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Off-Line Programming of Coordinate Measuring Machines

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Contents

Preface

Since 1990 I have learnt to enjoy the landscape of northern Sweden, which is far removed from the open moors and the tree clad limestone dales of Derbyshire. It is enough to know that these are only out of sight, and remain for me to return to should my future lie in that direction.

I have also had the opportunity to learn a little of the Swedish post graduate education system, the aims of which, less still the methods used to fulfil these, remain, to a large part, bound in mystery.

Despite this, my knowledge has widened, although not in the direction that I intended. This licentiate thesis allows me to share with you some of this knowledge concerning the ideas and practice which lie behind computer aided design and the off-line programming of co-ordinate measuring machines. It was written to be read.

When I was younger, I used to rock climb. On one occasion whilst hitching out into Derbyshire, I was given a lift by another climber. During conversation it turned out that he climbed routes far harder than those which I could or I even aspired to climb; a real hero. When I suggested that he must have to train really hard to climb at such a level the hero replied, "No, not really, it's just that all the people that I climb with climb at that standard." Nuff said.

Eur. Ing. David Ian Legge

Luleå, April 1996

Introduction

Whilst computer controlled (CNC) machine tools can now work virtually unattended 24 hours a day, the fact remains that manufactured components must be inspected to ascertain whether they lie within those limits set by the designer. The level of inspection applied varies from the in-process inspection of key dimensions of every component (often as the basis of in-process correction of tool offsets and wear) through to sample inspection of components downstream of the manufacturing operation for the purpose of statistical process control.

Co-ordinate measuring machines

Co-ordinate measuring machines (CMM’s) are a common piece of equipment used in manufacturing for inspection of components downstream of a manufacturing process. CMM’s vary in size from ‘desk top’ variants through to large, purpose built units capable of measuring motor vehicle and similarly sized structures. The basic function of a CMM is to allow the x, y, z position of a point on the surface of a component to be established. The CMM consists of a machine tool like structure, with precision slideways and scales and some form of sensor to determine the point of contact. A variety of sensor technologies are in common use; touch trigger probes, contact scanning probes and a variety of non-contact probes.

Programming of Co-ordinate measuring machines

CMM’s are usually computer controlled and, whilst they can be used interactively as a measurement tool, are usually programmed in order to carry out repetitive inspection on large batches or samples of parts. Once a programme has been developed, it can be ‘run’ to automatically inspect a component with little or no manual intervention. CMM programmes can be developed interactively at the CMM, so called ‘teach-in’ programming, or 'off-line' using a simple text editor or some form of programming aid. In this respect, CMM’s are very similar to robots or machine tools. Graphical off-line programming (OLP), which is common for CNC machines, was, for many years uncommon for co-ordinate measuring machines. ***One of the early research results of this work was the development of a CMM OLP system based upon the commercial software available at Luleå University; functionality which is now an accepted part of many computer aided design (CAD) or simulation packages.***

Analysis of Inspection Results

The results of CMM inspection is, in it’s raw form, simply copious data giving details about each inspection point. This data must be further processed in order to give meaningful results. The most typical analysis is the generation of a measured ‘feature’ from this raw data by fitting a circle, cylinder, plane etc., through the measured points. The measured feature geometry may be then compared to the nominal feature definition and the difference in position, orientation, size etc., compared to the allowable tolerance(s) associated with the feature. Geometry with a more complex mathematical definition, so called free form surfaces, present a more complex analysis problem. This analysis is typically carried out by the CMM, although the raw data may be output for transfer to a third party system for analysis, reverse engineering etc. The basic data that is required for meaningful analysis to be carried out is a mathematical description of the nominal feature, the raw inspection data and the tolerance applicable to the features being inspected. The first and last of these is available on component drawings, and usually keyed into the CMM, whilst the second results from the measurement itself.

Increasing Automation through Improved Data Transfer

A significant limitation to increasing the level of automation in OLP tools and in the software for analysing inspection results has been the lack of the necessary 3D geometry and tolerance data in a computer interpretable form. Whilst a human may 'read' a 2D drawing and interpret the information presented, computers are not able to do this. Integrated 3D geometry and tolerance (GD&T) models are now common in high end CAD systems, but this information is not available in downstream systems such as OLP systems as data transfer standards, which address the transfer of 2D drawings and 3D geometry, have not kept up with this development. The standard which comes closest to satisfying this is need is the dimensional measuring interface standard (DMIS) which is designed primarily for the transfer of inspection programmes and results between CAD / OLP and CMM's. DMIS deals with tolerancing, but is limited in its ability to handle the geometry of the component as a whole; DMIS works with 'features' which are seldom directly accessible in the CAD model. Conversely, the IGES standard, which is probably the most widely accepted neutral transfer standard for drawings and 3D geometry, has no provision for tolerance data and deals with geometry as a whole, rather than at the feature level which is necessary for inspection planning and evaluation of inspection results.

The principle conclusions that was drawn from this work is that the ability to transfer both tolerance data and its associated three dimensional model data from CAD via a common neutral format is important for the further evolution of computer aided inspection systems. The standard for the exchange of product model data (STEP) would appear the most likely tool for this as it is now widely accepted as the next generation neutral standard for CAD geometry, and allows new data transfer requirements to be satisfied by the further developed of the standard.

Definition, Inspection and Analysis of Free Form Surfaces

Related to computer aided inspection there are two principle areas of current interest; inspection and analysis of free-form surfaces, most commonly through non-contact inspection technique, and tolerancing of three dimensional models. These areas are topical as a result of the knock on effect of technical developments related to CAD and CMM's and also as natural progressions of ongoing research work related to inspection and OLP.

Both the above are of interest to users of inspection technology, especially designers and manufacturers of products with complex surface geometry. Products incorporating this kind of geometry are often manufactured 'indirectly' through the use of moulds and dies. These products are becoming increasingly technical and there is a need for both accurate manufacturing processes and a means of assessing and documenting both manufacturing process (e.g. tool geometry) and resulting product. These points are addressed more fully in the following papers as well as being the subject of ongoing research and development.

Summary of the Papers

This licentiate thesis consists of three papers:

Paper 1 ***Integration of Design and Inspection Systems - A Research Review.***

Paper 2 ***Semi-Automatic Probe Path Planning for Feature Based CMM Programming.***

Paper 3 ***Integration of Design, Inspection and Quality Management Systems.***

Paper 1 reviews a large proportion of the published work concerning the integration of design and inspection systems; specifically co-ordinate measuring machines.

Given access to a 3D model of component which includes tolerances set against key component dimensions, highly automated inspection planning is possible. To date this level of automation has not been found in commercial systems due to the lack of a tolerancing function in computer aided design systems. (On a 3D solid or surface model as opposed to simply having tolerances on a 2D drawings.) Limitations within existing formats for transfer of this toleranced 3D model to off-line programming systems is another problem which remains to be overcome. This paper has been accepted for publication in the International Journal of Production Research.

Paper 2 describes how component probing points and movements between these can be generated based upon a 'feature' based definition of component geometry.

The techniques described have been implemented in part in a prototype off-line programming system based upon the robotics simulation system GRASP. This prototype, known as the Inspection Planning Assistant (IPA), allows semi-automatic off-line programming to be carried out. IPA has been has been tested against a number of real CMM programming problems from industry. This work remains unpublished.

Paper 3 discusses the new standard for the exchange of product model data (STEP ISO 10303) and specifically a part of STEP (known as an application protocol or AP) for inspection process planning, AP219. This paper was presented at the 27th International Symposium on Automotive Technology and Automation in Aachen, Germany.

Work on STEP AP 219 is currently in a state of abeyance, this paper was one of the actions taken to raise interest, in this case within the automotive industry, in order that work on the AP could be continued. The relatively limited number of CMM manufacturers and off-line programming system developers and the wide range of these systems installed in the automotive industry place made this an ideal group to facilitate the development and demonstration of this AP. Although carried through to a draft proposal for funding within the European ESPRIT programme, it proved impossible to draw together all interested parties at the time. Despite this, the excersise generated widespread interest and a network of contacts within key organisations within Europe concerned with STEP and / or inspection technologies. This network will certainly be of use in the future.

Paper 1

Integration of Design and Inspection Systems
- A Research Review

Paper 1

Integration of Design and Inspection Systems - A Research Review.

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Abstract

This article reviews some 75 published papers in areas related to the integration of design and inspection systems. The principle aim of this integration is the automatic or semi-automatic off-line programming of co-ordinate measuring machines (CMM). The level of automation possible depends upon the availability of toleranced geometric model in a computer aided design system. Building upon this base, numerous techniques have been developed for the creation and validation of inspection process plans for subsequent execution in a CMM.

Keywords

Co-ordinate Measuring Machines, Inspection, Off-Line Programming, CAD

1. Introduction

To take a component model from a computer aided design (CAD) system and automatically generate all the information required for down stream activities such as machining, assembly and inspection represents a utopian situation which is many years away from realisation.

The situation facing manufacturing industry today is far from this ideal, with numerous separate systems linked, at best, through transfer of files in standard formats or via specially written routines. Individual systems have often limited or no facilities to help the user or to automate the process. The linking and automation of the activities involved in the design and manufacture of components hence provides fertile ground for research and development.

This article reviews a significant proportion of the published research work related to the linking of CAD, automated inspection process planning for co-ordinate measuring machines (CMM's) and evaluation of inspection results and feedback to design. The first part of the article provides an overview of the development and current use of CMM's in industry. A brief background to CAD, and the application of tolerances to geometric models, is followed by a review of research inspection process planning systems. This includes all the key techniques applied in the automation of .inspection planning leading to valid inspection routines for a CMM. Brief mention is also made of the return of inspection data to CAD.

Many of the techniques discussed are now commonly available in commercial systems. Development and application of is limited by industry demand for off-line programming techniques, the availability of CAD systems allowing tolerancing of solid geometric models and by the availability of neutral interface standards for the transfer of these toleranced models to off-line programming systems. The current pace of development of the standard for the exchange of product data (STEP), which will allow this data transfer to take place, is likely to lead to increased automation of many process planning activities, not least of which will be inspection process planning. Possible future trends are hence briefly discussed at the end of the article.

This article provides a thorough and timely review of the state of the art for those working, or wanting to work, with off-line programming for co-ordinate measuring machines.

2. The Use of Co-ordinate Measuring Machines

The purpose of a manufacturing system is to produce parts of specific dimensions and form. The growing importance of product quality has lead to an increasingly important role being played by inspection within manufacturing systems.

An inspection system should be able to measure "the dimensional characteristics of randomly presented parts of virtually any configuration or complexity and provide real-time feedback to the manufacturing process." [1] Current 'State of the Art' co-ordinate measuring machines (CMM's) approach this ideal, being highly automated and often including automatic probe changers, articulated probe heads, protective enclosure, palletised part handling, automatic part identification, user friendly control software, and automatic statistical analysis [2] with data management software also becoming more common. [3]

CMM's were originally developed as a flexible means of performing fast and accurate dimensional inspection of prismatic parts. They have since become widely adopted as a general purpose tool with the capability to measure many different types of component. [4] A CMM may be used to inspect incoming finished and semi-finished parts as well as for the inspection of components before, during and after actual production processes. In-process inspection can be a part of the production equipment but is perhaps more commonly an accompanying activity, for example in a manufacturing cell. [5] Whilst CMM's are best located in an environmentally controlled room, improvements in CMM design, construction materials and isolation techniques means that they are now commonly placed on the shop floor. This increasing use of CMM's at or near individual production activities is reflected in the rapid growth for 'shop hardened' CMM's. [6]

CMM's are often used to indirectly check the capability of production processes and equipment. [7] Small batch sizes, just-in-time (JIT) manufacturing and highly productive numerically controlled (NC) machine tools used today requires near instant component verification. Techniques such as statistical process control (SPC) are not applicable with small batch sizes and one-off production. In these situations, the use of CMM's to inspect individual components can reduce scrap or rework. [8] This is also true even if inspection is for process refinement, for example when fine tuning the form of moulds and dies. [9]

The most obvious benefits from using CMM's are the significantly lower inspection times when compared with traditional inspection techniques; reductions of 90% being commonly quoted. [8] CMM's often eliminate the need and cost of complex gauging fixtures, with only simple fixtures being required to support the component correctly with respect to datum surfaces. In many cases even this type of fixturing is unnecessary, the component simply being located on the table of the CMM and datum faces being located as part of the inspection process.

The use of CMM's is changing the nature of inspection, many different inspection procedures which were once carried out using different techniques can now be carried out on the CMM. [6] However, in practice inspection remains a hybrid task with a mixture of traditional measurement techniques used in combination with a CMM.

3. Geometry Specification for Manufacturing and Inspection

3.1. Computer Aided Design Representations for Nominal Geometry.

3.1.1.Wireframes.

The earliest computer aided design (CAD) systems modelled geometry in the form of points, lines and arcs in two dimensional space; effectively acting as an electronic drawing board. These systems naturally evolved into three dimensional geometry. A 3D object modelled in this way is known as a 'wireframe.' When displayed, a wireframe model is 'transparent' as only edges and not the surfaces between these are explicitly represented. However, hidden line removal algorithms can be applied to give the impression of a solid. [10]

3.1.2. Surface and Solid Models.

One of the representations which explicitly defines the surfaces of a model, rather than just the framework or outline, is the boundary representation or B-rep. In a B-rep model, the object is described by the set of faces which bound the object, individual faces are bounded by a loop of edges which are in turn specified by their vertices; not unlike a wireframe. Neither the boundary of a face nor the face itself need by linear/planar, more complex surfaces or boundaries can be described by mathematical curves which are known as splines, the surfaces generated being known as surface patches. [11] B-rep modellers are generally acknowledged as offering a good basis for the visualisation of a component at a graphics terminal as the geometry of each surface is explicitly known.

Another common representation, known as constructive solid geometry (CSG), store component geometry as a set of Boolean operations, cut, join, intersect etc., applied to a limited set of solid primitive objects, cubes, cylinders, cones etc. CSG models are a good basis for calculating mass related properties. However, this data structure, known as a CSG tree, contains information about an object in an 'unevaluated' form which needs to be evaluated into the explicit vertices, edges and surfaces of the resulting solid for the purpose of visualisation. [12] In order to benefit from the advantages of both representations, many of today's CAD systems use a hybrid B-rep/CSG representation. [10]

3.1.3. Features, Product Data Models and Meta Models.

The basic geometric entities of a component model in a CAD system, such as a surface, edge or vertex, or an auxiliary geometric attribute of a part such as a centre line, are often referred to as primitive features. Within the component geometry, specific areas of geometry can be identified which perform particular functions. These are often known as form features. Examples of form features would included slots, holes, chamfers etc. [13] Some CAD systems allow geometry to be created using user defined form features or allow primitive features or surfaces to be identified and to have additional parameters associated with them for use in down stream activities such as process planning or NC part programming. These systems are often known as feature based systems. Techniques are also available for identifying features within none feature-based CAD systems. [14]

More comprehensive data structures which take account of the overall needs of engineering, not just nominal and toleranced geometry, are known as product data models, [15] or metamodels. [16]

3.2. Geometric Tolerancing

3.2.1. Geometrical Tolerancing Standards.

The current ANSI / ISO standard for dimensioning and tolerancing divides geometric tolerances into four categories; form, orientation, location and runout. Tolerances should only be applied "where they are essential, that is, in the light of functional requirements, interchangability and probable manufacturing circumstances." [17] Tolerances constrain a feature to lie within regions known as tolerance zones and may relate to a single feature, for example a diameter, or to several features, for example a distance between two holes. Features usually are referenced to datum features which are used to establish the location and orientation of component datum's or reference surfaces.

3.2.2. Geometric Dimension & Tolerance Data in CAD

The automation of many activities such as process planning and NC machining cannot be successfully achieved based solely upon ideal geometry. Therefore a major requirement for successful development and implementation of computer integrated manufacturing (CIM) applications is a product model which includes allowed manufacturing inaccuracies, tolerances, associated with the location and shape of component features.

Whilst 3D CAD modellers allow nominal geometry to be defined, they do not usually support geometric dimensional & tolerance (GD & T) information. This is a known deficiency which is a major problem when integrating systems which require tolerance data. [18] As GD&T information must be associated with component surfaces in the geometric model it follows that the user should operate through a common user interface to both the geometric model and the GD&T model. [19, 20] This seemingly trivial requirement is not without its problems. [21]

3.2.3. Preferred Geometric Representations for Tolerancing of CAD Models.

Component geometry presented in a two dimensional drawing is open to interpretation and cannot be relied upon to give an unambiguous representation of a product. It is therefore quite possible that the original design intent can be lost. [22] Wireframe models lack mathematically rigor therefore a surface or solid model based upon a boundary representation (B-rep) and/or constructive solid geometry (CSG) are required as a basis of a product data modeller which incorporates tolerances. [20,19]

If the underlying solid modeller uses boundary representation, linking tolerances to surfaces of the model presents few problems. However, with CSG modellers specific surfaces are not known to exist until the model is 'evaluated' in which case primitive surfaces may be split or even totally disappear. [21]

3.2.4. Tolerance Representation in Research CAD Systems

Roy and Liu [12] developed a structured face adjacency graph (SFAG) over a hybrid CSG/B-rep modeller. The face adjacency graph linked B-rep surfaces to CSG primitives in such a way that all kinds of tolerance could be attached to the part model.

Gossard, Zuffante and Sakurai [23] used a combined CSG/B-rep modeller in a graph structure known as an object graph. This stored dimensions as a relative position operator (RPO) which described the location of a feature face relative to a reference face.

Requicha and Chan [24] presented a variational graph or VGraph tolerance representation based upon CSG modeller PADL-2. The VGraph stores all tolerance information about an object linked to a traditional CSG tree through a set of nominal faces (NFaces) of the object.

Wang and Ozsoy [25] proposed a hybrid CSG/B-Rep structure in which the CSG tree was modified with the addition of constraining operator nodes (Cnodes) which constrains the position or orientation between two primitives.

Kanai, Kawamura, Kishinami and Saito [26] used a hyper-patch model which was toleranced through the application of Entity Attribute Relationships (EAR’s). These were also used to attach information about machining processes used to generate the referenced surfaces.

EPS-1 [20, 27, 28] used two separate databases, one for dimensional and tolerance data and one containing a B-rep model for nominal geometry. These two databases were accessed via a common programming interface which allowed calls to be made to the underlying data structure via an Application Interface Specification. The link between these two databases was a dimension and tolerance (D&T) node consisting of a datum reference frame, which pointed to the set of entities (features or surfaces) in the geometric model which were used as a reference, an entity linking node, pointing to the specific entity on the model which was being toleranced and an evaluated data node used to hold dimensions.

Walker and Wallis [29] used a CSG modeller which allowed attributes to be attached to surfaces. Yau and Menq [18, 30, 31, 32] used CATIA's Graphic Interactive Interface (GII) and the ATTRIBUTE function as a basis for associating tolerances with particular component surfaces.

Smolky and Vrana [22] described software which verifies that the model has been correctly toleranced to ANSI Y14.5M and from this develop a worst case part or Softgauge® which is a displayed along side the original geometry in the CAD system. This can be later used for generation of CMM part programmes and for validation of the component. This is also described by Foundyller [33] and Granquist. [34]

3.2.5. Tolerance Representation in Feature Based Systems

The use of form features or identification of features in an existing model (CSG or B-rep) offer a way of linking manufacturing data to the CAD model [35] However, the use of design features as a basis for subsequent or concurrent manufacturing process planning is not without its difficulties. What constitutes a 'feature' will differ in design, manufacturing, assembly or inspection contexts; the so called multiple-view problem. [13]. Also, a given component can be generated, or decomposed, into an almost infinite number of ways. In practice only a significantly small sub-set of these would be used but even this sub-set will not necessarily form a good basis for automation of down stream activities, for example manufacturing process planning or inspection process planning. [36] There is thus the need for 'feature' recognition, feature refinement, feature conversion or feature mapping where feature is a context dependent entity. All these are active areas of research interest. [13]

ElMaraghy and Gu [37] developed a feature based system offering a limited number of toleranced primitives with known engineering and dimensional attributes. The selection of features available representing a trade off between the flexibility and generality of the modelling system developed and the complexity of the feature data structure.

Merat and Radack [38, 39] developed a feature base design system, the strategic design driven inspector, based upon Concept Modeller™ [40] Associated with each feature type was a set of alternative schema's for dimensioning and tolerancing the feature. When developing a component, the user would create a starting feature, for example a block or cylinder, and add or subtract additional features. When creating a specific feature, the actual dimensions and method of tolerancing would be stated.

4. Component Inspection

4.1. Inspection Process Planning

4.1.1. Computer Aided Process Planning and CAD/CAM Systems.

Computer aided process planning (CAPP) systems are often regarded as being central to the realisation of computer integrated manufacturing systems as they provide the link between design activities and manufacturing activities. [19] Early CAPP systems were almost purely text based and not typically associated with another planning activity, that of generating cutter paths and the code necessary to drive computer numerically controlled (NC / CNC) machines. [41] Due to the common link with computer aided design, these machining related systems are known as CAD/CAM systems. In this article, the term Inspection Process Planning will be used to encapsulate the high levels of automation typically associated with CAPP and the generation of code for computer controlled machines or CAD/CAM.

4.1.2. Inspection Planning and the Programming of CMM's

To inspect a component requires knowledgeable interpretation of design intent presented in engineering drawings as well as a knowledge the processes used in its manufacture and of the capabilities of the inspection available. From this information and knowledge a method to inspect a component, which might not necessarily be on a CMM, can be developed. An inspection process plan will include the sequence of inspection of datum surfaces and individual features and, in the case of CMM's, selection of suitable component and probe orientations and the placing of probing points on the feature surfaces. [42] Inspection planning will also determine how the raw inspection data is to be evaluated and how these results are to be presented. An inspection plan may not necessarily be a formal document, but, in the case of CMM's would more commonly be embedded in the program used to drive a CMM. These programmes are still often 'taught in' to the CMM; an initial manually driven inspection routine being replayed for subsequent components. This programming overhead can be significant, especially when relatively few parts are inspected.

4.1.3. CMM and CAD Interface Standards

The transfer of CAD geometry to off-line programming systems is usually made by either bespoke routines or via standard CAD exchange standards such as IGES and VDA[43]. The major problem with these interface standards is that they do not encompass tolerance data which is an important data item for both the evaluation of inspection results, which is often done within the CMM software, and also the automation of many inspection planning tasks.

CMM's typically have their own programming language to which the off-line programming system must adhere. The Dimensional Measuring Interface Specification (DMIS) is a standard format used for bi-directional transfer of inspection data between CAD systems and CMM's. [44] DMIS is a high level programming language with a syntax similar to Automatically Programmed Tool (APT). DMIS format part programmes and returned inspection results are usually pre- and post-processed into a format usable by the CMM or CAD system. The advantages of such standard interfaces include the demonstrated need and commitment of those companies involved in its development. In the case of DMIS, numerous CMM suppliers and users were involved. [44, 45] The emerging standard for the exchange of product data (STEP) is likely to encompass geometric and process planning requirements in the future. However, the development and acceptance of STEP. [46]

4.1.4. Off-Line Programming of CMM's

Excluding metal removal, CMM programming is very similar to NC programming, both ideally building upon a common base, a three dimensional model of the part. [20] However, whilst the majority of expensive machining centres are today programmed either off-line or at the machine whilst it is running another part program, CMM's are just starting to follow this path. Programming software for both off- and on-line programming of CMM's is said to lie a decade behind comparable software for NC machining centres [47] although this situation is changing rapidly. A recent Delphi survey identified off-line programming tools as a major area of development for the 1990's. [48]

4.1.5. Commercial Off-Line Programming Systems

Due to the similarity between programming of CNC machines and CMM's, many CAD/CAM vendors already offer off-line CMM programming capability, as do vendors of some robot simulation systems. In addition, many CMM vendors have developed their own off-line programming software. The functionality of these systems varies considerably, the more advanced systems being totally integrated with a host CAD system and able to use the original CAD geometry directly without the need for this to be transferred to the off-line programming system via. a bespoke routine or a standard such as IGES or VDA.

Commercial offerings are typically a combination of an established CAD system coupled with a third party inspection program. Available off-line programming systems for CMM's include: Prime/Calma, [49] EDS/Unigraphics, IBM's CATIA with Audi AG's Audimess or Valisys, [33, 34] Matra Datavision's Euclid with GEMINI and CAMPS 3D, Silma with CimStation Inspection, [47] Tecnomatixs with Robcad/CMMxWorks, [50] Brown & Sharp with Microquindos, [51] Qualstar/First [49] and Mitutoyo with CMMCAD. Bespoke developments include Lehr Precision integrating with McDonnell Douglas [52] and Mitutoyo/Geopak with a number of CAD systems. [1]

4.2. Research Inspection Process Planning Systems

Few fully automated inspection planning systems have been realised, although all research into inspection process planning contain elements of automation. Those research groups that have reported complete systems, as opposed to concentrating upon elements of the process planning task, break the problem of process planning down into different stages.

4.2.1. Expert Planning System One - EPS-1

Expert Planning System One (EPS-1) is a research system developed by CAM-I. This testbed system aimed to develop an intelligent inspection process planning environment leading to highly automated dimensional inspection planning through the integration of CAD, CAM and CAPP. EPS-1 included a geometric modeller, a dimensioning and tolerancing modeller and an inspection process plan generator. Considerable use of built in logic aimed to automate the process as much as possible. Automated facilities included selection of appropriate CMM, fixturing, global inspection plans and probing sequences for individual features. [19, 20, 27]

EPS-1 breaks the problem of inspection process planning down into nine parts:

a) obtain/define inspection plan.
   Definition of part id's and inspection strategy constraints.
b) task decomposition/definition.
   Extraction of toleranced features and datum surfaces from the GD&T modeller. For each feature a 'work element' is added to the overall inspection plan.
c) determine methods.
   Selection of a suitable CMM based upon the types of features to be measured.
d) determine set-up
   Optimisation orientation of the part with respect to the CMM using orientation vectors for each feature. Work element accessibility is based upon machine axis, feature surface normal's or cylindrical axis and reference / datum feature orientation. The rules used minimised the total number of component orientations required.
e) determine tool/holder
   Probe orientations required are selected for each feature / work element heuristically. Strategy may be to minimise the number of probes used or to maximise the number of probing's from a given probe.
f) detail/optimise plan
   Sequencing of inspection activities / work elements is determined via heuristics and decision table logic. Datum and feature precedence is accounted for.
g) generate/simulate
   Individual feature probing sequences are generated using templates, and the path of viewed as a 3D line in the geometric modeller. Clash detection and avoidance must be carried out manually as no clash detection was available.
h) produce control information
   Produce DMIS output for the measurement task.
i) produce support information
   Add further information required by the operator.

4.2.2. Inspection Process Planning Expert (IPPEX)

Brown and Gyrog [19] developed Inspection Process Planning Expert (IPPEX) as a further refinement of the concepts demonstrated by EPS-1.

4.2.3. Intelligent Planning Environment

Yau and Menq [18, 30, 31, 32] implemented an automated inspection planning system based upon the commercial CAD system CATIA and a knowledge based expert system shell. This system suggested five steps in inspection planning;

1. Specification
   Translate product data, geometry, tolerances, manufacturing methods, inspection constraints etc. into a specification of what is to be measured and how.
2. Inspection Planning
   Locate probing points, defining approach vectors, plan moves between individual probing points and between features.
3. Program Verification
   Check this initial path for clash situations and if necessary corrected.
4. Execution
   Execute this verified program.
5. Analysis
   Analyse the resulting data points against the nominal geometry and generate an inspection report.

4.2.4. McMaster Inspection Planner

ElMaraghy and Gu [37] used an expert system written in Prolog coupled with a research geometric / GD&T modeller.

1. Feature identification
   Selects those features which are appropriate for inspection on a CMM
2. Accessibility Planning
   Identifies those features / datum's which can be inspected with the current probe/component orientation,
3. Sequence Planning
   Sequences datum inspection followed by inspection of features related to these datum's.
4. Tolerance Checking
   Provides feedback of inspection results.

4.2.5. Strategic Design Driven Inspector (SDDI)

Merat, with Radack and Galm [38, 39, 53] described a Strategic Design Driven Inspection system which uses 'fast' but limited accuracy techniques such as vision based systems as a method of eliminating features with relatively course tolerances or which are obviously outside tolerance, before using slower instruments such as a CMM and contact probe.

1. Generate Inspection Plan Fragments
   Each feature or datum surface is linked to an Inspection Plan Fragment Generator for that particular class of tolerance. The IPFG produces Inspection Plan Fragments which contain valid probe / component orientations for the particular feature.
2. Group measurement requests by part orientation
   All IPF's which can be measured with the same part orientation are grouped together.
3. Select an IPF to inspect each feature
   One IPF from those generated by the IPFG is selected based upon optimisation rules.
4. Eliminate redundant measurement requests
   IPF's for different tolerances can generate measurement requests for the same surface. Duplicate requests are removed.

5. Create measurement sequences from measurement requests
   Each IPF is used to generate a sequence of probe movements.
6. Sequence the operations
   A valid sequence, taking account of precedence etc. is generated using a topological sort algorithm.
7. Generate collision free path
   Configuration spaces are used to generate movements between individual features.
8. Generate executable code
   Executable code in DMIS format is generated.

4.2.6. Stuttgart IPA

Roth-Koch [54] described a system under development at Stuttgart IPA for the inspection of free form surfaces and evaluation of inspected data based upon the CATIA CAD system.

4.2.7. Brunel CMM-CAD

Mullineux with Medland, Singh, Sittas and also with Cowling [55, 56, 57] described a constraint based system under development at Brunel University.

4.2.8. New South Wales PC Based Inspection

Farmer and Smith [58] described a PC based inspection planning system where inspection data coded into feature attributes in a 2D AutoCAD drawing were used to drive a CMM.

4.3. Elements of Inspection Process Planning

4.3.1. Component / Probe Orientation Strategy.

Numerous valid orientations of a component / probe are possible. An important part of inspection planning is to establish which component orientations are required to allow inspection of all features. These orientations must take account of accessibility of features and datum surfaces, and also machine axis and possible probe orientations.

Spyridi and Requicha [59] developed the idea of feature accessibility cones. This abstracted the actual probe as a straight line and for each feature determined those probe orientations which allowed contact with the entire feature surface. The set of possible orientations was termed the Local Accessibility Cone (LAC). In order to account for situations where valid probe orientations intersected the workpiece, i.e. a clash situation, a Global Accessibility Cone (GAC) was also determined which was the set of probe orientations which did not pass through the workpiece. Given that a set of features can be inspected by the same probe if there is a none empty intersection of their GAC's, determining the minimum number of probe orientations required to inspect all features is a matter of finding the minimum number of sets of features with none empty GAC intersections. Finding the optimal minimum number of sets is an insoluble problem, but algorithms for determining sub-optimal sets are possible. Other techniques must be used to select appropriate orientations from the candidate orientations suggested.

Khoshnevis and Yeh [60] developed the similar concept of accessibility zones for given feature surfaces. An accessibility zone was the area of the feature accessible given the available probe orientations.

4.3.2. Probe Point Placement Algorithms.

An important aspect of inspection process planning is placement of probing points on a candidate feature. The number and location of inspection points should reflect both the geometry of a feature and the tolerance applied to it. When a 'hard' gauge is replaced by a CMM, the nature of the inspection changes. Inspection using a CMM only samples the surface at a finite number of points. This leads to two related problems; where to sample the surface and how to interpret the resultant data. [38]

Mullineux with Medland, Singh, Sittas and also with Cowling [55, 56, 57] used standard probing algorithms for regular features and point to point inspection for other, none regular surfaces. Standard algorithms included equi-distant points on the circumference of a circle, the number of points to be inspected could be defined interactively.

EPS-1 [19, 20, 27] used a template for each feature assuming an ideal relative orientation of probe and feature. This idea was extended by Legge and Åhman [61] to compensate for relative probe / feature orientation. Merat and Radack [38, 39] used a template known as an Inspection Plan Fragments Generator (IPFG) which produced inspection code fragments, i.e. process plans for individual feature, depending upon tolerance feature type.

Walker and Wallis [29] used a regular rectangular grid projected upon the surface of the feature to be measured, placing probing points at a random positions inside each grid cell. These points were then grouped into 'clusters', the cluster size (and grid mesh) depending upon feature type and tolerance. Each cluster was subsequently replaced by a representative probing point.

Vardar and Ozsoy [62] used a method for the placement of probing points on a planar surface which was derived from the technique of mesh generation for Finite Element Analysis (FEA). A candidate set of inspection points was given by the centroid of each of the triangular mesh patches from the mesh generation algorithms. Three methods of selecting the required number of points from this candidate set were presented; random selection, maximising the distance between selected points and selection of the outermost points within the meshed surface.

Kanai, Kawamura, Kishinami and Saito [26] used an integrated CMM / NC programming system to locate probing points in such a way as to detect expected inaccuracies from the machining process, for example surface waviness when face milling.

Yau and Menq [18, 30, 31, 32] used a statistical sampling plan to determine the number of probing points required based upon the design tolerance and the accuracy of the manufacturing processed used to generate the feature. This information was held as Inspection Attributes associated with each feature in the CAD system used. The sampling plan gave the number of inspection points but not their distribution over the feature and, as would be expected, increased the number of sample points in response to tighter tolerances, but reduces them as process capability improves.

Duffie, Feng and Kann [11] generated paths for probing complex sculpted surfaces which drove the probe normal to the surface, with a given scanning density. This technique was also described by Roth-Koch [54] and Reynolds [52] Kawabe, Kimura and Sata [63] increased the probing density at the edge free form surface to reduce the influence of a zero curvature assumption at the boundary. Mullineux with Medland, Singh, Sittas and also with Cowling [55, 56, 57] suggest a similar procedure in which probe points along two adjacent features are made closer together towards the expected/predicted feature transition.

Chen, Tang, Ni and Wu [64] described predictive algorithms for placement of probing points when scanning free form surfaces. These algorithms increased the scanning density where the surfaces experienced large rates of change. The same technique was used by Jennings [49]

4.3.3. Sequence of Probing

The probing points on a given feature can usually be probed in any sequence. Likewise, the sequence of inspection of features is only constrained by the requirement to inspect datum features first. It is therefore possible to minimise the overall inspection time by selecting an optimum sequence of execution of features and feature probing sequences.

Merat and Radack [38] determine the sequence of probing for the set of points related to a feature by starting from an arbitrary point and moving to the nearest unprobed point on the current feature. Walker and Wallis [29] introduce the idea of a cost function proportional to the weighted distance between the points being considered; the weighting accounts for different axis of the CMM taking different times to move the same distance. The same technique is used to select the next feature to inspect.

4.3.4. Clash Avoidance

A CMM can be regarded as a Cartesian robot whose end effector is the probe tip. The aim of inspection process planning is to generate a collision free path through all inspection points. Two possible methodologies are possible; clash avoidance and clash detection / evasion. In clash avoidance schemes, clash situations are avoided when defining a probe path. In clash evasion schemes candidate probe paths are evaluated for clash situations which, if found, are corrected. [65] In both situations it is important to know the distance between objects during relative movement as well as the extent of a clash if it should occur. Dong and Yuan [66] identify a variety of techniques including vertex based, surface based and convex object based methods for calculating the distance between object.

Merat and Radack [38] used pre-calculated configuration spaces for given feature orientations and CMM / probe combinations. Using the fact that the configuration space for a component is the union of the configuration spaces of its individual features, were able to generate a component configuration space. This was then used with a minimum path algorithm to derive allowable paths within the configuration space.

Yau and Menq [18, 30, 31, 32] consider the avoidance of clash by selection of alternative probe orientations. The idea of a local accessibility cone developed by Spyridi and Requicha [59] were modified to take account of only those points being inspected rather than the entire surface of the feature. From the candidate orientations found, the probe orientations which allow access to the inspection points can be determined. A heuristic method was used to select a probe orientation that does not clash with the component during approach to these points.

4.3.5. Clash Detection and Evasion

Walker and Wallis [29] approached the problem of clash detection by using the technique of shrinking the model of the probe tip (or any other part of the probe model) to a point and growing the model of the component being inspected by a corresponding amount. If the probe tip centre lies inside the grown component at any time a clash situation exists. This is a technique well known in the robot path planning community. [66, 67] This clash was subsequently avoided by using a heuristic search technique to locate a point on the edge of the surface to be avoided which was closest to the destination point. A transit point is created which is offset from this edge point.

Yau and Menq [18, 30, 31, 32] used a heuristic method of clash detection and correction. In this work, the probe tip was taken to be a point and the CMM was assumed to move with straight line path segments. A clash situation occurred if the line representing the movement of the tip intersected the component surface. This idea was extended to include modelling of the stem of the CMM probe as a line, (which becomes a face when the stylus moves along a straight line path) and the column as a cylinder, (with a swept volume approximated to a box). A clash situation was known to have occurred when the stem 'face' or any face of the column 'box' intersects the component. A heuristic method was then used to modify the probe path by the placement of additional transit points if a clash situation was discovered however no details were given.

4.3.6. Generation of DMIS Programmes

A final stage is for the validated inspection paths to be output in a format acceptable for the CMM to be used. This format could be the CMM's native programming language or the dimensional measuring interface standard (DMIS).

Pham, Martin and Khoo [68] described a knowledge based expert system to provide a generic link from inspection planning systems to a CMM. Through a dialogue with the user, the expert system was given information relating to the format of the input data file and subsequently generated a pre-processor to convert an inspection plan into Neutral Data Format (NDF - an equivalent of DMIS.)

4.3.7. Scanning and Digitisation of Free Form Surfaces.

Scanning of a surface where the actual geometry is not known is a special case where the inspection process plan must be created dynamically.

Chen, Tang, Ni and Wu. [64] noted two conditions for accurate digitisation: a.) that the measuring probe contacts normal to the component surface and b.) that a sufficient number of measurement points are taken. Two ways to achieve the first were reported, the use of probes that detect the contact point and the use of the original CAD model to generate the probe path. Three methods for scanning a free form curve were presented; Linear Prediction, Polynomial Prediction and Spline interpolation. These methods used on-line measured data to predict the form, and hence contact points and normal, of the surface being scanned. The sampling rate being adjusted dynamically based upon actual changes in the curvature of the curve.

4.4. Evaluation

4.4.1. Deterministic and Random Measurement Errors

In order to evaluate the raw data from the CMM, it has to be known that this raw data is in its self accurate. Yau and Menq [18, 30, 31, 32] proposed a statistical method of separating random errors from deterministic errors when measuring surfaces of a known form.

Deterministic errors can be compensated for by correcting the measured probe points with a mathematical model of the CMM determined by either measuring a testpiece with known geometry, for example a three dimensional ball plate, or by measuring individual geometric parameters using an independent measurement technique such as laser interferometry. These are known as artefact testing and parametric calibration respectively. A total of 21 parameters can be identified: three scale errors, vertical and horizontal straightness and three angular errors per axis, and three squareness errors. These techniques can improve accuracy by a factor of ten. [6, 69]

4.4.2. Conversion of Raw Data Points to Actual Geometry

A CMM, like many other methods of inspection, only generates samples of data points on an individual component. There are currently no standards or obvious interpretations of this measurement data, which is regarded by many as a significant problem. However, formal algorithms for the evaluation of point data, based upon functional tolerancing rather than ease of computation, are being developed. [70, 71, 72] It must also be noted that analysis software itself is a potential source of error. [6]

4.4.3. Location of the Component on the CMM.

Yau and Menq [18, 30, 31, 32] reiterate the commonly used 3-2-1 method; three points on a primary plane, two on a secondary plane and one on a tertiary plane. A 'localisation' algorithm was then used which minimised the sum of the squared distances between a probed point at a known location and the corresponding points on the CAD model and from this data derives a transformation matrix. Further points were fitted to the model using this matrix. However, although the component has been mathematically oriented to the original CAD geometry, this localisation is itself influenced by manufacturing inaccuracies.

4.4.4. Fitting of Inspected Points to Regular Features

The use of least squares fitting of inspection data to nominal form features, lines, circles etc. is extensively used. Yau and Menq [18, 30, 31, 32] propose an Optimal Match algorithm to eliminate the offset error between measured and design data by minimising the squared shortest distances from each point to the nominal feature geometry. The same technique was used by Mullineux with Medland, Singh, Sittas and also with Cowling [55, 56, 57]

Jennings [49] also presented a least squares solution for mapping inspected data points onto nominal geometry. His technique used the measured point and a point projected onto the nominal feature surface; the measured point assuming to lie on a vector normal to this nominal feature point. It was pointed out that by skewing the density of the measured data points in a certain area, the fit would be skewed towards the more densely probed area. This problem was eliminated by the development of a geometric tolerancing best fit whereby each feature surface was assigned a tolerance which was converted into a tolerance band. The inspected data was then allowed to 'float' until it sat within the tolerance band. A correction matrix for position and alignment could then be produced. Duffie, Feng and Kann [11] reported 'best fitting' of sets of data points and error compensation in applications such as mould design.

4.4.5. Curve Fitting

Kawabe, Kimura and Sata [63] used curve fitting, increasing the probing density at the ends of the curve in order to reduce the influence of a zero curvature assumption at the boundary.

Reynolds [52] reports a system for feeding back inspection data from aerofoil sections to a CAD system. Granquist [34] describes an environment where die casting moulds are inspected and error reports fed back graphically to the CMM inspector. Smith [9] reports similar work with injection moulding dies as does Duffie. [73] Gupta and Sagar [74] reported a system for the capture and interpretation of 3D point data.

The geometry of a component feature generated by curve fitting may be significantly different to that expected from the original CAD model. If this error is unacceptable Mullineux with Medland, Singh, Sittas and also with Cowling [55, 56, 57] suggest a method of sub-division where the inspected feature is divided into two and re-inspected. This procedure isolates the geometric inaccuracies in the actual component into a specific part of the curve.

4.4.6. Graphical Feedback

Mullineux with Medland, Singh, Sittas and also with Cowling [55, 56, 57] assessed circular features by comparison of nominal features with actual features; the error in the position and size of the actual feature being scaled by a factor of 100. Jennings [49] used a similar technique, providing graphical feedback of errors was made by scaled error vectors showing the deviation from nominal position. This was also reported by Duffie, Feng and Kann. [11]

4.4.7. Evaluation of Source of Errors

Kanai, Kawamura, Kishinami and Saito [26] used Entity Attribute Relationships (EAR’s) to not only attach tolerance information but also the machining processes used to generate the referenced surfaces. If a feature was out of tolerance the EAR was used to identify the manufacturing process which caused the error. A similar technique was presented by Danzer. [75]

5. Conclusions and Future Developments

The techniques for automatic and semi-automatic off-line programming of co-ordinate measuring machines have been well researched and continue to be incorporated into commercial systems. This development will continue, probably at a pace driven by market demand rather than availability of techniques.

A significant bottleneck to system development today is the availability of CAD systems that allow tolerancing of 3D models and secondly the available of neutral interface formats for transfer of this information; many of the more competent off-line programming systems have bespoke links to market leading CAD systems.

6. Acknowledgements

As this article represents a review of published work it is impossible to include the most recent developments. Limitations of space also preclude a more detailed analysis of individual aspects of inspection process planning, which, after all, are dealt with most thoroughly in the original works. I hope that the researchers and research groups whose work is mentioned here will bear this in mind when criticising me for the poor coverage I have given their work.

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P.H. Gu	***37***
J.G. Galm	***53***
D.C. Gossard	***23***
J. Granquist	***34***
V.K. Gupta	***74***
D.A. Gyorog	***19***
I. Ham	***69***
Y. Hari	***71***
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L.P. Khoo	***68***
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Paper 2

Semi-Automatic Probe Path Planning for Feature Based CMM Programming.

Semi-Automatic Probe Path Planning for Feature Based CMM Programming.

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Abstract

This article describes algorithms used for the automatic generation of feature probing sequences in an off-line programming system for co-ordinate measuring machines (CMM's). These algorithms were formulated during development of a prototype inspection planning module for a commercial off-line programming system originally developed for the programming of robots. The algorithms form a basis for the automation of inspection planning tasks which are tedious to perform, whilst leaving the operator free to apply inspection methodology to the overall inspection task. Inspection planning in the system developed is therefore semi-automatic.

The algorithms presented address the placement of probing points on a feature surface, predictive modification of the probing pattern to prevent clash due to the relative orientation of the probe/feature and clash avoiding probe path planning. Clash evasion when traversing between features is also considered.

Keywords

Co-ordinate Measuring Machines, Inspection, Off-Line Programming, Features.

Background

The Need For Off-Line Programming Tools.

The benefits of Co-ordinate Measuring Machines (CMM's) are well recognised [1]. The high productivity of Numerically Controlled (CNC) machines requires near instant component verification; indeed the purpose of a co-ordinate measuring machine is often to evaluate and monitor the performance of a machine tool [2]. For this verification to be carried out effectively, especially in the case of first-off inspection, pre-prepared part inspection programmes are required.

Using and Programming CMM's.

The majority of CNC machine tools are now programmed either off-line or at the machine whilst it is running another part program, CMM's are only just starting to follow this path. Software for off-line programming of CMM's being said to lie a decade behind comparable software for CNC machines [3]. A recent Delphi survey highlighted good off-line programming tools and the integration of computer aided design (CAD) systems with CMM's as major areas of development for the 1990's [4].

CMM's have many modes of operation, the simplest being to work interactively and use the CMM to evaluate component features by specifying the feature type and probing the feature by manually driving the machine. This sequence can be saved and re-run with the next component; the so called 'teach in' mode of operation.
An inspection sequence or programme can also be modified or the CMM's own programming language used to write an inspection sequence from scratch.

Another mode of operation is off-line programming (OLP) which is carried out at a PC or Workstation unconnected with the CMM. Off-line programming may be an integrated function in a CAD/CAM system, or a separate system using geometric data transferred from a CAD system as a basis for programming. Instead of developing probe paths with a real component and CMM, OLP uses the CAD model. Many CAD/CAM vendors already offer off-line programming capability, vendors of robot simulation systems also offer this functionality [3, 5, 6, 7]. Commercial systems are often a combination of an established CAD system coupled with a third party inspection program. In this way, interface problems between CAD system and off-line programming system are avoided.

Off-line programming in a third party system, for example a CAD/CAM system, requires that this systems native CNC programming language be converted to the CMM's language. Initially this was done via bespoke translators, however a neutral format, the Dimensional Measuring Interface Standard (DMIS) [8] has been defined to rationalise the communication between CMM’s and other computer systems.

Benefits of Off-Line Programming.

Off-line programming offers many benefits including:

- i Elimination of non-productive programming time on the CMM thereby offering the potential to increase machine utilisation.
- ii Avoidance of unexpected clash, reach and access problems, hence removing unproductive re-programming time at the CMM.
- iii Possibility to minimise the time required to inspect a given component, allowing greater throughput of work at the CMM.
- iv Reduction in the work involved in defining feature probing sequences, allowing better use to be made of inspection staff's time.

The extent to which these constitute a strategic advantage will depend upon batch quantities, component complexity and other manufacturing or production related constraints. These, coupled with the ease of use of off-line programming tools will dictate their take-up in industry.

System Overview

A prototype off-line programming system has been developed based upon an 'open' version of a commercial robot programming system; instead of a robot a model of the CMM, complete with interchangeable tooling, is used. The off-line programming functionality for the CMM has been created by the addition of two new system menus and a separate programming window.

The CMM movements required for the probing sequences generated can be simulated within the system and corrected for access, clash and reach problems not prevented by the predictive clash avoidance techniques described. Additional transit points and other DMIS statements required in the final inspection program can also be added and the finished program exported in DMIS format to the CMM.

Definition of Feature and Component Geometry.

In the off-line inspection planning system developed, component features are described in the format given by DMIS. These feature definitions are entered via a screen form or imported from a CAD system in the form of a DMIS text file. Component geometry is handled separately by the host simulation system, being imported in IGES format[1] [9]. From the DMIS feature definitions the required probing points and probe paths are automatically generated for each feature following the algorithms described.

Scope of the Algorithms.

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[1] Whilst this results in an almost parallel information flow, one stream to the inspection planning software and one to the simulation system, feature recognition within the incoming IGES file was not deemed to be within the scope of this work, having been well covered elsewhere [10].

Of interest here is the automatic generation of the DMIS statements necessary to drive a CMM to probe a given component feature. The algorithms must first place probing points on the feature, secondly adjust these so that they can be reached with the configuration of probe used and thirdly generate a path between these points which avoids clash with the component. The path generation algorithms can also be used for clash evasion when moving between features if clash occurs with a component feature that has known geometry.

Placement of probing points on a given feature.

The position of probing points on a measured feature are generated automatically with reference to those given for a standard feature of the same type[2] (Fig. 1). Any number of probing points to be used when measuring a feature; given the minimum required to establish the size, position and orientation of a particular feature type.

A general method to describe the location of 'n' points on a feature is not possible, so for each value of 'n' used, a probing pattern on a standard feature must be defined. This pattern is given in the form of a list of either a single or double co-ordinates[3], which may be linear or angular depending upon the feature type.

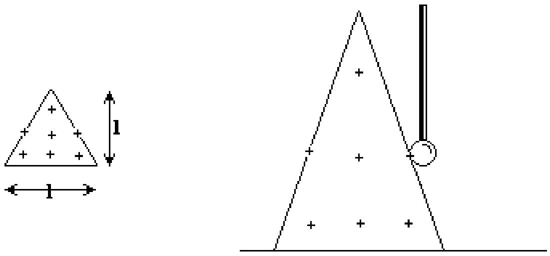

Figure 1. Use of a 'unit' feature as a probing template.

In order to use the above probe point location data, a feature must be of finite size. The extent of some features can be found from their DMIS definition, whilst others DMIS considers unbounded. DMIS allows for an unbounded feature to be limited with bounding planes. Such boundings are used primarily for the purpose of defining tolerance zones and their use for describing the actual feature geometry, whilst permissible, would be potentially extremely complex.

In the system developed, the size of unbounded feature is found by prompting the user for key dimensions when defining the feature or when invoking the 'auto-measure' function. Alternatively, reference could be made to the actual feature geometry if this is known.[4]

Access to a feature with the probe used.

The basic probe point positioning algorithms assume that the probe has free access to all areas of the feature defined. In practice, areas of a feature may be inaccessible to the probe. Several conditions affect accessibility to a given point, and can be used to adjust the position of the probing points so that they lie within reach of the probe.

* *Actual depth of features penetrating a surface*

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[2] In the system developed, several probing patterns can be stored and selected when generating the probing sequence. This is a manual decision, the structure of the off-line programming system being such that the tolerance being evaluated may not known until the user chooses to evaluate an already measured feature. Because of this, it is impossible to use pattern/tolerance selecting routines developed by other research groups. [9]

[3] Single co-ordinates on 2D features, double co-ordinates on 3D features.

[4] Interaction with the original component geometry is not currently possible. The interactive definition of features with reference to component geometry will be implemented in the future.

A probe has finite length which may be greater or less than the depth that a feature penetrates a surface, or the height of a feature which protrudes from a surface. If the length of a feature is greater than the declared length of the probe, the probing points must be corrected to lie within reach of the probe. (Fig. 2a) This can be done by scaling the position of all probing points so that they lie within reach of the probe (Fig. 2b) or by shifting those that fall outside the probe's reach (Fig. 2c).

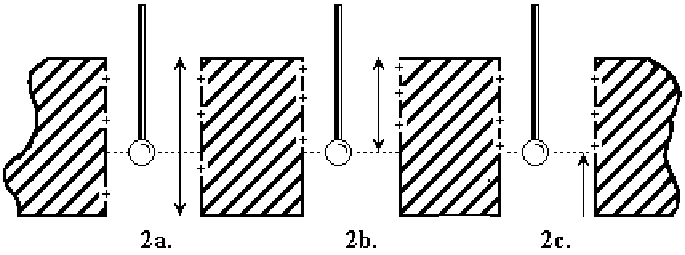

Figure 2. Correction of probing points to take account of probe length.

Other situations can occur when a feature, in effect, penetrates the component. For example, the x,y position of a hole may be established by probing a circle some distance down the hole being measured. In this case, if the circle lies outside the reach of the probe, it must be redefined within the probes reach or an alternative probe selected.

** Probe diameter*
Apart from the obvious problem of probe diameter relative to a limiting dimension of a penetrating feature, the diameter of the probe tip can also affect the area of a sphere or 'inverted' conical feature that may be probed. In the case of a sphere, slightly less than 50% of its surface is hidden from view, an 'inverted' conical feature has almost its entire probed surface hidden from view[5]. In these situations, a larger probe tip diameter allows access to a proportion of these hidden areas (Fig. 3).

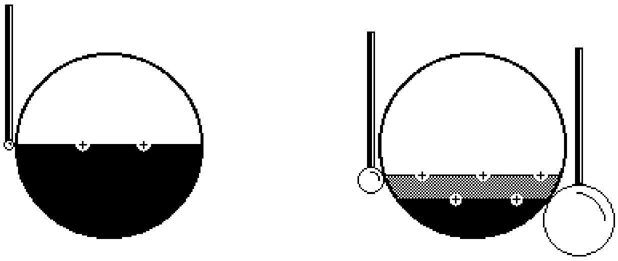

Figure 3. Correction of probing points taking account of probe diameter.

** Relative orientation of probe and feature.*
If the axis of the probe does not align with the feature axis, or with the normal to the plane on which the features lie, a situation similar to that encountered with spheres and inverted conical features occurs. The area of the feature that becomes inaccessible depends upon the relative miss-alignment, the size of the feature and the diameter of the probe used. (Fig. 4)

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[5] Assuming that the feature axis aligns with the declared sensor axis, the actual area hidden depends upon the probe tip diameter and stem diameter.

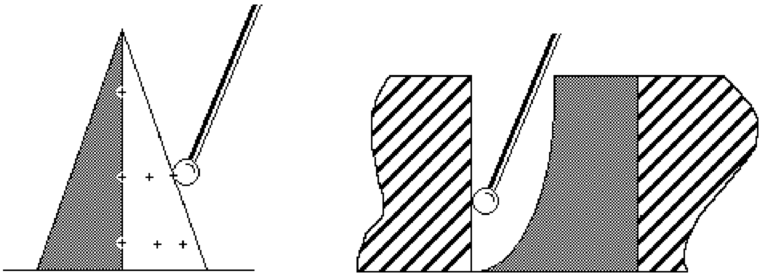

Figure 4. Correction of probing points to take account of probe orientation

Development of a clash free probe path.

Once the probing points on the feature surface have been created, the probe path between these points can be generated. This involves placing a start and end point for the entire feature probing sequence plus the creation of approach and retract points for each probe point. The approach point should ensure that a normal approach to the feature surface is carried out. Finally, transit points which avoid the feature surface may have to be added between each approach / probe / retract cluster (Fig. 5).

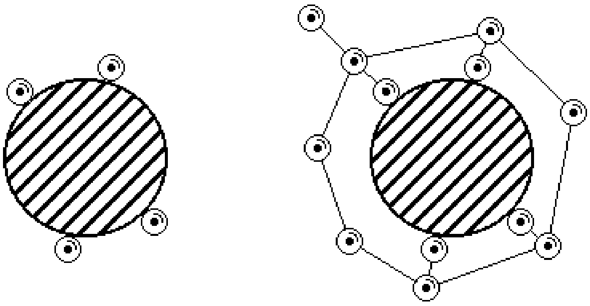

Figure 5. Development of clash free probe paths.

** Start and End Positions*

Placing sensible start and end points with respect to a feature can make the task of generating an overall clash free path when the probing sequences for all features are executed sequentially. An optimal location for start and end position is assumed to lie on some clearance plane lying above the feature.

** Normal Approach Paths*

In order that probe compensation be correctly applied, the probe should approach normally to the probe surface. For each contact point, corresponding 'approach / retract' points which results in a normal approach to the component surface must be generated.

** Clearance Transit Points*

When probing the outside of objects, it is often necessary to traverse around them to avoid a clash situation; for example measuring two points on opposite sides of a cylindrical boss. The number and location of transit points depends upon component dimensions, probe tip diameter and required clearance distance[6].

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[6] The algorithms do not attempt to minimise the distance traversed by the probe by altering the sequencing in which the probing points are visited. However, this technique has been used by other researchers.[11]

Clash evasion when moving between features.

** Contact / Clash Points*

Clash situations can occur when moving between one feature measurement and another. If a clash situation is detected[7] between the probe and a component feature that is of known geometry, the techniques described above can be applied to carry out clash evasion (Fig. 6). The straight line transit path between two features will pass through two points on the feature surface with which clash occurs. These two points can be taken as probing contact points when applying the evasion techniques described above.

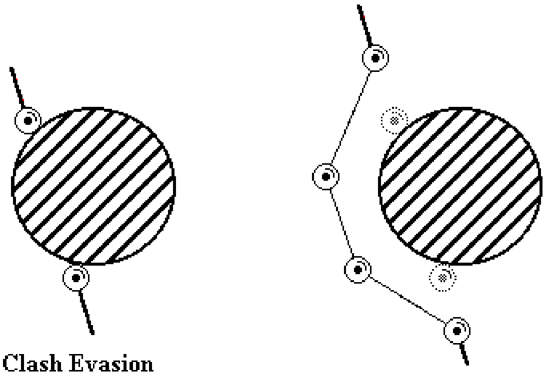

Figure 6. Clash Evasion

** Start and End Positions of Evasive Paths*

The start and end positions of the evasive path should be the clearance distance away from the impacted feature surface. As it is not known if the impact is normal to the surface, account must be taken of feature and probe dimensions in order to find start and end points on the original transit path that is sufficiently far away from the feature surface.

** Clearance Transit Points During Evasion*

Clearance transit points can be generated in the same way as before with the number of transit points being dependant upon component dimensions, probe tip diameter and required clearance distance.

Conclusions.

The algorithms described above take a 'feature' view of the problem of the placement of probing points on a feature and the probe paths between these points. These can be used as a sound basis for the rapid generation of feature probing sequences in both off-line and on-line programming systems. The algorithms described are especially applicable in feature based systems or where feature recognition is implemented although the ideas expressed should also have a place in non feature based systems.

Acknowledgements

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Acknowledgement is also duly given to my co-workers in the Department of Manufacturing Engineering at Luleå University of Technology and especially to NUTEK for funding this work.

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[7] Clash detection routines exist in the robot simulation system used.

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Paper 3

Integration of Design, Inspection and Quality Management Systems

Integration of Design, Inspection and Quality Management Systems.

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Abstract

This paper discusses the standard for exchange of product model data (STEP - ISO 10303) and the proposed STEP application protocol (AP) for inspection process planning (AP219). The need for a concerted industry lead initiative to develop this AP is suggested. An industry consortium should include users and vendors of the hardware and software associated with inspection related activities and would build upon work already ongoing including work related to STEP. The goal of such a consortium would be to develop and promote the use of STEP for inspection process planning and related activities and will act as a focus for development of both AP219 and software tools to support it's adoption and implementation.

Keywords

Co-ordinate Measuring Machines, Off-Line Programming, STEP

The Scope and Nature of Inspection

Quality is no longer 'inspected in' to a product at the end of production. However, inspection is still a very important activity and increasingly sophisticated automated and semi automated inspection systems have become available. This equipment may use contact or non-contact methods, may be dedicated to a particular purpose or may be programmable and may stand alone or be integrated into other pieces of equipment.

One of the most common pieces of programmable inspection equipment in use today is the co-ordinate measuring machine or CMM. Whilst this paper discusses the integration of design, inspection and quality management systems using STEP with particular reference to CMM's, the discussion is equally applicable to other programmable inspection equipment.

Co-ordinate Measurement - Current Status

CMM’s are commonly used for component inspection both in metrology rooms and, increasingly, on the shop floor as independent resources or as part of closely coupled manufacturing lines and cells. Inspection using a CMM is typically a three stage activity; programming, execution of the programme and evaluation of the results. These activities are often carried out on separate systems which leads to complex interface problems. (see Figure 1.)

Programming of CMM’s is, even today, often carried out in a 'teach-in' mode. This is both time consuming and, for small batch quantities, results in a high proportion of unproductive time whilst an inspection strategy is planned and a valid programme generated. Manual editing the inspection program, which is invariably in the CMM’s own native language, is often at a similarly basic level, often relying upon relatively unfriendly text editors such as 'vi.'

Software is now becoming available which allows 'off-line' development of part programmes for CMM’s in a similar manner to the off-line part programming of CNC machine tools (CAD/CAM). Such off-line programming (OLP) tools are becoming more commonplace, although their use is still far from widespread. The leading OLP tools offer a 3D graphical presentation of the component being inspected as well as varying levels of automation for creating inspection paths for individual features and of overall inspection planning.

Like CAD/CAM, OLP systems fall into two classes; those that are integrated into a host CAD system, via functionality written into the CAD system or in the form of a third party system which is closely integrated through bespoke data transfer routines or through access to common database, and those which are 'stand-alone' but which can import data from the source CAD system in a neutral format such as the initial graphics interface standard (IGES).

Commercial OLP systems usually offer semi automation of the planning process. In the case of independent, 'stand alone,' systems, the user must typically decide upon the overall sequence of inspection as well as identifying which features are to be measured and how they are to be evaluated. The lack of tolerance data in geometry transferred from CAD in IGES format means that tolerances must be entered manually. Research systems have demonstrated high levels of automation when a fully toleranced geometric model is available. This functionality is likely to become more commonplace in commercial systems in the future.

OLP systems generate inspection process plans which have then to be passed onto the CMM. This is done by producing output in either the CMM's native programming language or in the dimensional measurement interface standard (DMIS - ANSI 101 1990). DMIS programmes are invariably translated into the CMM’s native language in a pre-processor before being run.

Most companies will claim to have unique inspection problems, however, virtually all inspection situations fall into one of two categories:

a) Process evaluation / validation; where the principle aim is the comparison of production process and product. This would include development of forming tools and first off-inspection of products manufactured on CNC machine tools.

b) Product validation; where inspection is carried out for acceptance / rejection and product tracability or statistical process control (SPC) of production processes of known capability.

Evaluation of a component is typically by assessment of individual features against tolerance, although more complex evaluation may include fitting of several inspected features to nominal geometry simultaneously. Evaluation may be carried out by the CMM control software or by analysis of raw or part processed data output from the CMM. This output is typically in a user defined format, although the DMIS covers output of raw or evaluated data in a comparable format to the inspection plan used to generate the data. Feedback of data to computer aided design (CAD) systems is more typically the case in the former category of problem.

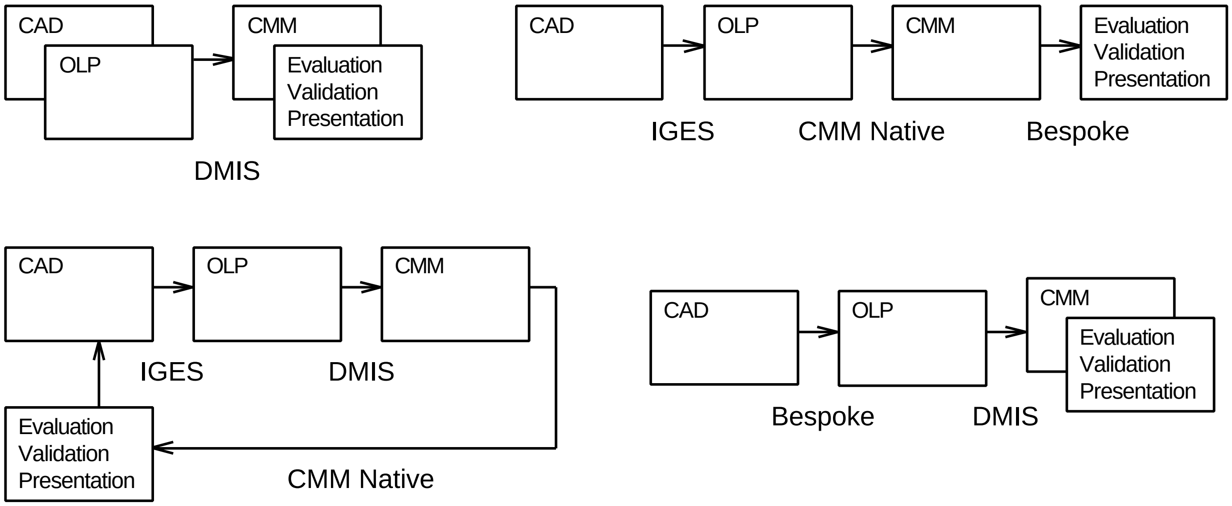

Figure 1. Possible integration combinations for design, programming and inspection systems.

The Standard for the Exchange of Product Model Data

STEP (ISO 10303) aims to " specify a form for the representation and unambiguous exchange of computer-interpretable product information throughout the life of a product. The form is independent of any particular computer system. This form enables consistent implementations across multiple applications and systems .... The approach for representation is to provide one definition of product data common to many applications. "

From this it follows that STEP could (and should) be used in place of the many existing standard and non standard formats in use for the integration of design and inspection related systems today. (see Figure 2.) This consistent format for all information involved in the inspection process can only offer benefits in the long run.

3D CAD to OLP - AP203.

STEP is already well developed in the area of definition of nominal geometry. Vendors of off-line programming systems are already working towards STEP interfaces from the AP's in the initial release of STEP. At this level, STEP would appear to offer no immediate benefits over IGES, the data format is not dissimilar and only nominal geometry is covered.

However, the adoption of STEP as a commercial necessity is encouraging. This also will allow experience to be gained in the techniques and data structures typical of STEP.

Toleranced 3D CAD to OLP - AP 2??

Leading commercial CAD systems can now offer tolerancing of 3D geometric models, functionality which is of great help in the automation of down stream planning activities. Given a toleranced CAD model, it is possible to achieve high levels of automation in OLP systems. Research systems have demonstrated automatic selection of the features to be inspected, selecting the number of inspection points necessary and determining an overall sequence for the inspection task. This level of functionality should become commonplace in commercial OLP systems the future.

Integrated OLP systems will be the first to benefit from the availability of 3D toleranced models and subsequently, as the ability to transfer toleranced geometric models from CAD to down stream activities becomes addressed by STEP AP's, non-integrated off-line programming systems will be able to use this information, allowing the automation of overall inspection strategy and development of individual probing sequences.

OLP to CMM - AP219
The STEP application protocol, AP219, for inspection process plans has already been identified, although little work has been done towards its development. The current standard for transfer of inspection process plans, DMIS, will obviously act as a basis for AP219, however, DMIS is recognised as lacking explicit structure and being underdefined in some areas whilst being overdefined in others. Users experiences of DMIS as well as developments in off-line programming systems and CMM control software must also be taken into account.

CMM and Evaluation - AP219
AP219 should also cover the results of the inspection, as either raw data, semi-evaluated data or fully evaluated data. This information should obviously be suitable for evaluation in external systems as well as being fed back to CAD. Feed-forward to product management systems, (MRP and quality control software.) is also a possibility.

Inter-operability with other AP's
Inspection process planning is not only carried out on stand alone CMM's. In process gauging is becoming increasingly important in both machines and cells and AP219 should also be usable in this type of system. It would seem likely that this level of development will take place once the basic format for AP219 has been established, although this base must take some account of the other AP's which concern process planning.

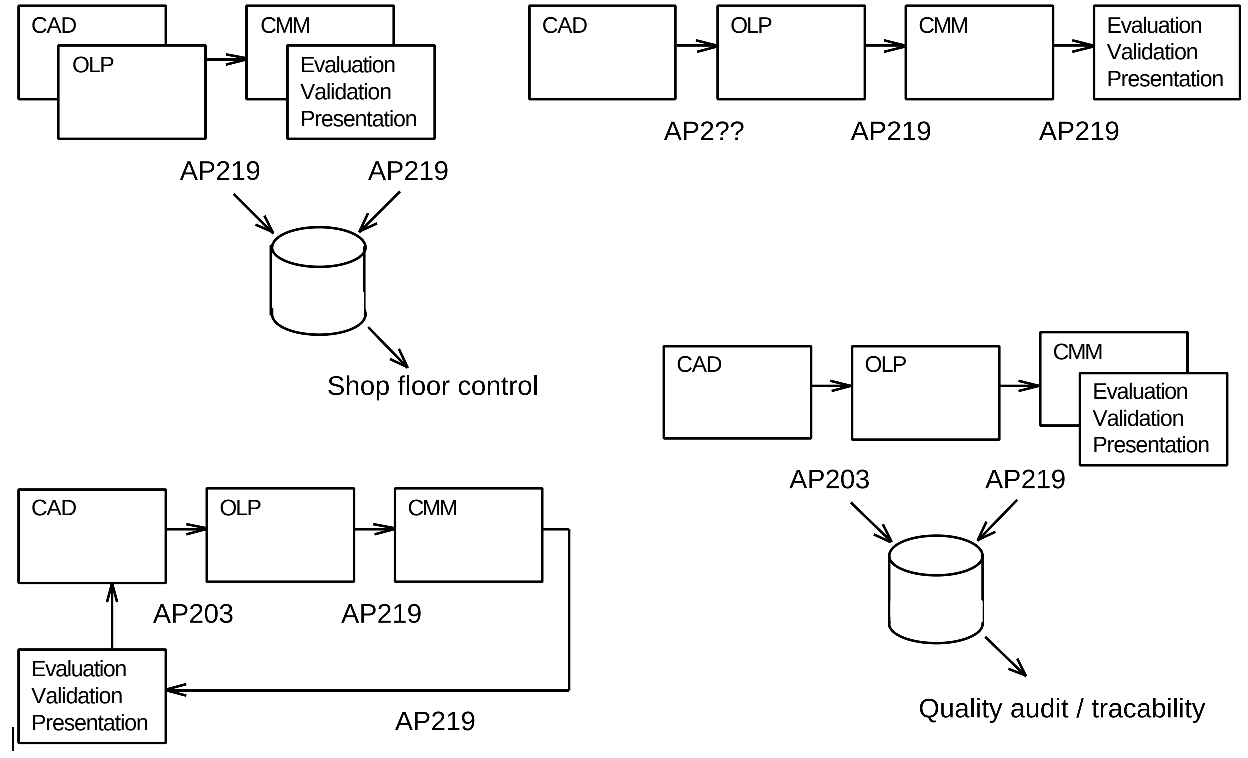

Figure 2. Possible integration combinations using STEP.

Proposed Industry Consortium

Formal development of the AP for inspection process planning, AP219, is currently in a state of abeyance and is regarded as being of low priority by WG3. Work related to STEP which includes reference to inspection planning is being carried out by an industry consortium centred on CAM-I (The organisation responsible for the development of DMIS.) in the USA. The european ESPRIT Vision Based On-Line Inspection of Manufactured Parts (VIMP) project has apparently included some work although this is not ongoing.

The scope of AP219, and the relatively limited number of hardware (CMM) and software (OLP) vendors potentially involved in the development of this AP, make it an ideal candidate for the rapid and successful development and demonstration of STEP based data transfer.

It is proposed that an industry consortium be formed to adopt, develop and promote the work which has been carried out to date on this AP in Europe and the USA. The consortium would act as a catalyst for the implementation of AP219 in commercial systems and in company databases through the development of the AP and of software tools to assist in the implementation and use of AP219.

The automotive industry is ideally placed to provide the impetus necessary for the proposed consortium to be effective. Not only is the automotive industry well placed to motivate commercial development of STEP AP219, it also has representative hardware and software systems from the majority of the off-line programming and CMM suppliers.

Industry lead initiatives are not unique. The US Navy Industry Digital Data Exchange Standards Committee (NIDDESC) is looking at the use of STEP for ship outfitting, whilst the UK process industries are promoting the use of STEP through the PISA programme.

Development of AP219

On the assumption that sufficient interest to develop AP219 exists, the first step must be to establish the current status of ongoing work related to STEP and inspection planning

A number of groups working in this area are known, whilst the remainder should be contactable without too much difficulty. Once the status of the work carried out to date is known, a more detailed strategy for development can be established. Input from individuals or groups with experience of development of STEP AP's would obviously be actively sought.

It would seem likely that some software tools specific to AP219 could beneficially be developed. These would allow parsing of STEP files, interface to commonly used databases, input, interrogation and editing of data within STEP format files or databases. Such tools would be of use to both system developers and users.

The original estimate for development of AP219 was in the order of three years. This still remains a realistic, but not overly conservative, estimate.

Conclusions

Development of STEP in the areas related to inspection, e.g. transfer of toleranced 3D geometry will lead to a significant increase in the functionality and level of automation offered by off-line programming systems including off-line programming of co-ordinate measuring machines. For this to become a reality, STEP must become more widely adopted and seen as a necessary development by industry.

The STEP application protocol for inspection process planning, AP219, is not being actively developed at present. Development of AP219 will provide an ideal opportunity for individuals and companies to develop knowledge of and expertise in the use of STEP.

The scope of AP219, and the relatively limited number of hardware (CMM) and software (OLP) vendors potentially involved in the development of this AP, make it an ideal candidate for the rapid and successful development and demonstration of STEP based data transfer.

Development of AP219 will ideally be with the support of an industry consortium.

The automotive industry is ideally placed to provide the impetus necessary for the proposed consortium to be effective. Not only is the automotive industry well placed to motivate commercial development of STEP AP219, it also has representative hardware and software systems from the majority of the off-line programming and CMM suppliers.

A range of either public domain or consortia specific software tools will be developed as a means of providing support to both system developers and users

Epilogue:

” In the search for truth there are certain questions that are not important. Of what material is the universe constructed ? Is the universe eternal ? Are there limits or not to the universe ? What is the ideal form of organisation for human society ? If a man were to postpone his search and practice for Enlightenment until such questions were solved, he would die before he found the path. ”

- *Buddha*