
<td>120.0466</td>
<td>100.0267</td>
<td>21.9596</td>
<td>79.9666</td>
<td>49.96</td>
<td>0.0006</td>
</tr>
<tr>
<td>3</td>
<td>120.0455</td>
<td>100.0268</td>
<td>21.9587</td>
<td>79.9667</td>
<td>49.9599</td>
<td>0.0004</td>
</tr>
<tr>
<td>4</td>
<td>120.0472</td>
<td>100.0268</td>
<td>21.9586</td>
<td>79.9663</td>
<td>49.9599</td>
<td>0.0008</td>
</tr>
<tr>
<td>5</td>
<td>120.048</td>
<td>100.0261</td>
<td>21.9585</td>
<td>79.9653</td>
<td>49.9598</td>
<td>0.0006</td>
</tr>
<tr>
<td>6</td>
<td>120.0482</td>
<td>100.0263</td>
<td>21.9613</td>
<td>79.9657</td>
<td>49.9593</td>
<td>0.0005</td>
</tr>
<tr>
<td>7</td>
<td>120.0471</td>
<td>100.0258</td>
<td>21.9608</td>
<td>79.9681</td>
<td>49.9599</td>
<td>0.0003</td>
</tr>
<tr>
<td>8</td>
<td>120.0484</td>
<td>100.0256</td>
<td>21.9626</td>
<td>79.9687</td>
<td>49.9596</td>
<td>0.0004</td>
</tr>
<tr>
<td>9</td>
<td>120.0478</td>
<td>100.0261</td>
<td>21.9623</td>
<td>79.9677</td>
<td>49.96</td>
<td>0.0006</td>
</tr>
<tr>
<td>10</td>
<td>120.0467</td>
<td>100.0256</td>
<td>21.9614</td>
<td>79.9664</td>
<td>49.9591</td>
<td>0.0003</td>
</tr>
</tbody>
</table>

Table C.1 Measurement data from dimensional inspection on BRIDGEPORT
APPENDIX D

D.1 Graphical comparison of part measurement results on CMM (FERRANTI) Vs CNC machine (BRIDGEPORT) Vs CNC machine Centre (WADKIN)

The measured results data comparison for the two machining centres and the CMM includes the following dimensions:

1. Length of the part
2. Width of the part
3. Length of the pocket
4. Width of the pocket feature
5. Hole feature diameter.
D.2 Comparison of measured length of the part:

<table>
<thead>
<tr>
<th>CMM</th>
<th>B/PORT</th>
<th>WADKIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>120.0312</td>
<td>120.0468</td>
<td>120.075</td>
</tr>
<tr>
<td>120.0293</td>
<td>120.0466</td>
<td>120.077</td>
</tr>
<tr>
<td>120.0301</td>
<td>120.0455</td>
<td>120.074</td>
</tr>
<tr>
<td>120.031</td>
<td>120.0472</td>
<td>120.077</td>
</tr>
<tr>
<td>120.0298</td>
<td>120.048</td>
<td>120.075</td>
</tr>
<tr>
<td>120.0304</td>
<td>120.0482</td>
<td>120.075</td>
</tr>
<tr>
<td>120.0304</td>
<td>120.0471</td>
<td>120.076</td>
</tr>
<tr>
<td>120.0304</td>
<td>120.0484</td>
<td>120.075</td>
</tr>
<tr>
<td>120.0298</td>
<td>120.0478</td>
<td>120.074</td>
</tr>
<tr>
<td>120.0304</td>
<td>120.0467</td>
<td>120.077</td>
</tr>
</tbody>
</table>

| Mean Value | 120.0303 | 120.0472 | 120.0755 |
| Std Dev “σ” | 0.00057  | 0.00089  | 0.00118  |
| Mean Dev    | 0.00043  | 0.00069  | 0.0010   |
| Repeatability “R” | 0.0021 | 0.0034  | 0.0045   |

Table D.1 Inspection results data for measured length of the part

Figure D.1 Graphical comparison of measured length of the part
Figure D.2 (a) Error bars on CMM data of measured length of the part
(b) Error bars on Bridgeport data of measured length of the part
Figure D.2 (c) Error bars on WADKIN data of measured length of the part
### Table D.2 Inspection results data for measured width of the part

<table>
<thead>
<tr>
<th></th>
<th>CMM</th>
<th>B/PORT</th>
<th>WADKIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>100.032</td>
<td>100.0275</td>
<td>100.014</td>
<td></td>
</tr>
<tr>
<td>100.0385</td>
<td>100.0267</td>
<td>100.02</td>
<td></td>
</tr>
<tr>
<td>100.0367</td>
<td>100.0268</td>
<td>100.014</td>
<td></td>
</tr>
<tr>
<td>100.0362</td>
<td>100.0268</td>
<td>100.019</td>
<td></td>
</tr>
<tr>
<td>100.0368</td>
<td>100.0261</td>
<td>100.017</td>
<td></td>
</tr>
<tr>
<td>100.0368</td>
<td>100.0263</td>
<td>100.017</td>
<td></td>
</tr>
<tr>
<td>100.0364</td>
<td>100.0258</td>
<td>100.015</td>
<td></td>
</tr>
<tr>
<td>100.0367</td>
<td>100.0256</td>
<td>100.014</td>
<td></td>
</tr>
<tr>
<td>100.0362</td>
<td>100.0261</td>
<td>100.015</td>
<td></td>
</tr>
<tr>
<td>100.0367</td>
<td>100.0256</td>
<td>100.014</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Mean Value “A”</th>
<th>Std Dev “σ”</th>
<th>Mean Dev</th>
<th>Repeatability “R”</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100.0363</td>
<td>0.00165</td>
<td>0.00091</td>
<td>0.0058</td>
</tr>
<tr>
<td></td>
<td>100.0263</td>
<td>0.000615</td>
<td>0.00049</td>
<td>0.0023</td>
</tr>
<tr>
<td></td>
<td>100.0159</td>
<td>0.00223</td>
<td>0.00188</td>
<td>0.0086</td>
</tr>
</tbody>
</table>

#### Figure D.3 Graphical comparison of measured width of the part
Figure D.4 (a) Error bars on CMM data of measured width of the part
(b) Error bars on BRIDGEPORT data of measured width of the part
Figure D.4 (c) Error bars on WADKIN data of measured width of the part
D.4 Comparison of measured length of the pocket:

<table>
<thead>
<tr>
<th></th>
<th>CMM</th>
<th>B/PORT</th>
<th>WADKIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>79.994</td>
<td>79.9674</td>
<td>80.031</td>
<td></td>
</tr>
<tr>
<td>79.995</td>
<td>79.9666</td>
<td>80.03</td>
<td></td>
</tr>
<tr>
<td>79.991</td>
<td>79.9667</td>
<td>80.03</td>
<td></td>
</tr>
<tr>
<td>79.993</td>
<td>79.9663</td>
<td>80.033</td>
<td></td>
</tr>
<tr>
<td>79.9936</td>
<td>79.9653</td>
<td>80.032</td>
<td></td>
</tr>
<tr>
<td>79.9931</td>
<td>79.9657</td>
<td>80.031</td>
<td></td>
</tr>
<tr>
<td>79.993</td>
<td>79.9681</td>
<td>80.033</td>
<td></td>
</tr>
<tr>
<td>79.9935</td>
<td>79.9687</td>
<td>80.031</td>
<td></td>
</tr>
<tr>
<td>79.993</td>
<td>79.9677</td>
<td>80.032</td>
<td></td>
</tr>
<tr>
<td>79.9931</td>
<td>79.9664</td>
<td>80.031</td>
<td></td>
</tr>
</tbody>
</table>

Mean Value “A" 79.9669 79.9933 80.031
Std Dev “σ” 0.00107 0.00010 0.00107
Mean Dev 0.00087 0.00064 0.00188
Repeatability “R” 0.004 0.001 0.0051

Table D.3 Inspection results data for measured length of the pocket

![Graphical comparison of measured length of the pocket](image)

Figure D.5 Graphical comparison of measured length of the pocket
Figure D.6 (a) Error bars on CMM data of measured length of the pocket
(b) Error bars on BRIDGEPORT data of measured length of the pocket
Figure D.6 (c) Error bars on WADKIN data of measured length of the pocket
D.5 Comparison of measured width of the pocket:

| Measurement | 49.993 | 49.9608 | 49.99 | 49.994 | 49.96 | 49.991 | 49.996 | 49.9699 | 49.988 | 49.996 | 49.9699 | 49.988 | 49.9965 | 49.9698 | 49.988 | 49.998 | 49.9593 | 49.991 | 49.997 | 49.9596 | 49.989 | 49.9981 | 49.96 | 49.991 | 49.993 | 49.9691 | 49.989 |

Mean Value “A” | 49.9591 | 49.9598 | 49.9893
Std Dev “G” | 0.00201 | 0.00046 | 0.00116
Mean Dev | 0.00169 | 0.00030 | 0.0001
Repeatability “R” | 0.0077 | 0.0017 | 0.0036

Table D.4 Inspection results data for measured width of the pocket

Figure D.7 Graphical comparison of measured width of the pocket
Figure D.8 (a) Error bars on CMM data of measured width of the pocket
(b) Error bars on BRIDGEPORT data of measured width of the pocket
Figure D.8 (c) Error bars on WADKIN data of measured width of the pocket
### D.6 Comparison of measured diameter of the hole:

<table>
<thead>
<tr>
<th>Diameter of the hole feature</th>
<th>CMM</th>
<th>BRIDGEPORT</th>
<th>WADKIN</th>
</tr>
</thead>
<tbody>
<tr>
<td>21.9724</td>
<td>21.9591</td>
<td>21.9505</td>
<td></td>
</tr>
<tr>
<td>21.97216</td>
<td>21.9587</td>
<td>21.9505</td>
<td></td>
</tr>
<tr>
<td>21.97255</td>
<td>21.9586</td>
<td>21.9485</td>
<td></td>
</tr>
<tr>
<td>21.9728</td>
<td>21.9585</td>
<td>21.9515</td>
<td></td>
</tr>
<tr>
<td>21.9732</td>
<td>21.9613</td>
<td>21.9515</td>
<td></td>
</tr>
</tbody>
</table>

**Mean Value “A”**

<table>
<thead>
<tr>
<th></th>
<th>21.9727</th>
<th>21.9602</th>
<th>21.9510</th>
</tr>
</thead>
</table>

**Std Dev “σ”**

<table>
<thead>
<tr>
<th></th>
<th>0.00078</th>
<th>0.00157</th>
<th>0.00134</th>
</tr>
</thead>
</table>

**Mean Dev**

<table>
<thead>
<tr>
<th></th>
<th>0.00058</th>
<th>0.00140</th>
<th>0.00111</th>
</tr>
</thead>
</table>

**Repeatability “R”**

<table>
<thead>
<tr>
<th></th>
<th>0.0029</th>
<th>0.0061</th>
<th>0.0051</th>
</tr>
</thead>
</table>

Table D.5 Inspection results data for measured diameter of the hole

![Graphical comparison of measured diameter of the hole](image)

Figure D.9 Graphical comparison of measured diameter of the hole

181
Figure D.10 (a) Error bars on CMM data of measured diameter of the hole. (b) Error bars on BRIDGEPORT data of measured diameter of the hole.
Figure D.10 (c) Error bars on WADKIN data of measured diameter of the hole
APPENDIX E

E.1 Results of part measurement on 3-axi s CNC machining centre BRIDGEPORT (SEIMENS CONTROLLER with SHOPMILL) using STEP-Compliant approach

STEP-NC-COMPLIANT INSPECTION FILE:

#1=PROJECT(Project1'#6,(#2),S,S,S);
#2=WORKPIECE(Example prc',S,S,S,'3,(S,S,S));
#3=BLOCK(Rectangular block',S,120.0,100.0,50.0);
#4=CLOSED_POCKET(closed pocket feature',S,S,#33,S,S,S,S);
#5=ROUND_HOLE(diameter',S,0.44,S,38,S,S);
#6=WORKPLAN(workplan',(#7,#8,#9),S,S,S);
#7=PROBING_WORKINGSTEP(closed pocket',S,120.0,#20,#21,#22,#23,#35);
#8=PROBING_WORKINGSTEP(workpiece block',S,11.1,#14,#15,S,S);
#9=PROBING_WORKINGSTEP(round hole feature',S,12.0,#37,#41,S,S);
#10=PROBING_OPERATION(probe workpiece',#47,#53);
#11=PROBING_OPERATION(probe closed pocket',#47,#13,#53);
#12=PROBING_OPERATION(probe round hole',#47,#53);
#13=PROBING_STRATEGY(user defined');
#14=TOLEOURED_DIMENSION_ITEM(Length of workpiece',#54,S,#16,#3,S);
#15=TOLEOURED_DIMENSION_ITEM(Workpiece width',S,55,S,#17,#3,S);
#16=TOLEOURED_LENGTH_MEASURE(120.0,#18);
#17=TOLEOURED_LENGTH_MEASURE(100.0,#19);
#18=PLUS_MINUS_VALUE(120.0,119.0,1.04);
#19=PLUS_MINUS_VALUE(100.0,99.99,4.0);
#20=TOLEOURED_DIMENSION_ITEM(Length of pocket',#56,S,#25,#4,S);
#21=TOLEOURED_DIMENSION_ITEM(width of pocket',#57,S,#26,#4,S);
#22=TOLEOURED_DIMENSION_ITEM(depth of pocket',#59,S,#27,#4,S);
#23=TOLEOURED_POSE_ITEM(parallelism x',#60,#4,#31);
#24=TOLEOURED_POSE_ITEM(parallelism y',#61,#4,#22);
#25=TOLEOURED_LENGTH_MEASURE(80.0,#28);
#26=TOLEOURED_LENGTH_MEASURE(50.0,#29);
#27=TOLEOURED_LENGTH_MEASURE(30.0,#30);
#28=PLUS_MINUS_VALUE(80.0,79.99,4.0);
#29=PLUS_MINUS_VALUE(50.0,49.99,4.0);
#30=PLUS_MINUS_VALUE(60.0,29.99,4.0);
#31=PARALLELISM_TOLERANCE(0.01,#52,S);
#32=PARALLELISM_TOLERANCE(0.01,#52,S);
#33=AXIS2_PLACEMENT_3D('centre of pocket',S,#34,S,S);
#34=CARTESIAN_POINT(null',#0.01,70.0,30.0);
#35=TOLEOURED_SHAPE_ITEM(flattness of pocket bottom',#62,S,#36);
#36=FLATNESS(0.01,S);
#37=TOLEOURED_DIMENSION_ITEM(#58,diameter of hole1',#38,#5,S);
#38=TOLEOURED_LENGTH_MEASURE(22.0,#39);
#39=PLUS_MINUS_VALUE(22.0,21.99,4.0);
#40=TOLEOURED_SHAPE_ITEM(#63,#5,#42);
#41=TOLEOURED_SHAPE_ITEM(#64,#5,#43);
#42=CIRCULARITY(0.01,S);
#43=CYLINDRICITY(0.01,#43);
#44=AXIS2_PLACEMENT_3D('null',#45,#46,#50);
#45=CARTESIAN_POINT('null',#60.0,80.0,0.0);
#46=DIRECTION('hole axis direction',#0.0,0.0,1.0);
#47=REFERENCE_DATUM_SETUP(#48);
#48=AXIS2_PLACEMENT_3D('inspection datum origin',#49,#50,#51);
#49=CARTESIAN_POINT('inspec ion datum origin location',#0.0,0.0,0.0);
#50=DIRECTION('inspection datum x axis',#1.0,0.0,0.0);
#51=DIRECTION('inspection datum y axis',#0.0,1.0,0.0);
#52=PLANE(.security plane',S);
#53=TOUCH_PROBE('touch trigger probe');
#54=INSPECTION_RESULT(S,#8);
#55=INSPECTION_RESULT(S,#8);
#56=INSPECTION_RESULT(S,#8);
#57=INSPECTION_RESULT(S,#8);
#58=INSPECTION_RESULT(S,#8);
#59=INSPECTION_RESULT(S,#8);
#60=INSPECTION_RESULT(S,#8);
#61=INSPECTION_RESULT(S,#8);
#62=INSPECTION_RESULT(S,#8);
#63=INSPECTION_RESULT(S,#8);
#64=INSPECTION_RESULT(S,#8);

INSPECTION CODE:

N10 T=Probe
N15 M6
N20 G0G54X0Y0
N25 Z100
N30 L9800
N35 R26=10 R9=3000
N40 R7=22 R11=0.25 R23=1
N45 L9814
N50 L9800
N55 R26=20
N60 L9810
N65 R24=120 R25=100 R19=1 R26=-5 R18=7
N70 L9812
N75 L9800
N80 R24=70 R25=35
N75 L9810
N80 L9800
N85 R24=80 R25=50 R19=1 R26=5 R18=10
N90 L9812
N95 L9800
N100 R25=10
N105 L9800
N110 L9810
N115 Z100

184
E.2 Measured inspection results:

L = Length of the part
W = Width of the part
D = Diameter of the hole
$L_p$ = Length of the pocket
$W_p$ = Length of the pocket
Z = Z-coordinate of the datum surface (Top surface of the part)

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>W</th>
<th>D</th>
<th>$L_p$</th>
<th>$W_p$</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>120.0448</td>
<td>100.0273</td>
<td>21.9589</td>
<td>79.9664</td>
<td>49.961</td>
<td>0.0004</td>
</tr>
<tr>
<td>2</td>
<td>120.0461</td>
<td>100.0269</td>
<td>21.9586</td>
<td>79.9656</td>
<td>49.9598</td>
<td>0.0008</td>
</tr>
<tr>
<td>3</td>
<td>120.0456</td>
<td>100.0262</td>
<td>21.9590</td>
<td>79.9637</td>
<td>49.9587</td>
<td>0.0004</td>
</tr>
<tr>
<td>4</td>
<td>120.0463</td>
<td>100.0268</td>
<td>21.9588</td>
<td>79.9663</td>
<td>49.9593</td>
<td>0.0007</td>
</tr>
<tr>
<td>5</td>
<td>120.0468</td>
<td>100.0265</td>
<td>21.9587</td>
<td>79.9663</td>
<td>49.9591</td>
<td>0.0007</td>
</tr>
<tr>
<td>6</td>
<td>120.0462</td>
<td>100.0263</td>
<td>21.9584</td>
<td>79.9647</td>
<td>49.9592</td>
<td>0.0004</td>
</tr>
<tr>
<td>7</td>
<td>120.0467</td>
<td>100.0256</td>
<td>21.9601</td>
<td>79.9691</td>
<td>49.9589</td>
<td>0.0006</td>
</tr>
<tr>
<td>8</td>
<td>120.0471</td>
<td>100.0259</td>
<td>21.9606</td>
<td>79.9679</td>
<td>49.9587</td>
<td>0.0007</td>
</tr>
<tr>
<td>9</td>
<td>120.0469</td>
<td>100.0267</td>
<td>21.9621</td>
<td>79.9688</td>
<td>49.9604</td>
<td>0.0007</td>
</tr>
<tr>
<td>10</td>
<td>120.0464</td>
<td>100.0256</td>
<td>21.9617</td>
<td>79.9654</td>
<td>49.9594</td>
<td>0.0008</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>W</th>
<th>D</th>
<th>$L_p$</th>
<th>$W_p$</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Values</td>
<td>120.0463</td>
<td>100.0264</td>
<td>21.95969</td>
<td>79.96642</td>
<td>49.95945</td>
<td>0.00062</td>
</tr>
<tr>
<td>Std deviation</td>
<td>0.000684</td>
<td>0.000567</td>
<td>0.001357</td>
<td>0.001736</td>
<td>0.000162</td>
<td></td>
</tr>
</tbody>
</table>
STEP-NC-COMPLIANT INSPECTION FILE (Updated with results):

#1=PROJECT('Project1',#2,$,$,$);
#2=WORKPIECE('Example part',S,S,$,#3,$,$$);
#3=BLOCK('Rectangular block',S,120.0,100.0,50.0);
#4=CLOSED_POCKET('Closed pocket feature',S,S,#33,S,S,S,S);
#5=ROUND_HOLE('Diameter',S,0.044,S,#38,S);
#6=WORKPLAN('Workplan',#7,#8,#9,$,$,$);
#7=PROBING_WORKINGSTEP('Closed pocket',#52,S,#10,#21,#22,#23,#24,#25);
#8=PROBING_WORKINGSTEP('Round hole feature',#52,S,#11,#14,#15,#55,S,S);
#9=PROBING_OPERATION('Probe workpiece',#47,#53);
#10=PROBING_OPERATION('Probe closed pocket',#47,#13,#53);
#11=PROBING_OPERATION('Probe round hole',#47,#53);
#12=PROBING_STRATEGY('User defined');
#13=TOLERANCED_DIMENSION_ITEM(Length of workpiece,#54,S,#16,#9,$);
#14=TOLERANCED_DIMENSION_ITEM(Workpiece width,#55,S,#17,#3,$);
#15=TOLERANCED_LENGTH_MEASURE(120.01,119.04);
#16=TOLERANCED_LENGTH_MEASURE(100.01,99.99,4);
#17=TOLERANCED_LENGTH_MEASURE(21.01,20.99,4);
#18=TOLERANCED_LENGTH_MEASURE(30.01,29.99,4);
#19=TOLERANCED_LENGTH_MEASURE(80.01,79.99,4);
#20=TOLERANCED_LENGTH_MEASURE(50.01,49.99,4);
#21=TOLERANCED_LENGTH_MEASURE(40.01,39.99,4);
#22=TOLERANCED_LENGTH_MEASURE(22.01,21.99,4);
#23=TOLERANCED_LENGTH_MEASURE(11.01,10.99,4);
#24=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#25=TOLERANCED_LENGTH_MEASURE(-0.01,0.99,4);
#26=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#27=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#28=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#29=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#30=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#31=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#32=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#33=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#34=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#35=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#36=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#37=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#38=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#39=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#40=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#41=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#42=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#43=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#44=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#45=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#46=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#47=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#48=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#49=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#50=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#51=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#52=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#53=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#54=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#55=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#56=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#57=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#58=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#59=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#60=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#61=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#62=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#63=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#64=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#65=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#66=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#67=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#68=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);
#69=TOLERANCED_LENGTH_MEASURE(0.01,0.99,4);

186
APPENDIX F

F.1 Machine Error on CMM (FERRANTI), CNC machine tool BRIDGEPORT and CNC machine tool WADKIN

The machine error for the three machines is as follows:

CMM (FERRANTI) Error = ±10μm
(Certificate of calibration for measuring machine error is attached)
CNC (BRIDGEPORT) Error = ±6μm (approx.)
CNC (WADKIN) = ±17μm (approx)

using Renishaw Ball Bar System for dynamic test (ISO 230-1), the results are attached
Certificate of Calibration

Issued by: Status Metrology Solutions Ltd
Date of issue: 24-Nov-00 Certificate number: CN 1871

Status works order number: W 10889
Customer: Dept. of Manuf. Eng.
Address: Loughborough University, Loughborough, LE11 3TU
Order number: 41144

Machine
Manufacturer: Feranti
Model / size / type: Merlin / 7-7-4 / bridge type cmm
Serial number: EN1956
Output resolution: 1 μm
Software: IMS Accudat

Location: AMTC
Probe: Type: Renishaw TP2 serial number: 85040
Stylus: 4mm dia x 20mm long
Probe holder: Renishaw PH9
Probing speed: Manual

Date of verification: 27-Oct-00
UKAS approved operator responsible for the verification: S C Anderson

Method: The above cmm was subject to verification tests made in accordance with EN ISO 10360-2: 1996 using material standards of length and environmental measuring equipment having calibration traceable to National Standards via NAMAS certificates of calibration.

Results: Machine error:

Formula: \( E = A + \frac{L}{K} \) μm or \( E \) as a maximum

\[
\begin{align*}
E &= 7 + \frac{L}{200} \mu m \quad \text{or} \quad E = 10 \mu m \\
\end{align*}
\]

Where:
\( E \) = error of indication of length measurement (mm)
\( L \) = the measured length (mm)
\( A \) = a constant (μm)
\( K \) = a dimensionless constant
\( R \) = probing error (μm)

Estimated uncertainty of dimensional measurement = \( \pm \left( 4 + 2 \frac{L}{200} \right) \) μm

Probing error:

\( R = 5 \mu m \)

Estimated uncertainty of measurement for probe calibration = \( \pm 6 \mu m \)

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor \( k=2 \), providing a level of confidence of approximately 95%. The uncertainty evaluation has been carried out in accordance with UKAS requirements.

Signature: S. Anderson

This certificate is issued in accordance with the laboratory accreditation requirements of the United Kingdom Accreditation Service. It provides traceability of measurement to recognised national standards, and to units of measurement realised at the National Physical Laboratory or other recognised national standards laboratories. This certificate may not be reproduced other than in full, except with the prior written approval of the issuing laboratory.
1 Operating and environmental conditions.

1.1 Area - the machine is installed in a room with limited temperature control. Sunlight is able to shine on the machine at times during the day causing localized heating of machine elements.

1.2 Temperatures - the following ambient temperatures were recorded during measurement

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>21.33 °C</td>
</tr>
<tr>
<td>Minimum</td>
<td>18.24 °C</td>
</tr>
<tr>
<td>Average</td>
<td>20.64 °C</td>
</tr>
<tr>
<td>Gradient</td>
<td>2.33 °C</td>
</tr>
</tbody>
</table>

(top of machine to plate)

1.3 Humidity - no measurements were taken

1.4 Vibration - there was no perceived influence from vibration

1.5 Electricity supply - the characteristics were not tested and no effects were observed which may be attributed to supply faults.

1.6 Machine air supply - no problems were encountered that may be attributed to incorrect air pressure or flow rate.

2 Interim checking

EN ISO 10360-2: 1996 strongly recommends that the cmm be checked regularly between periodic re-verifications. It suggests the use of an article that represents typical geometric elements, is dimensionally stable, mechanically robust and which has a surface finish that does not significantly affect the uncertainty of measurement.

Also strongly recommended are checks on the probing system.

Further advice on interim checking and probe checking may be obtained from the Calibration Department at Status Metrology.
Analysis chart - measured data

Available sizes

Length bar sizes used

Existing specification -
E = A + L/K

Difference from nominal

Run 1
Run 2
Run 3
Run 4
Run 5
Run 6
Run 7

Largest measured value
Smallest measured value

Specification following this test
E = A + L/K

Single value
E = B
Analysis chart - measured data

- Spread of measured errors
- Specification (where available)
- Specification following this test (length dependent)
- Specification following this test (single value)
- Collected data points
Certificate of Calibration

UKAS Accredited Laboratory No. 0605 SIII

Certificate Number
CN 1871
Page 5 of 6 pages

Location of tested volume (plan)

Measuring volume

<table>
<thead>
<tr>
<th>Axis</th>
<th>Measuring</th>
<th>Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>0</td>
<td>750</td>
</tr>
<tr>
<td>y</td>
<td>0</td>
<td>750</td>
</tr>
<tr>
<td>z</td>
<td>0</td>
<td>-400</td>
</tr>
</tbody>
</table>

Tested volume

<table>
<thead>
<tr>
<th>Axis</th>
<th>Measuring</th>
<th>Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>x</td>
<td>75</td>
<td>675</td>
</tr>
<tr>
<td>y</td>
<td>75</td>
<td>675</td>
</tr>
<tr>
<td>z</td>
<td>-50</td>
<td>-375</td>
</tr>
</tbody>
</table>

Location of tested volume (elevation)
Certificate of Calibration

UKAS Accredited Laboratory No. 0605 SIII

Certificate Number
CN 1871

Page 6 of 6 pages

<table>
<thead>
<tr>
<th>Time</th>
<th>11.27</th>
<th>11.51</th>
<th>13.05</th>
<th>13.16</th>
<th>13.57</th>
<th>14.55</th>
<th>15.07</th>
<th>15.24</th>
<th>15.34</th>
</tr>
</thead>
<tbody>
<tr>
<td>x axis</td>
<td>CH 2</td>
<td>18.24</td>
<td>18.38</td>
<td>18.79</td>
<td>18.81</td>
<td>18.77</td>
<td>18.87</td>
<td>18.91</td>
<td>18.93</td>
</tr>
<tr>
<td>length bar</td>
<td>CH 3</td>
<td>19.52</td>
<td>19.75</td>
<td>20.39</td>
<td>20.49</td>
<td>20.63</td>
<td>20.85</td>
<td>20.86</td>
<td>20.96</td>
</tr>
<tr>
<td>CH1 - CH2</td>
<td></td>
<td>2.18</td>
<td>2.26</td>
<td>2.28</td>
<td>2.33</td>
<td>2.43</td>
<td>2.46</td>
<td>2.36</td>
<td>2.32</td>
</tr>
</tbody>
</table>

Temperature / time

Temperature difference z to x axis

Maximum recorded temperature °C  21.33
Minimum recorded temperature °C  18.24
Mean of measured values °C  20.64
Mean of z to x axis °C  2.33
DYNAMIC ISO 230-1

Circularity: 12.0 µm
Max: +5.7 µm, 295.5°
Min: -6.2 µm, 89.9°

BPT1500.RTB
By:
Machine: Bridgeport
Date: 26 AUGUST 2004

Length: 150.0000 mm
Radius: 150.0000 mm
Centre Off X: -6.3 µm
Centre Off Y: -12.7 µm
Sample: 37.50 per sec
Feed: 1500.0000 mm/min

Start End
Machine 180.0° 180.0°
Data 0.0° 0.0°
2 runs, Bidirectional

Renishaw Ballbar System

Scale: 2.0 µm/div
DYNAMIC ISO 230-1

Circularity: 34.2 μm
Max: +16.5 μm, 320.3°
Min: -17.6 μm, 249.9°

WAD2NVoS.RTB
By:
Machine: Wadkin U4-5
Date: 26 August 2004

Length: 150.0000 mm
Radius: 150.0000 mm
Centre Off X: +9.8 μm
Centre Off Y: -2.1 μm
Sample: 37.50 per sec
Feed: 1500.0000 mm/min

Start End
Machine 180.0° 180.0°
Data 0.0° 0.0°
2 runs, Bidirectional

Scale: 4.0 μm/div
APPENDIX G

AUTHOR'S PUBLICATION AND CONFERENCE PRESENTATION

