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**Analyzing Sculptured Surfaces In a
Computer Integrated Manufacturing Environment**

Master's Thesis prepared by
Bert Van den Berg

A thesis submitted to
The Faculty Of Graduate Studies And Research
in partial fulfillment of
the requirements for the degree of
Masters of Engineering

Department of
Mechanical and Aeronautical Engineering
Carleton University
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April 1986
c 1986, B. Van den Berg

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The undersigned recommends to the faculty of Graduate Studies and Research, acceptance of the thesis: Analyzing Sculptured Surfaces in a Computer Integrated Manufacturing Environment, submitted by Bert Van den Berg in partial fulfillment of the requirements for the degree of Master of Engineering.

Thesis Supervisor

Chairman
Department of Mechanical
and Aeronautical Engineering

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Glossary of Terms and Abbreviations

- **Coordinate Measurement Machine** - A computer controlled machine tool used to precisely measured point coordinates of features to be inspected. The controlling computer can analyze measurements made on common shapes.
- **CAD** - Computer Aided Design
- **CAI** - Computer Aided Inspection
- **CAM** - Computer Aided Manufacturing
- **CIM** - Computer Integrated Manufacturing
- **CMM** - see Coordinate Measurement Machine
- **Database** - An electronic organization of information, for the purposes of this thesis containing geometric characteristics and associated information
- **DATUM** - a reference point from which positions and orientations are measured
- **DESIGN** - a specification of the characteristics of an object, including tolerance information to aid in the production of functional objects
- **FACET** - the triangular area formed between adjacent points on a surface
- **FEATURE** - a portion of the surface of a part to be inspected (features are usually distinct geometric elements)
- **FIXTURE** - a clamping device used to hold a part during machining or inspection
- **FORM TOLERANCE** - the allowed deviation between any point on a feature of a manufactured item and the defining shape which has been fit to that feature (form tolerances are often indicated separately for the inside and outside of a surface)
- **GEOMETRIC TOLERANCE** - a tolerance which controls a dimensioned geometric characteristic of a shape

- **GOUGE** - the condition of having less than the required amount of material on a manufactured item (less than the shape indicated by the design)
- **INTOL** - a form tolerancing which controls the amount of missing material allowed on a functional part
- **MDP** - Minimum Distance Point
- **MEASUREMENT** - a point measured near or on the machined surface of an object (a point measured near the surface is actually the coordinates of the center of the spherical tip which touched the surface)
- **MINIMUM DISTANCE POINT** - the point on a surface whose surface normal passes through a measurement, and is the shortest distance to the measured point
- **NBS** - National Bureau of Standards (Washington D.C.)
- **NC** - Numerical Control (computer control of machine tools such as lathes, drills and milling machines)
- **ONLINE PROGRAMMING** - measurement programming of a CMM which requires exclusive access to the CMM
- **OFFLINE PROGRAMMING** - measurement programming for a CMM which permits the CMM to continue to be used for inspection
- **ORIENTATION TOLERANCE** - a tolerance which controls the allowed angular deviation between a reference axis of the part and the corresponding reference axis on the design feature when fit to the measured data
- **OUTTOL** - a form tolerance which controls the amount of excess material allowed on a functional part
- **PART CENTROID** - a point of rotation used when calculating the rotational fit of the measurement data to the design surface
- **POSTION TOLERANCE** - a tolerance which controls the allowed deviation between a reference point of the design feature and the corresponding reference point on the design feature when fit to the measured data
- **ROTATION MOMENT** - a vector indicating rotation which will improve the fit between the design surface and measured data

- **SCULPTURED SURFACE** - a mathematical representation of free-form shapes (typically using a cubic polynomial function interpolated along two parameters)
- **SPINDLE** - the part of a coordinate measurement machine which carries the measurement probe
- **SPLINE** - a mathematical representation of a free-form curve in space (typically using a cubic polynomial function interpolated along one parameter)
- **STOCK** - the condition of having excess material on a manufactured item (excess to the shape specified by the design surface)
- **SURFACE POINT MESH** - the mesh of points created on the surface to help locate the region of a surface containing a particular MDP
- **TOLERANCE** - a quantitative means of indicating a functional requirement, allowing people not familiar with the function of an object to manufacture functional objects
- **TOOL** - an aid in obtaining a goal the tools discussed in this thesis may be hardware (sensors) or software programs (analysis, measurement programming)
- **TRACE** - the curve formed by joining a set of measured points which follow a particular characteristic of a surface

Chapter 1

Introduction

The use of computers has revolutionized the manufacture of discrete metal components. In a Computer Integrated Manufacturing (CIM) environment, the design, manufacture, and inspection activities should be supported by an integrated flow of information via computers.

The design activity is well supported by commercial CAD systems which allow the creation of an electronic design data base. The manufacturing activity is also supported by process planning and NC programming tools which can access the design geometry for information on the shape of the part. The inspection function should relate the part design specification to measurement data on the manufactured item to provide the control information which ensures that proper parts are produced.

The tools available for the inspection activity are less developed than those available for design and manufacture. The object of this thesis is to develop methods to analyze point measurements made on sculptured surfaces, thus providing a tool to the inspection function. This analysis tool will allow the inspection function to **close the loop** in the Computer integrated manufacturing environment.

Coordinate Measuring Machines (CMMs) are the most common tool used to inspect dimensions of sculptured features. CMMs measure points at programmed positions on sculptured surfaces. These point data must be analyzed to extract the information related to the tolerances specified with the design.

1.1 Specific Thesis Objectives

This study focuses on the problem of extracting dimensional control information from the measurement data obtained from a CMM using the design database. To solve this problem, the thesis investigated the tolerances used on sculptured surfaces, as well as the criteria used to evaluate tolerances on prismatic shaped features. Algorithms for evaluating tolerances on sculptured surfaces were then developed and a method designed for determining the shortest vector between a measured point and the design surface it relates to. The problem of determining the error vector is critical in extracting tolerance information from the measurement data. To demonstrate the potential of the approach developed, the thesis also presents an exemplary implementation of a surface inspection and analysis system, and evaluates the results obtained to date.

1.2 Thesis Organization

The thesis is divided into six chapters including this introductory first chapter. The second chapter reviews the state of CMMs in the literature and industry to understand current trends and determine methods currently being used to integrate CMMs into a computer integrated man-

ufacturing environment. The design and accuracy of sensors used to measure the part features are evaluated, and their impact on measurement result analysis is investigated. Offline programming methods for CMMs are considered, with special attention being placed on the effect of offline programming methods on measurement analysis. Finally, the literature on analyzing point measurements made by CMMs is reviewed, with a focus on methods that could be useful for sculptured surfaces.

The third and following chapters report the investigations, problems and solutions developed as part of this study. Specifically, Chapter 3 investigates the general nature of the analysis problem, possible solutions, and then develops the most promising approaches. This work includes investigation into the methods used to specify the shape of sculptured surfaces (tolerancing), the proposal of methods to analyze point measurements on sculptured surfaces, and the development of algorithms to evaluate common tolerances on sculptured surfaces. The analysis algorithms developed in the study are designed to extract dimensional control information from the parts measured, and assess dimensional quality control criteria.

During the development detailed in Chapter 3, a significant problem had to be solved involving the determination of the shortest vector between a measurement point and a sculptured surface. Other researchers have discussed this problem, but this study presents results on possibly the first general (and successful) method for determining the shortest vector between a point and a surface. Chapter 4 describes this problem in detail as well as the solution implemented.

The fifth chapter presents work on a complete measurement and analysis system being developed for sculptured surface parts. This includes a

CAD, CAM based offline programming method for surfaces, a computer integrated measurement execution program, and an implementation of a general surface measurement analysis system. The analysis system has been tested, and the results are discussed. The final chapter summarizes the study, draws conclusions and investigates directions for future work.

Chapter 2

Literature Survey and Fundamental Concepts

This chapter presents background information important to understanding the measurement and analysis methods developed later. The state of the art of coordinate measurement is reviewed with a view to developing an understanding of tools and methods useful for measuring sculptured surface parts, and determining current issues and trends. The principle measurement tool for precision measurement of sculptured surfaces is the CMM. The types of CMMs and probes are described, and the methods used to program CMMs are reviewed. A special emphasis is placed on the review of methods used to analyze coordinate measurements. This includes a review of approaches, current issues, and the development of the measurement analysis concept and the measurement fitting concept. These two concepts form the basis of the dimensional analysis system described in Chapter 3 and the integrated measurement and analysis system described in Chapter 5.

2.1 Coordinate Measurement Machines

A Coordinate Measuring Machine (CMM) is a device used to measure dimensional features of physical objects. Previous methods relied on special purpose tools (micrometers, analogue tracing machines, fit rings, etc.) to make measurements. A CMM is not capable of measuring features directly but rather uses the flexibility of a computer to combine point measurements into meaningful results (e.g. length, diameter, distance, parallelism, etc.).

CMMs have a probe to measure a point on the surface, axis of movement to move the probe through space, position measuring equipment on each axis of motion, optional motor drive to move the probe, a control system, and a computer to combine the points measured into meaningful features (Figure 1). Some CMMs are not equipped with computers such systems are not considered in this thesis.

CMMs are seeing increased use as quality assurance tools in flexible manufacturing cells, and are often used to make measurements on sculptured surfaces such as car body panels, turbine blades and other hydrodynamic shapes.

2.2 Coordinate Sensors

A sensor is required to provide precise dimensional data on parts produced in a computer integrated manufacturing (CIM) facility. The most common device used is the CMM which combines high accuracy, flexibility and the possibility of integration into the CIM environment. The different types of CMMs, the type of probe used in the CMM, and alternative measurement devices are outlined below.

Many different types of sensors have been developed for use on CMMs. Early sensors (solid probes) evolved from form gauges used in quality assurance (i.e. corners were measured with an angle plate, holes measured with a tapered plug). Such sensors severely limit the flexibility of a CMM and more flexible sensors were developed. Modern sensors are electronically based for improved flexibility and can be divided into contact sensors and non-contact sensors (Figure 2).

2.2.1 Contact Sensors

Contact sensors are by far the most prevalent sensors used today on CMMs. They consist of a spherical tip on a slender shaft, a contact sensor and probe controller. There are two types of contact probes, touch trigger probes and contouring probes. A touch trigger sensor measures the coordinate positions of the probe center when the probe makes contact with the part surface, while a contouring sensor measures the probe position as the tip is moved along the surface.

Contact probe systems usually accommodate a variety of probe tips (up to five at once), and can use a variety of probe tip sizes. Each probe tip must be referenced to indicate to the CMM the probe tip's position with respect to the measurement head. This is usually done by touching a sphere of known radius at several positions.

Most contact probes are equipped with a spherical tip of a hard material (Carbide, Ruby) which avoids gouging the part to be measured (a problem with tapered tips) and ensures repeatability of results. However, the use of a spherical probe tip results in a measuring error equal to the probe tip radius (Figure 3). Although the probe makes contact with the

surface at some point on its circumference. most probes return the coordinates of the tip center at the point of contact. When measuring regular geometric objects (such as planes, cylinders, spheres, etc.) the probe radius error can easily be analytically compensated for by measuring several points and calculating a geometric feature passing through the probe center points, and then altering the feature's position by the radius of the probe tip. (Features of measured objects include holes, bosses, planes, and airfoil surfaces.) However, when measuring objects with sculptured surfaces (such as turbine blades or sculptured molds), the probe tip compensation is much more difficult. At present no commercial system is capable of measuring and analyzing general sculptured surfaces directly although significant progress is being made in this direction.

A probe which can determine the actual contact point from the probe center and the surface contact normal would eliminate this *tip radius* error (Figure 3). One approach to determining the contact point is to measure the force on the probe tip. This force has two components, a friction force acting along the direction of the contact velocity (sliding) between the part and the surface, and a contact force normal to the part surface at the point of contact (Figure 4). This normal force necessarily passes through the probe center, and thus can be used to calculate the contact point. The key problem is to compensate for the effect of the friction force. Leitz Inc. '69 has recently announced a contact-point-sensing probe, and if it proves capable, this will greatly simplify the measurement of sculptured surfaces. No indication is given of the method used to compensate for the friction force.

Japanese researchers have reported the development of an inexpensive

probe capable of sensing the contact point [42]. The probe is constructed much like a touch trigger probe, but includes an oscillating tip (500 Hz). The friction force of the contact is measured by a dynamometer on the shaft, while a 3-D load cell is used to measure the total force. When the friction force vector is subtracted from the total force vector, the resultant is surface normal contact force. The probe has a reported contact normal sensing accuracy of 1.5 degrees, and is said to be accurate to 1 micron for probe tip sizes less than 2 mm. The effect of surface roughness, and the required calibration for various parts is not discussed.

Touch Trigger Probes

Although some touch trigger probes use the completion of an electrical circuit with the measured part to sense the probe-surface contact [5], most probe tips use an internal microswitch arrangement to sense surface contact [20]. Touch trigger probes usually measure while the probe head is in motion, allowing the probe tip to be deflected from its rest position by up to 5 mm in the X,Y,Z directions. This allows the CMM to move quickly as it approaches the part surface while producing good measurement results, and preventing damage to the probe. Some research into features for an ideal probe has been published [39]. Desired features include: low mass on probe head to reduce deformation of the contact point, omni-directional probe contact sensor, and motion control such that the probe approaches along the theoretical surface normal of the part.

Touch trigger probes operate largely independent of the CMM they are used with, and are well suited to measuring regular geometric features. Although many manufacturers equip their CMMs with a sensor of their

own design, at least one probe vendor has successfully developed a line of touch trigger probes [30]. At least one type of touch trigger probes has two motorized axes of positioning which allows one tip to access many features on a part. Touch trigger probes are being used on machine tools to measure tool dimensions and to locate parts to be manufactured accurately within the machine tool workspace.

Contouring Probes

Some contact probes can be used to measure surface contours. A contouring probe can be thought of as a small CMM mounted on the end of the measuring arm of the CMM [28]. The probe contains three independent axes whose positions are measured by precise linear potentiometers. The CMM's motion controller is continually given information by the probe on the tip's displacement from its *rest position*, and attempts to move the CMM axes (X,Y,Z) so as to keep the displacement of the head within a given range. The position of the tip can be calculated as the displacement of the three axes of the probe, plus the displacement of the three axes of the CMM [20]. The CMM control computer scans the position of the probe tip frequently (≈ 30 samples/second) while the control circuit drives the tip at constant velocity over the surface to be measured ($\approx 1-5$ mm/s).

Contouring probe systems are used for measuring sculptured surfaces (including gears [29] and air foil shapes) and for digitizing models whose shape are to be captured into a computer database. In the case of gear measurements, the probe trace can be compared with a master gear trace, or an analytical model for quality assurance [45]. Systems that use contouring CMMs for model digitizing often are equipped with auxilliary software

to turn the points digitized into a machine tool path 14. This software allows the reduction of digitized data by eliminating sequential points that lie on (or very near) a straight line (a data reduction of 30:1 is not unusual 58.). Some CMMs using touch trigger probes have also been used for model digitizing 67,23.

A novel probe system, which is being developed for contouring measurements 39, uses a tip which rolls along the part surface to measure a part contour. The probe is not capable of measuring contours on the rotational axis, but promises to be cheaper than existing contouring systems.

2.2.2 Non-Contact Probes

Non-contact probes measure the distance to the object's surface using various ranging methods. These include laser interferometry, acoustic waves, and, more commonly, simple laser ranging.

One system 24 has been developed using a 'cat's eye' puck which slides over the part surface, and is triangulated by four laser interferometers. This system is highly accurate and is used for measuring large retro-reflecting surfaces (mirrors and lenses). This method of positional measurement has yet to be applied to the measurement of common manufactured objects.

An ultrasonic digitizer has been reported 64 using three detectors to detect the position of an ultrasonic emitter located in a sphere. The sphere can be moved over the object, and thus used to quickly digitize a surface. The unit developed had a reported accuracy of approximately 1 mm and a working envelope approximately 300 mm on a side. The probe sphere used was approximately 20 mm across. No mention was made of the effect of reflections, or obscuring one of the receivers on the measurement results.

Another probe mentioned in the literature 44 is based on acoustic ranging, but this system suffers from errors due to local pressure, temperature, and noise variations. It appears to be still a laboratory project.

A very popular non-contact measuring device is based on a small laser reflecting light off the part surface and a sensor to measure the angle of reflection. These probes must be positioned within a specified stand-off from the part surface 16 (typically 20 to 100 mm) and have a measuring accuracy comparable with contact sensors (4 - 8 microns). This system relies on proper surface finish and material optical properties and is being applied to the measurement of irregular surface topology. One such device has been developed by Diffracto (Windsor Ontario), and is currently available with measuring software on commercial CMMs. It is limited to measuring surfaces whose normal varies from the beam axis by less than 30 degrees. The probe is described as being capable of emulating both a touch trigger probe and a contouring probe. A British manufacturer of CMMs (LK) with significant experience in the measurement of turbine blades and other sculptured surfaces is working with a Swedish manufacturer of a similar device. A new commercial scanner has appeared that is constructed like a vertical column CMM with the scanner mounted on the supporting bridge. The system boasts an accuracy of 8 microns and can measure at high data rates (1000 points/second). The system also scans a line of surface data at once, rather than scanning a point.

A system is under development at NRC's Division of Electrical Engineering to create a 3-D digitizer based on laser ranging 61. The system is capable of capturing a large number of surface point measurements in times of less than one second. Software has been developed to filter the

measurement data and eliminate system errors. The system measures accurately to 0.25 percent of the depth of field of view. This translates to accuracies in the order of 25 microns (0.001 inches) for objects about 10 cm (4 inches) high. These prototype instruments are not as rigid and accurate as production versions would be. Development is now underway to integrate a turntable into the digitizing system for capturing a complete surface of the object.

Non-contact measurement based on laser ranging is fast and accurate. Fast measurement rates are important in reducing inspection time, while the laser probe's measurement of a point on the part surface eliminates the probe radius error induced by most contact probes.

2.2.3 Problems With Current Probing Methods

Contact probes limit the speed at which part features can be measured. This is especially important when all parts must be inspected or many points are required (i.e. sculptured surfaces) to ensure quality requirements are met.

Current laser probes are limited by the indices of refraction and reflection of the materials to be measured. As well, the accuracy of laser scanners is defined by the field of view (height variation in part measured along the beam axis). Thus for parts with significant changes in elevation, the measurement accuracy will decrease. Laser probes have difficulty measuring features whose size is less than the laser spot size. This is important in measuring the leading and trailing edges of turbine blades which is critical in the inspection of turbine blades. The capabilities and applications of laser probes should increase in the future. Contouring probes must be inte-

grated to the axis control function of the CMM. This makes them difficult to retrofit to contact probe equipped CMMs. The complex control requirements and the expense of contouring probes make the cost of contouring CMMs is significantly higher than for touch trigger CMMs.

2.2.4 Significance to Analysis of Surface Coordinate Measurements

The capabilities of probes are critical in the types and quantities of objects which the CMM can measure efficiently and accurately.

The development of electronic probes has provided improved measuring flexibility (over solid probes) in the types of features that can be measured. The development of non-contact and contouring probe systems has created the opportunity to measure surfaces accurately and quickly. Probes capable of measuring a point on the part surface (rather than the probe center point) reduce the number of calculations that must be done to evaluate the dimensional accuracy of a feature. Recent developments in both contouring and non-contact measurement probes have the capability of creating an information explosion that will require effective analysis tools to manage.

2.3 CMM Programming Methods

One bottleneck in the use of CMMs for quality assurance has been the time required to develop programs to measure part features. Even in cases where the CMM is manually driven, significant savings have been reported by developing offline programming aids. This section deals with current methods used to program a CMM with a view to developing a system for offline programming of CMMs for measurement of sculptured surfaces.

The literature on CMM programming indicates that a variety of methods are used to control CMMs for measuring the dimensional accuracy of features. These include teaching, offline but local systems, machine independent programming systems, and CAD/CAM based systems. Some of these systems are rich enough in the description of the to-be-measured features, that immediate pass/fail decisions can be made by the CMM control computer. Others rely on human evaluation, possibly graphically assisted.

2.3.1 On-Line Programming Methods

CMMs have evolved from manually driven positional digitizers into computer controlled systems capable of measuring geometric features and doing some evaluation of dimensional accuracy. CMM programs are often created by teaching the CMM how to measure the part much like some robot programming methods.

Teach programming systems may have a simple editor to permit minor changes to the program. The original program is usually created by moving the probe to the measurement points using the joysticks provided on the *teach pendant*. It is important to note that intermediate positions must also be *taught* to the CMM to prevent the probe colliding with the part or fixture while under automatic inspection.

The part program created by a teach-mode system may be a binary file of coordinates and codes, or (enhanced) NC machine tool codes. 62

CMM programs typically contain information to direct the motion of the probe, information on how to analyze the points measured, and comments to the operator to assist in the execution of the measurement program. For example, a typical (pre-programmed) measurement program

might require the operator to locate a reference coordinate system on the part, and then automatically measure some features on the part such as diameters, distances, parallelism, recording the feature analysis on paper, a computer file, or a plot. The operator typically locates the coordinate system on the part by indicating a plane, a line lying in the plane, and a point on the line. The plane can be measured using three or more points, the line would be constructed from other features (such as planes), the point would be constructed from other features (such as the projection of a circle's center into another plane). Comments to the operator indicate what feature to measure next and how many measurement points are required.

Measurement programs give each of the features to be measured a label: individual points, circles, planes, (P1,C2,PL3 etc). Each of these labels indicates what has been measured, and allows the measured features to be related to other features in the program. Some programming systems allow the ideal geometry, and tolerances to be input as part of the CMM program 56.75. This is useful for analyzing the measurement data, and for evaluating the pass/fail status of the part.

Basic geometric elements are analyzed according to their element type and may be analyzed in combination with other elements as requested by the programmer (i.e. the distance between the center of two circles must specifically be requested, although the analysis of the circles is executed automatically from the measurement program).

As well as multi-purpose programming systems, CMM vendors also produce special application systems for measuring and analyzing such features as gears and airfoil cross sections 16.29,46.66.

2.3.2 Off-line Programming Methods

On-line programming often delays production. A common complaint about CMMs is that it takes longer to prepare the inspection program for the first part than it does to make the part. A CMM is an expensive resource, and taking the machine off inspection to develop an inspection program is costly. In some cases (such as measuring parts where the master geometry is stored in a CAD/CAM system), creating a measurement program in the teach mode is inefficient at best.

One alternative to online programming is to develop the CMM program at a computer workstation remote from the CMM and possibly remote from the CMMs computer. Many CMMs are equipped with a multi-user computer, so one person can be preparing a new program, while another is inspecting a part. However, this approach requires that a programming language exist to create these programs. CMM offline programming languages range from number codes for particular CMM systems, to APT-based languages complete with postprocessors to produce programs for individual systems.

When developing programs offline, care must be taken to ensure the motions requested of the CMM are physically possible, and that the motions do not cause the machine to collide with the part to be measured. Good offline programming systems must allow quick and efficient development of safe measurement programs. Few offline systems have capabilities for collision avoidance, thus most measurement programs must be *debugged* at the CMM before being run automatically.

A second alternative to an offline programming system is to develop a special purpose measurement program using a library of measurement

functions provided by the CMM vendor 15 .

CMM Vendor Based Programming systems

Each vendor of CMMs has a different programming language which controls the machine's movement. Some systems have established offline programming capabilities. These include BMIL 58 , CAP, MFT, PROG 72 , UMESS 34 and VALMES. As these systems become more sophisticated they will include graphic displays and may eventually evolve into special purpose CAD /CAM systems.

As well as general purpose offline programming systems, most CMM vendors supply a library of basic functions which enhance a familiar programming language such as BASIC or FORTRAN. This lets the user develop special purpose measurement programs (e.g. family-of-parts measurement programs) and integrate inspection functions with other aspects of the manufacturing operation, such as information communication. In some cases this enhanced language is the method used to program the CMM 78 .

CMM-Independent Programming Systems

Machine-tool independent programming languages for NC tools have long been established and form the basis of some CMM programming systems and CAD/CAM applications for CMM programming.

At a state center in Aachen, Germany, an offline programming system for CMMs (NCMES) has been developed based on EXAPT, an APT derivative programming language for other machine tools [63]. The system allows the programmer to define with APT commands the geometry

to be inspected, and then define motion commands to create a measuring program. Tolerances specified by the programmer allow the system to report dimensional accuracy results (pass fail). The system includes post-processing facilities to translate the APT program into a program for a particular CMM.

Another measurement language developed in Germany (GDR), is the MAUS language 54. This language is based on geometric descriptions of the part, and has been ported to many small computers. The system can make quality assurance decisions, based on user specified criteria, and consists of cryptic value assignments statements. It is also being used as an offline programming tool for a particular CMM 20.

The CAM-I organization has undertaken a major project for offline programming of CMMs. They are attempting to define a new language (DMIS) which will provide a universal interface to CMMs. The language specifies both a common CMM input (programming) and output (reporting) format. The adoption of a standard for CMM information transfer would be a significant step forward as different CMM vendors each have their own peculiar formats. The DMIS language is not an APT derivative language 47.

One paper in the literature 75 describes a simple programming system for measurement of rotationally symmetric parts, with the capability of automatically determining if the measured part meets the dimensional accuracy criteria specified by the programmer.

Another APT derivative language described in the literature is MCL 77. This language is intended for controlling an entire flexible manufacturing cell, and as such might be general enough to be used for GMM

programming (although no mention of the language for this use is made). The language does include inspection commands for vision, and decision and control structures necessary for measurement evaluation control.

User Developed Offline Programming

Some effort has been devoted to creating a computer integrated programming environment for CMMs which are manually driven (i.e. the operator moves the probe to touch various features as required) [26,54]. In this case the measurement program functions like a roadmap, giving instructions on what part to inspect next, and how many measurement points to take.

The programs also manage the information produced, providing results analysis and presentation. These systems are reported to be a significant improvement over previous methods (where the operator worked from drawings or a paper inspection plan).

At least one user has reported an inhouse developed CMM programming system based on APT with post-processing for the particular CMM [48]. The system includes tolerancing of features to allow the CMM to make quality assurance decisions to accept or reject a part.

CAD/CAM System Based Programming Systems

CAD/CAM vendors are developing systems for CMMs including offline programming, post-processing for specific CMMs, and measurement upload capabilities [7,17]. The programmer selects entities to measure from the graphical display and indicates the measurement criteria (number of points, tolerance).

The program determines a set of points, which when measured, allow the feature to be measured, and then specifies a probe motion to perform the measurements. Since these application programs are built on a wire frame representation and not a solid model representation, it is not possible for the software to determine a collision free probe path. Thus the probe motion is animated and the user is responsible for altering controlling parameters until the measurement program is acceptable. The output is an APT-like program which can be post-processed (translated) for execution by a particular machine. The CAD/CAM based CMM programming tools are just entering industrial use.

An important feature of CAD/CAM based programming systems is their ability to create measurement programs for sculptured surfaces. These systems allow the user to create a mesh of measurement points on a sculptured surface which are connected with a *hopping* motion (approach, touch, retract) suitable for a touch trigger probe. Ideally, a measurement program should be created such that each measurement point is approached along a vector normal to the surface at the contact point. This minimizes the difference between the programmed contact point, and the measured point (Figure 5). However due to limitations in some CMM designs (poor servo systems), a variety of approach strategies should be allowed. These include approaching the contact point parallel to one of the CMM's axis of motion.

A useful feature of the CAD/CAM based CMM programming systems would be the labeling of measurement geometry features. Most CAD/CAM systems allow the user to attach attribute information to geometric features created (such things as materials, tolerances, names etc., are common attributes assigned by the user to geometric entities). Addition of such at-

tribute information would allow the automation of feature analysis by allowing a program to compare specific geometries. If the geometry is not labelled, the design geometry corresponding to a specific measured feature would have to be indicated by the user to analysis software.

New Methods in Offline CMM Programming

At the University of Tokyo, researchers have developed an offline programming system for simple CMM measurement which includes collision avoidance [41]. The system presents the user with a display of the part to be inspected. The user first indicates *safe planes* which the system uses for collision avoidance.

The user then specifies the sequence features (planes, cylinders) are to be inspected, and enters quality assurance data (tolerances, measuring points). The system is capable of distributing measurement points over the feature surface and then creating a program to measure the features with some simple collision avoidance built in.

Research is currently underway to automate the development of offline programming. A paper by Lau [47] describes a general CAD/CAI system for CMM programming based on geometric decomposition. Although no implementation is mentioned, the system describes the design feature database, and a technological database required for programming specific CMMs. The system aims at increasing the efficiency of CMM programming by providing an improved representation of the geometry to be measured, and a method for automatically determining measurement points (based on features and tolerances). The system uses the geometrical description of the part, and a description of the CMM provided by the technological

database to produce a measurement program for collision free measurement of the part. A solid model representation of the part makes collision avoidance calculations practical. CAD systems based on surfaces, or wire frames surface representations are less suited to generating inspection programs automatically.

The National Bureau of Standards has a project underway to automate CMM programming using a boundary representation (solid model) of the part (extracted from a suitable CAD system) and a *world* model of the CMM to be used [31,32]. The *world* model contains information about the CMM and measurement methods. This project is partly based upon Lau's work [47] described above.

A paper from the University of Wisconsin-Madison [22], describes a method for inspection of sculptured surfaces whose ideal geometry is described in a CAD database as bicubic spline patches. The system distributes measurement points over the surface area of interest, with the touch trigger probe approaching each measurement point along the design surface normal. This system is one of the first reported systems for offline CMM programming for sculptured surfaces.

2.3.3 Summary of CMM programming Methods

A wide variety of CMM programming methods exists. These include online *teach pendant* driven systems, CMM specific offline programming systems, CMM independent programming languages, special purpose measurement software, and CAD/CAM system based programming systems.

The CMM programming capability for measuring sculptured surfaces is poorly developed, especially in the context of touch trigger probes and

CAD/CAM based programming systems.

There is an increasing trend to use the power of the computer to provide graphics assisted CMM programming, either through improvements to products offered by the CMM vendor, or the CAD/CAM system vendor.

Features to look for in new CMM programming tools include:

- automatic generation of measurement sequences for user defined part features,
- automatic selection of part features from the geometric database,
- collision avoidance capabilities with varying levels of sophistication,
- improved capabilities to create measurement programs for sculptured surfaces,
- development of a high level CMM programming language,
- increased part geometry description in the measurement program to allow increased results analysis.

2.3.4 Significance of CMM Programming to Measurement Analysis

Analysis of measurement results is hampered by the large amount of low level information the CMM produces. This in turn is partly due to the low level of compatibility between CAD systems and CMM systems.

Consider the measurement of a surface curve or sculptured surface by a CMM equipped with a touch trigger probe. The instructions come to the CMM as instructions to measure a sequence of points. The CMM has no representation for sculptured surfaces, and thus can only report the deviation between the points programmed and measured. Unfortunately, there is a significant barrier to developing a CMM representation for sculptured surfaces. The representations for surfaces being measured are often stored

in a CAD/CAM system, and different representations are used to describe these entities in different CAD/CAM systems.

In general, the differences in CMM specific programming languages will continue to result in lowest-common-denominator level information being produced by the CAD/CAM systems for CMM programming. The successful introduction of a generic CMM programming language will raise the level of abstraction of information passed to the CMMs.

2.4 Measurement Analysis Methods

Since CMMs measure points, and the applications using CMM data are not satisfied with point data, processing or analysis of the measurements is required. The different analysis methods used are described in the paragraphs below, separated according to the type of output required. CMMs have three common uses:

- capturing geometric data about geometric features on parts for design, analysis and/or manufacture (digitizing),
- performing quality assurance of dimensional tolerances on manufactured parts,
- providing geometric manufacturing control information to manufacturing systems such as flexible manufacturing cells.

2.4.1 Capturing Geometry of Part Features

The most basic use of a CMM is to measure the geometric features of an object. Typically this is done by tracing the probe over the contour of a part while the CMM scans the position of the tip center. Presented below are applications which use CMMs as digitizers. The typical digitizing

application smooths and condenses the data for entry into a geometric database for use in computer aided design, analysis or manufacture.

Most general purpose CMMs come with software which can be used to fit prismatic shapes to geometric features. The software is capable of calculating the characteristic dimensions of a shape (plane, cylinder, sphere, cone) which passes through the measured points with a best fit according to some fitting norm (this is described later). This is useful in digitizing prismatic shapes which will be entered into a CAD database. There are four fitting methods commonly used to synthesize part features from measured point data: linear fit, least squares fit, minimum zone (MZ) fit and maximum material condition (MMC) fit [75]. These methods are outlined below and are related to the tolerancing requirements.

Linear Fit

For the linear fit, the sum of the magnitudes of the error vectors are minimized:

$$S = \sum_{i=1}^n R_i \quad \min$$

Where R_i are the calculated residuals

Thus for the case of fitting a circle to a set of measured points, the linear fit circle is that circle for which the sum of the error vector magnitudes is minimized (Figure 6B). It can be seen that this method gives each error an equal weight, regardless of the error's magnitude. This has the effect of calculating the *linear average* feature. This method is not generally used due to problems encountered in developing the algebraic solution. Mathematically, this is an l_1 norm.

Gaussian Fit - Least Squares

For the Gaussian fit, the sum of the squares of the error vectors must be minimized (Figure 6B).

$$S = \sum_{i=1}^n R_i^2 \rightarrow \min$$

Where R_i are the calculated residuals for n measured points

Most of the commercial CMM packages use implementations of the least squares fit methods [51,72] since it is relatively tractable for most regular geometric shapes. In brief, the least squares approach attempts to determine the required feature form for which the sum of the squares of the error magnitudes is minimized. The least squares fit give a weighting equal to the magnitude of the error to each error. Mathematically this is an l_2 norm.

Minimum Zone Fit

The minimum zone fit requires that the maximum error vector, calculated from the computed form be minimized. This criteria is also known as the minimax criteria and is expressed mathematically by

$$S = (\sum_{i=1}^n R_i^P)^{1/P} \rightarrow \min$$

$$MIN(MAX(|R_i|))$$

Where R_i are the calculated residuals for n measured points

$$P \rightarrow \infty$$

For the case where $P \rightarrow \infty$, this is known as the Chebychev approximation of the minimax theory. For actual fitting calculations on prismatic shapes Weckenmann [70] suggests P can be set to 30. Note that for $P = 1$

we get a linear criteria, and for $P = 2$ we get a least squares criteria. Equivalent to evaluating the l_p norm is to iteratively fit the feature so as to minimize the maximum residual. This has the effect of weighting the most extreme residual to the extent that all other data residuals are insignificant. An iterative solution to determining the minimum zone fit for circles and cylinders is presented in [67]. Mathematically this is an l_∞ norm.

Maximum Material Condition Fit

For dimensioning, the ISO 1101 tolerancing standard [35] requires that the maximum material condition (MMC) be applied. The maximum material condition fit corresponds to calculating a feature which includes all of the points measured, while the minimum material fit corresponds to calculating a feature which excludes all of the points measured.

This fitting criteria is different from the three fitting criteria outlined above in two ways: firstly the fitting criteria does not average the measurement data, but rather produces an extreme fit to the data, and secondly, the minimum, maximum material criteria may require a scaling of the design feature to fit to the measured data. In practice, this fitting criteria has not often been applied in CMM analysis software, as effective MMC fitting algorithms have not been developed.

The State of Feature Digitizing Systems

- One CMM manufacturer has developed software for capturing a surface design using a contouring probe [68]. The system uses the closely spaced points along a trace to approximate the surface tangent in one direction, and interpolates (using a quadratic) between three parallel traces to ap-

proximate the surface tangent across the trace.

The tangents combined with a reduced set of trace points, are sufficient to define a *patch* type surface. How the resulting surface is to be compared to a design surface is not clear. Further, no mention is made of any effort to provide surface smoothing tools to remove the noise inherent in part measurements.

A program has been developed at NRC for providing probe tip radius compensation for measurements on a sculptured surface using a quadratic approximation [8]. The system uses parallel traces to determine a least squares fit for a quadratic surface patch in the region of interest. Once this is determined, the surface normal at the center point is calculated and a point estimated to be on the part surface is calculated (all the trace points are probe center points). This is repeated to obtain a set of points on the part surface. The system has proven most effective for surfaces where the deviation of the surface normal from the Z axis is not large. A limitation of the explicit surface representation (i.e. $Z = F(X,Y)$) used by Beenan [8] and Kozono [44] is that the system cannot deal with cases where the surface normal lies in the XY plane.

A Japanese paper reports on a system for analyzing car body panels. The system includes a CMM, a digitizer, structural analysis software, and support equipment [44]. The car body panel is digitized by the CMM and a quadratic *patch* is interpolated from the results. A finite element mesh is then created on the surface points and analyzed for structural rigidity.

Researchers at the University of Tokyo [41], have reported a system for digitizing sculptured surfaces for the generation of NC commands. The system uses a B-spline surface patch on knot points generated from the

digitizing data. A minimum elastic strain energy method is used to smooth the surface splines. This reduces the effect of imperfections in the physical part being digitized. The effect of system errors encountered at the surface edge (a characteristic of the B-spline used), is compensated by decreasing the spacing between surface traces (of the probe over the surface) at the surface edge.

It can be seen that for each surface digitizing application, special purpose software is written to process the data into a suitable format. A general purpose surface analysis tool for dimensional inspection has not been described in the literature.

2.4.2 Quality Status Evaluation: The Current State

Most CMMs are equipped with analysis software used to evaluate the quality control status of parts. The accuracy and usefulness of this software is being called into question. This section reviews current methods used for quality assurance, indicating briefly those aspects that are at issue. In Chapter 3, the quality status evaluation problem is investigated and alternatives to the existing approaches developed.

The General Approach

The CMM, when used as a quality evaluation tool, must determine if a part meets the tolerance requirements. As described in Chapter 3, tolerances on sculptured surfaces are usually indicated as form, position, and or orientation tolerances. Briefly, these tolerances respectively control the size and location and orientation of the manufactured part's features. To evaluate these tolerances the CMM must synthesize a feature's geometry

from the measured points, and then compare the position and shape of the synthesized feature with that of the design feature.

Relationship of Fitting Methods to Geometric Tolerancing

One useful goal of fitting features to measured data is to evaluate geometric tolerances. Instruments such as micrometers and calipers have traditionally been used to check tolerances on prismatic features. However, these tools measure the maximum/minimum material condition (i.e. they do not average the data but rather use the extreme values of feature). None of the fitting methods described above correspond to the maximum/minimum material criteria and therefore do not in general match the results produced by standard *hard gauging* (Figure 6a). The maximum/minimum material condition relates directly to the functional requirement of tolerancing in assembly (i.e. if the largest size of a pin is bigger than the smallest size of the hole, the two parts will not assemble even if the average size of the pin and hole indicate satisfactory dimensions) The maximum material principle is outlined in ISO 2692 [36].

Analysis Standards for Feature Synthesis

Virtually all commercial CMMs use a least squares method to synthesize geometric elements for tolerance evaluation.

The method of least squares is well understood, and most CMM software can fit lines, planes, conics, cylinders, and spheres to a set of data.

However, the implementation of these algorithms by CMM manufacturers is often not an exact implementation of the least squares method. As a result, errors in feature measurement are introduced by the analysis soft-

ware. Recent attention has focussed on developing admissibility standards for CMM analysis software.

Work underway for DIN has focussed on virtual software tests to determine the accuracy, and implementation characteristics of analysis software [72,73]. Virtual standards involve feeding the analysis software coordinates of points known to test a certain feature of a particular algorithm. Typical tests involve using sets of points designed to test software analysis of circles and lines [73]. In the future, analysis software might be certified, much as physical machine accuracy now can be.

Current Sculptured Surface Error Determination Methods

CMM software is not able to evaluate the tolerance on sculptured surfaces since a common sculptured surface representation has not been agreed upon. The increased complexity of dealing with sculptured surfaces (as compared to regular shapes) has meant that CMMs can only generally measure probe center coordinates (Figure 3) on sculptured surfaces. Researchers focussing on this problem have primarily looked at two issues:

- determining the error vector between a measured point and a design surface (including probe radius compensation),
- determining the rigid body transformation which fits the measured points to the design feature.

The first issue is a critical problem in evaluating the form tolerance, and may be important in fitting a measured feature to the design feature. The second issue is important in evaluating the position tolerance of a part.

Some commercial routines are available for analyzing two dimensional splines. They include a fitting routine which fits a spline (of user input data) to the measured points [55].

Lotze [51] has presented a general method for determining the minimum distance between a measured point and a parametric sculptured surface. This approach solves an algebraic equation for the point on the master surface nearest the measured point. Unfortunately, this algebraic solution is susceptible to finding local minima (Figure 7), and is explicitly tied to one surface representation.

Xianyuan [77] describes some BASIC subroutines which can be used to determine the minimum distance between a measured point and surface. The surface must be input by the user as a grid of points.

Software (like Xianyuan's) using its own surface representation allows general measurements to be made on sculptured parts. However, the measurements made using surface representations local to a CMM may be of questionable value since the CMM surface representation may differ significantly from the design surface representation.

It is important to note that unlike regular geometric shapes (lines, points, arcs, planes, spheres, etc.) a sculptured surface is defined both by the data used to create that particular surface (knot points, tangents, curvatures) and the particular surface definition (e.g. Coons patches, b-spline surfaces, bi-cubic spline patches, etc.). In the case of regular geometric shapes, the definition of the shape parameters is sufficient (i.e. radius and center point for circle) - the method for constructing a circle is clear.

In the precision manufacture of sculptured surfaces, form tolerances are typically quoted in the range of 25-125 microns (0.001 - 0.005 inches). Different surface representations may easily have positional differences equal to this.

Weckenmann et al [70] describe a method of storing a surface as a series

of iso-height contours. The iso-height curves are used to determine the error between the measured point and the part surface by determining the point on the design surface (curves) which is nearest the measured point.

Surface Fitting Methods - Current Approaches

The methods used to determine a best-fit between a master surface and a set of measured points are still under development. As reported above, Weckenmann 70, has briefly discussed the concept of mapping measured points onto a surface representation including determination of the rigid body mapping between the measurement points and the design surface.

Another paper 11 describes two algorithms for fitting a measured and master surface. The first is the least squares method, which results in six equations - one for each of the transformation parameters to be fit (translation in X,Y,Z, and three rotations). The second approach requires that the complex sculptured surface model be replaced by a set of planes tangent at each surface minimum distance point. The method then determines the rigid body transformation which best fits the measurements to this simplified surface representation by applying the method of linear programming. It is an attempt to apply the minimum zone criteria to free form surfaces and is suitable for small fitting transformations. The method is briefly described and merits further investigation.

It is worth noting that although some of the approaches published in the literature take an analytical approach, all results reported have involved some form of iterative solution. This suggests that a purely analytic approach is not tractable for bi-cubic spline type surfaces.

2.4.3 Special Purpose Analysis Systems

For some families of parts, special analysis software can be developed. This software can both analyze the measurements from the CMM, and possibly determine manufacturing criteria to correct the errors observed. Quality assurance of gears and designing plastic injection molds for manufacture have been areas of advanced analysis development.

Gear Grinding Machinery Setting

Gears are usually ground on special purpose machines, with up to twelve different features to set. Previous testing methods used subjective *running* tests or special purpose analogue instruments to determine the acceptability of gears [9].

From the running tests, both the noise and contact pattern of the teeth indicated if the gear was acceptable or not. Analogue devices are also used to produce traces that are compared with results of traces on a master gear to determine quality assurance. The analogue instruments require the use of a master gear, and do not easily permit one to perform quantitative analysis of the results.

One CMM manufacturer has worked extensively with gear manufacturers on developing a method for quality assurance of gears in a more objective manner [25,45]. The system involves a grid of point measurements on the face of the gear tooth, and contoured tracing of features of the gears. The analysis of the grid points includes a point-to-point error map, with a graphical display.

Work is now underway to extract from measurement results the necessary corrections to the settings of the gear manufacturing equipment to

produce the desired gears [25,45]. This involves simulating the changes in a gear manufacturing machine required to make the observed errors. The corrective machine settings are then the opposite of those required to make the errors.

Plastic Injection Mold Manufacture

The University of Wisconsin is developing a system for producing plastic mold parts which includes CAD/CAM based offline programming (as discussed above) and fitting of measured results to the design surface [22,23].

The CAD database contains a parametric description of the surfaces, and the iterative least squares fitting method allows variation in sixteen of the surface patch parameters; variation in the magnitude of the surface normal and slopes at each corner point, as well as variation in the position of the corner point position along the surface normal. The new surface is calculated to provide a best fit between the measured points and the new surface by varying only these sixteen parameters. This allows for editing of CAD/CAM mold geometry based on measurement of parts produced by the mold. This system can provide information to *close the loop*, providing control information to the manufacturing process. Note that the intent of the system is not to compare the measured shape to the old shape, but rather to determine what *new* shape of mold can be used to produce the correct shape of part (compensating for dimensional changes in the plastic injection molding process). An essential part of this system is a function which determines the point on the design surface nearest the measured point.

2.4.4 The Role of Graphics in Feature Analysis

An alternative to having the computer analyze the results is to present the results graphically to the user for verification. Some CMM packages include plotting facilities to graphically depict the measurements made. This is most often used for measuring sculptured surfaces, where the measured data is plotted against the expected data and the operator makes quality assurance decisions. The need to have the operator evaluate the manufacturing and quality control information displayed in the graphical representation indicates that the relationships between manufacturing processes and observed error trends is not yet well enough understood to be formalized (unlike the gear grinding and plastic injection mold systems described above).

Instead of presenting the results graphically at the CMM when the program is executed, the measurement results can be stored in a file and then loaded back into a CAD/CAM system for graphical verification of the results. CAD/CAM systems allow the user to determine minimum distances between design and measured features. The CAD/CAM systems' ability to magnify the differences between the design and measured geometry is useful in determining manufacturing trends.

2.4.5 Summary of Analysis Methods for Sculptured Surfaces

Systems have been developed to measure and analyze gears, manufacture plastic molds, produce CAD representations of models with complex surfaces, and perform simple point-to-point analysis of sculptured surface measurement results.

Issues in analysis of sculptured surface measurements are:

- methods used to fit sculptured surfaces to measurements of objects (for digitizing),
- evaluating the dimensional error in individual measurements,
- fitting methods that are used to map measured points onto design surfaces,
- standardized surface representations so that measurement and tolerance evaluation can be performed by the CMM computer, or failing this, a method for creating equivalent surface representations in different databases (CAD-CMM-CAE),
- smoothing methods suitable for sculptured surface measurements,
- algorithms for applying ISO standards (Maximum Material Principle) to interpretations of sculptured surface measurements,
- methods of integrating process technology (manufacturing knowledge) into some analysis systems.

2.5 Summary of State of Measurement and Analysis

It would appear unlikely that a general tool will be developed that can analyze CMM data for all sculptured surfaces. Instead, special purpose analysis tools will be developed for each industry providing information required to improve control on the manufacturing process. As the computing power available in CMMs increases, there will be an increased effort to develop analysis systems on the CMM. At present, one of the better places to perform this analysis is on the CAD/CAM system. A CAD/CAM system provides useful tools: surface representations, low level geometric functions, and important graphics and terminal handling functions.

Coordinate measuring systems are being integrated into manufacturing systems with various degrees of automation, to provide production control information.

Coordinate Measuring Machines (CMMs) synthesize all measurements from point coordinate data. Most CMMs are capable of automatically measuring such standard features as planes, cylinders, spheres, and most conics produced by the intersection of these elements. Trends in coordinate measurement machines point towards the introduction of laser scanning machines, and faster, more accurate CMMs.

Three types of probes are available for use by CMMs: touch trigger probes, contouring probes, and non-contact probes. The probe radius error given by most contact probes is a serious limitation. Currently, software must compensate for this error, although hardware solutions (including new probe technologies) are emerging. The non-contact probes are a new measurement technology and promise to improve the capture of measurement data. General trends in probes indicate that data from measurement hardware may soon overload the abilities of analysis systems.

A large variety of offline programming methods have been described in the literature. The trend is towards high level programming languages in graphics assisted workstations, both at the CMM and at the CAD/CAM system. This thesis presents a CAD based approach to CMM programming.

Analysis methods to synthesize features from point measurements are based on a *best fit* usually determined by least squares regression. The accuracy and usefulness of these methods is currently being questioned, and alternatives are being developed. These alternatives include linear, minimum zone and maximum material condition fitting methods. As well,

standards are being developed to test the accuracy of software for geometric synthesis. Current commercial analysis software is limited to dealing with regular geometric shapes and not sculptured surfaces.

The state of measurement analysis for sculptured surfaces is not advanced. Specialized tools have been developed for analyzing particular surfaces (such as gears and planar surface sections). Various approaches to the general problem of surface measurement analysis have been proposed. The different representations used in commercial CAD systems for sculptured surfaces will hamper the development of general (portable) surface analysis tools.

Chapter 3

Measurement Analysis Methods

The previous chapter reviewed the state of the art in computer integrated dimensional inspection and presented some concepts important to measuring dimensional accuracy of sculptured surfaces.

Little in the way of general quality assurance tools exists for CMM measurements on sculptured surfaces. Further, the tools used for regular shapes are not well suited to analyzing sculpture surface features on manufactured parts. This chapter investigates the problem of evaluating dimensional tolerances on sculptured surfaces and looks at methods for extracting geometric information for manufacturing control from the measurement results.

3.1 Quality Assurance Analysis

A contact probe CMM of the type we are concerned with, measures the coordinates of the center of the spherical tip. For quality assurance, an analysis tool is required which can relate the part design to the mea-

sured points and determine if the dimensional accuracy of the part passes tolerance criteria.

To understand how this should be done, we need to understand something about geometric tolerancing. Geometric tolerancing is a quantitative means of describing a functional requirement. Thus a tolerance on a feature indicates the range of possible dimensions of that feature which still ensure proper function of the part. Three types of tolerances are commonly specified on sculptured surfaces: form, position, and orientation tolerances (Figure 8).

3.1.1 Form Tolerances

Form tolerances describe how closely the shape of the manufactured feature has to match the design feature. In the case of a circle, a form tolerance can be thought of as a limit on how far any measured point can deviate from a circle fitted to the measurement data. (In general, form tolerances are meant to ensure the shape of the manufactured part is similar to the design shape). Errors encountered in measured features can be divided into local errors found only in a region of the feature (such as nicks, and bumps), and global errors found over the entire feature (such as a net translation, or rotation of the feature). This thesis determines errors at individual points (local errors) but does not further deal with local errors. Instead, attention is directed at extracting *net* global error ~~correction~~ information from the point measurement data. Thus local errors are included in the data when extracting the *net* global error correction information.

In some cases, it may be required to specify tolerance on the orientation

as well as position and form of a feature (allowing specific control of the orientation of a feature fit to measured data). In cases where orientation tolerances are specified, the position tolerance evaluation is dependent on the datum used (Figure 9 shows how the translation vector depends on the selection of the rotation point). Orientation tolerances are rarely specified on sculptured surfaces, and this thesis does not investigate how best to specify the feature datum when both position and orientation tolerances are specified. Orientation fitting is described in the sections below along with the translation fitting. Orientation tolerances can be thought of as one component of form tolerancing.

Tolerancing is a means of translating functional requirements into quantitative geometric characteristics. Sculptured surfaces are typically used for hydrodynamic shapes, exteriors of consumer goods, and precision engineering components. For the first two categories certainly, the form tolerance on sculptured features usually describes a functional need for the manufactured part to be free of undesired characteristics such as unevenness or nicks, as opposed to general form errors, such as the absolute size of the feature. For these sculptured surface applications, an averaging fitting criteria might be more suitable than the extreme fitting provided by the Maximum Material Condition (MMC). For precision engineered parts, the tolerance may also indicate an assembly limit, where the extreme fit characteristic of the MMC is useful. Thus it would appear that different fitting criteria are useful in evaluating sculptured surfaces, depending on the intended use of the feature. This indicates the need to evaluate form tolerance based on a variety of fitting criteria. Sculptured surface features seldom are required to mate with other parts in assembly. In the case of a sculptured part like a

turbine blade, the form tolerance indicates the maximum permitted normal deviation between the 'fitted' blade surface and the design surface.

Evaluating Form Tolerance: Sculptured Surfaces

The form tolerance of a fitted feature is evaluated simply by determining if any of the error vectors exceed the tolerance envelope around the fitted feature. If none of the vectors exceed the envelope, the part passes inspection, otherwise it fails.

To determine if a measured point lies within the feature's tolerance envelope one must:

1. Determine the point on the *fitted* feature's surface nearest to the measured point. This point we will call the Minimum Distance Point or MDP. A method for determining the MDP is presented in Chapter 4.
2. Determine the length of the vector between the MDP and the measured point, including compensation for the probe radius. This vector length is the error at the measured point or the residual vector.
3. Determine the sign of the error: i.e. which *side* of the feature's surface the measured point lies, and the tolerance magnitude associated with that *side*.
4. Compare the tolerance with the error (magnitudes) to determine the quality status of that measured point.

3.1.2 Position Tolerances

The position tolerance is the maximum distance the reference point of the measured feature can deviate from the reference point of the design feature. The translation vector which best fits the measured feature into the design feature indicates the feature's position error. In the case of a circle, the position error would be the allowed deviation between the centers

of corresponding design and measured circles. For sculptured features, the positional tolerance is the translation vector which maps the measured points into a *best fit* condition with the design feature.

Evaluating Position Tolerance: Sculptured Surfaces

It is common for sculptured parts to have no positional tolerance specified. Thus the form tolerance describes the maximum deviation of any point on the measured part from the design features surface. If a positional tolerance is specified, then the maximum allowed displacement of the measured feature from the design feature is effectively increased by the positional tolerance. When no positional tolerance is specified, translational feature fitting is not required for quality assurance, since the fitted feature can be taken as the design surface. Similarly, if an orientation tolerance has not been specified, then no orientation fit is required, and the measured data are evaluated directly against the design feature.

3.1.3 Feature fitting method

The fitted surface might be calculated using one of the four fitting principles reviewed in Chapter 2: linear, least squares, MMC, Minimum zone (MZ). For most manufacturing work, the MMC principle should be used (ISO 1101) to evaluate assembly tolerances. The MMC fit for common geometric elements is discussed briefly by Lotze [51] who mentions that an iterative solution is required. However, for sculptured surfaces, where feature assembly is often not critical, the required feature fitting approach is not obvious. To learn more about sculptured surface fitting, we will develop the linear and MZ fit approaches. No compelling reasons have been

found to prefer either of the approaches.

Minimum Zone Fit Criteria

To better understand how to evaluate the MZ feature fit, it may be enlightening to describe the MZ fit of a circle (Figure 6A). For a circle, this is defined (ISO 1011) as the circle midway between two concentric circles, the circles being located such that their radial difference is minimized, yet all the measured points lie on or between the circles. In the case of the circle, we can see that the MZ fit was obtained by varying the two parameters that define a circle, the center and radius of the circle definition.

The MZ fit feature has measured data on both sides of the feature (thus it is an averaging fit) and ignores all but the most extreme measurement residuals. In a bi-cubic spline surface, each *patch* segment of the surface is described by 16 variables (position, tangents (2), twist vector at each corner). Duffie [22] describes an iterative least squares fit of a sculptured design surface to a set of measurement data. However, the resulting surface is not as *smooth* as the original surface, and it is not clear how geometric tolerances (position, orientation or form) could be evaluated on a deformed version of the original feature. The 16 parameters describing a surface patch do not directly relate to tolerances. What is required is a fitting approach that allows evaluation of tolerances specified on the design feature. This requires that the shape of the design feature be preserved, and a rigid body transformation be determined between the measured data and the design surface. Therefore, it is proposed that the MZ fit be defined as the position and/or orientation of the design surface for which the maximum distance to all measured points is minimized. This would introduce up to six degrees

of freedom: translation in 3 space and orientation in 3 space. By using the design surface shape to perform the MZ fit of the manufactured feature, we eliminate any differences in shape (defining data and surface type) between the design and fitted feature, which allows us to evaluate a form tolerance on the fitted feature.

3.1.4 Evaluating Position and Form Tolerances - An Algorithm

This section develops an analysis method suitable for evaluating position and form tolerances on sculptured surfaces. The MZ and linear fit methods will be developed in parallel.

Positional Tolerancing: Fit of Design Surface to Measured Points

As was described in Chapter 2, algebraic approaches to the fitting problem of complex shapes have shown little results. Iterative fitting approaches have a more immediate, if less efficient, potential. The approach described below follows an iterative fitting approach, repeatedly improving the fit between the measured points and the design surface. The criteria used in judging the fit can be any of the four approaches reviewed in Chapter 2. The general approach is outlined in Figure 10.

The first step is to determine the MDPs on the design surface for the measured points. Next the vectors between the measured points and the MDP must be determined. These vectors (after probe radius compensation) represent the residuals to be minimized according to the fitting criteria. A method for determining the residual vectors is described in Chapter 4.

Since the residual vector orientations are dependent on the relative position of the measured points with respect to the design surface, any rigid body transformation of the data will require the re-evaluation of the residuals.

Once the fit of the current residuals against the fitting criteria has been evaluated, transformation estimates for improving the fit must be determined. The approach taken in this thesis is to iteratively improve the fit between the design surface and the feature, each time choosing the motion which most improves the fit. After each improvement of the fit the residuals are recalculated. We have three degrees of freedom for position tolerance evaluation: vector translation in 3 orthogonal axis, and three degrees of freedom for orientation tolerance evaluation: rotation about an axis in space (3 orthogonal rotations). Methods for fitting the design surface to the measured points using a rigid body translation and/or rotation are developed below.

Evaluating the Linear Fit Criteria

The linear fit criteria is satisfied when the sum of the magnitudes of the error residuals is minimized (l_1 norm):

$$S = \min \left(\sum_{i=1}^n |MDP_i - \vec{R}_i| \right)$$

where MDP_i is the minimum distance point of the i th measurement
 P_i is the measured point coordinate

Evaluating the Minimum Zone Fit Criteria

The MZ fit criteria is satisfied when the maximum of the measurement residuals is minimized (l_∞ norm):

$$\hat{S} = \min \left(\max (|R_1|, |R_2|, \dots, |R_n|) \right)$$

Where $R_1, R_2, \dots, R_n$ are the measured residuals:

$$R_i = MDP_i - P_i$$

With the current fit criteria evaluated, the next step required is to estimate the rigid body transformation which will minimize the norm. This may include translations, and or rotations calculated so as to minimize the fit criteria.

Predicting the Linear Fit Translation

The net translation which best fits the measurements to the feature is the vector average of the residuals. The residuals are area weighted to reduce the effect of different densities of measurement points:

$$D = \frac{\sum_{i=1}^n R_i \cdot AF_i}{\sum_{i=1}^n AF_i}$$

where AF_i is the area weighting factor for the i th measurement as shown in Figure 11

D is the translation vector estimated

Predicting the Minimum Zone Translation Fit

The estimate of the translation according to the MZ criteria is driven by the maximum residual (without making another residual greater than the *reduced* maximum residual).

The direction of the MZ fitting translation will be along the direction defined by the maximum residual. The length of the fitting translation will be the amount that is estimated to make another residual of equal length to the maximum residual. If we model the surface in the neighbourhood of

each MDP as a plane (after Bourdet 11), then the estimated length of a residual after a translation in the direction of the maximum residual is:

$$R'_i = R_i + D \cdot \sin(B_i)$$

and the inequality:

$$R_{max}' = \text{MAX}(R'_i)$$

where R'_i is the residual after translation

R_i is the residual of the i^{th} residual

D is the displacement vector in the direction of R_{max}

B_i is the angle defined in Figure 12 between the i^{th} residual and the maximum residual

The procedure to solve for D is an iterative one and might benefit from linear programming techniques (not investigated in this thesis):

1. determine the maximum residual (R_{max}).
2. make an initial estimate of the translation vector's length as 50% of R_{max} .
3. calculate the maximum of the new estimated residuals.
4. if $\text{MAX}(R'_i)$ greater than R_{max}' then reduce estimate of D by 50%, otherwise increase it by 50%.
5. If the difference between $\text{MAX}(R'_i)$ and R_{max}' is less than a tolerance value then stop, otherwise repeat from step 3.

Note that this fitting translation is always along the vector of the maximum residual, but the measured point which has the maximum residual may change after each fitting (and recalculation of the residuals). This suggests that the minimum zone rotation fitting method is not optimum.

Rotational Fit

The rotation transformation is defined as an angle (theta) by which the measured points can be rotated around a line to reduce the vector sum

of the rotation moments to zero. The line of rotation defines both the axis of rotation and the point of rotation. In the sections below, methods are suggested for calculating the rotational fitting for the linear and MZ criteria.

As with translation mapping, the error vectors must be re-calculated after the rotation is applied, giving rise to use of iteration to obtain a satisfactory solution.

Estimate of Rotational Transformation by Linear Fit Criteria

To understand the linear rotation transformation some terms must be introduced. The part centroid (P_c) is defined to be the point located at the area weighted average of the MDP point facets:

$$P_c = \frac{\sum_{i=1}^n A_i \cdot P_{c_i}}{\sum_{i=1}^n A_i}$$

where A_i is the area of the i^{th} facet region

P_{c_i} is the centroid of the i^{th} facet region (see Figure 11 for facetting method)

This point acts as a reference point for the rotation. This centroid is not a volumetric centroid, and worse yet, may bear no relation to the point of rotation of the actual part. This has the effect of reducing the fitting convergence rate and inducing an unwanted translation in the measured data (Figure 9).

We will define the minimum distance point offset vector ($Omdp$) as the vector from the part centroid to the surface MDP's, and the measured point offset Om as the vector from the part centroid to the measured point:

$$Omdp_i = MDP_i - P_c$$

$$O m_i \quad P_i \quad P_i$$

where MDP_i is the i^{th} minimum distance point
 P_i is the i^{th} measured point

The geometry for the rotation moment calculation is shown in Figure 13. The net rotation moment vector, is the area-weighted cross product of the minimum distance-point offset and the measured point offset.

$$\vec{M}_r = \frac{\sum_{i=1}^n A F_i \cdot \sin \left(\frac{O m d p_i \cdot O m_i}{O m d p_i \cdot O m_i} \right)}{\sum_{i=1}^n A F_i}$$

where M_r is the rotation moment

The axis of rotation is in the direction of the net rotation moment vector and the length of the net rotation moment corresponds to the angle of rotation.

$$\theta = M_r$$

$$axis = UNIT(\vec{M}_r)$$

Minimum Zone Estimate of the Rotational Fit

The MZ fit by definition reduces the maximum residual. To estimate the rotational fitting transformation, three parameters are required: a vector to rotate about, a point to locate the axis of rotation, and an estimate of the rotation to optimize the fit.

Several possible methods can be used to estimate the point of rotation. Three possibilities are suggested:

- estimated part centroid (taken as the volumetric centroid for a solid model, or the area centroid for a surface model). In the case of an area centroid, the approach described above for determining the linear rotation estimate can be applied

- center of sphere passing through the four MDPs with the minimum residual vectors (points must be non planar)
- User specified point (allows input of user *knowledge*)

As well, various approaches can be considered for defining the axis of rotation:

- the axis defined as the cross product of the MDP offset vector and the measured point offset vector (offsetting from the centroid determined above)
- user input vector (allows input of rotation axis expected from manufacturing process)
- axis of rotation calculated by another fit criteria (i.e. linear fit)

Finally the angle of rotation must be calculated. One strategy might be to rotate the measurements about the (above specified) line such that the reduced maximum residual is equal in length to another of the residuals.

$$R'_i = R_i + D_i \cdot \cos(B_i)$$

$$D_i = \frac{UNIT(Om_i, M)}{(Om_i, M) \cdot 2 \cdot \sin(A/2)} \cdot Om_i$$

$$B_i = \sin^{-1} \left(\frac{(N_i \cdot D_i)}{(N_i \cdot D_i)} \right)$$

Hence we must satisfy the inequality:

$$MAX(R'_1, R'_2, \dots, R'_n) = R_{max'}$$

Where D_i is the displacement induced by a rotation angle A

R'_i is the modified residual

M is the rotational axis vector

A is the angle of rotation

B_i is the minimum angle between D_i and M

N_i is the i^{th} point's surface normal

$R_{max'}$ is the modified maximum residual

This procedure can be repeated until the change in A is less than some specified tolerance (i.e. 10% of the original estimate of A).

Discussion of Fitting Methods

When the largest possible improvement in the fitting criteria is below a specified system tolerance, the form fit has been accomplished and the form tolerance can be evaluated.

The fitting methods presented above are for displacement and rotational transformations according to the linear and MZ norm. Similar approaches can be developed for the two other fitting criteria: least squares, and maximum material condition.

A limitation in the solution speed of fitting is the time required to compute the MDPs after applying a fitting transformation. Alternative methods for computing MDPs for small displacements from previous values is discussed in chapter 4.

It is clear that the algorithms described above may not be the most efficient means of determining estimates of the optimum fitting transformation. As well, situations can be envisaged when the measured feature is 90 degrees (Figure 14) or 180 degrees out of phase from the design feature (we will call this a phase-shift local minimum). To improve the convergence rate and ensure the global optimum fit is determined, several strategies are suggested:

- Develop more sophisticated algorithms for estimating the fitting displacements and rotations.
- Evaluate the fit improvement of a variety of fitting strategies, and then select the strategy which improves the fit criteria the most. This may be a costly alternative as evaluation of the residuals (required for each fit estimate) is currently the major computation bottleneck.

- To avoid the phase shift minimum problem, the minimum fit feature should be rotated 90° about one of three orthogonal axis, and the minimum fit solved again. The fit with the best fit criteria would be determined to be the *best* fit. Note that if the maximum error is much less than the characteristic length of the part, then it is not likely that such a *phaseshift* minimum exist

Comparison of Fitting criteria For Tolerancing

In this thesis, four different fitting criteria have been discussed: linear, least squares, MMC, and MZ. ISO standards require that the MMC fit is to be used for all measurements.

Based on the ISO standard's requirement for MMC fitting, one may ask why most general purpose CMMs have analysis software based on least squares regression. There are two main reasons for this: CMMs are new devices and users are only beginning to fully understand how to use the machines in a manufacturing environment. Secondly, the least squares method is well understood and has been relatively easy to apply to simple prismatic shapes. As was discussed in Chapter 2, the least squares analysis software is coming under increasing scrutiny and alternative fitting methods are being developed. Traditionally, least squares methods have been used to fit data that were assumed to be noisy due to measurement inaccuracies. However, the measurement errors of a CMM are typically below tolerances specified on sculptured parts, and any noise in the data should be assumed to come from inaccuracies of the part which the user is interested in knowing about. Thus, the *averaging* nature of the least squares fit for geometry tolerancing is not useful since it discards useful information. When used to capture feature geometry (digitizing) the least squares fit is useful since a smoothed, or average feature shape is desired. Therefore various fitting

methods should be available on the CMM, and elsewhere, to analyze CMM measurements

3.2 Extracting Manufacturing Control Information

The CMM has the potential to become a manufacturing sensor, providing feedback to control the manufacturing process [64]. The tolerance analysis provides useful information in determining the quality control status of the individual points and the part in general. However, higher level quantitative information is required to control a manufacturing cell. A tool is needed which will provide information about the types of errors, and quantitative information which can be used to correct the manufacturing process. The errors observed in the measured parts can be divided into global errors and local errors. As was discussed earlier in the thesis, the global error information extracted actually includes the local error data, and thus should be considered *net* global error information.

To extract global errors, analysis of the measurement data must extract information related to the manufacturing processes. Typically this information includes:

- the position and orientation of the manufactured feature (with respect to the design feature)
- the size (scale) of the manufactured part with respect to the design part

Analysis to extract geometric manufacturing control information can be thought of as a special version of the geometry fitting described above. By fitting the measured points to the geometry (or vice-versa) we can determine easily visualized parameters such as the rigid body translation.

rotation, and scaling that relate to some of the differences between the measured part and the designed feature. These parameters might be used directly to correct the manufacturing process.

For example, to evaluate the tolerance status of a sculptured feature with form, orientation, and position tolerance requirements, the rigid body transformation which minimizes the distance between the design surface and the measured points is required to evaluate the positional tolerance. This transformation also indicates the reverse of the translation and rotation which can be applied to the manufacturing process to improve the tolerance status of the next part. In the case where all measurement points indicate stock or undercut, a scaling or translation of the part is suggested to improve the form tolerance status of the next part produced. Thus some of the manufacturing control information is directly linked to the form, orientation, and position tolerance data. However, in cases where the orientation or positional tolerances have not been specified, then the complete rigid body best fit (translation and rotation) must be evaluated before extracting the manufacturing control information from the fitting transformation matrix.

3.2.1 Obtaining Quantitative Manufacturing Process Control Information

The analysis used to evaluate the positional tolerance of the part, produces a transformation which contains some geometric manufacturing control information. When the analysis has been completed, the homogeneous transformation which maps the measured points to their final position can be extracted directly from the net transformation matrix as a translation:

and a rotation in a plane through the origin.

The net fitting is a homogeneous transformation defined by a the standard 4 x 4 matrix, where the first three items of the last column indicate the net translation vector, and the first three items of the first three columns indicate the direction cosines of the net rotation about the origin:

$$T_n = \begin{pmatrix} C_{11} & C_{12} & C_{13} & D_x \\ C_{21} & C_{22} & C_{23} & D_y \\ C_{31} & C_{32} & C_{33} & D_z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

where D_x, D_y, D_z are the net translation vector

$C_{11}, \dots, C_{33}$ are the direction cosines of the rotation matrix

The rotation about some point which is not the origin is given by:

$$T'_n = \begin{pmatrix} 0 & 0 & 0 & X_o \\ 0 & 0 & 0 & Y_o \\ 0 & 0 & 0 & Z_o \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot T_n$$

where T_n is the 4 x 4 net transformation matrix

X_o, Y_o, Z_o are point about which to rotate

T'_n is the new net transformation

A translation error vector has several possible sources in the machining process, and as well, several possible methods of correction. If 2 or 3 axis machining is performed, then a translation vector along the axis of the tool spindle indicates improper tool length, or improper part placement. If the translation vector is normal to the tool axis then part mis-location is indicated. In the case of multi-axis machining, the possible causes of a translation are less clear.

A net rotation in the measured part data generally indicates mis-alignment or slippage of the part in the fixture.

3.2.2 Surface Normal Scaling

Surface-normal-scaling can be defined as a translation of each measured point along its current error vector by a specified amount. This is a deforming scaling that has interesting properties. Firstly, the surface normal scaling represents quite well the case of a semi-finished part surface with evenly distributed excess material (stock) on the surface. Secondly, the MDPs after this transformation do not need re-computing as the transformation of each point is along the MDP's surface normal. This makes it possible to evaluate semi-manufactured and final manufactured parts using the same design surface feature. Due to its deforming nature, the surface normal scaling should be applied only after the rigid body transformation.

With a MZ fit applied, the surface normal scaling factor can be estimated as half the scalar difference between the maximum residual and the smallest residual (or largest opposite residual).

$$S_r = \frac{MAX(R_1, R_2, \dots, R_n) - MIN(R_1, R_2, \dots, R_n)}{2}$$

Where S_r is the scaling amount. When using a linear averaging fit, the surface normal scaling factor can be estimated as the area weighted average of the measurement residual lengths (including direction).

$$S_r = \frac{\sum_{i=1}^n A_i R_i}{\sum_{i=1}^n A_i}$$

From a manufacturing viewpoint, it is sometimes useful to apply the maximum residual, or the minimum residual length to scale the points.

3.2.3 Summary of Manufacturing Control Information Analysis

In summary, the techniques developed to extract tolerance information

from measurement data can be applied to obtain useful manufacturing control information. As well a surface normal scaling fit is useful for evaluating semi-manufactured items. As for tolerance evaluation, the interpretation of analysis results for cases involving both translation and rotation is not clear. The selection of the point of rotation is important, as was discussed for tolerance analysis.

Chapter 4

Calculation of Minimum Distance point on Surface

This chapter describes the algorithm used to determine the minimum length vector from a sculptured surface to a measured point. At the end of the chapter, the algorithm is evaluated, and alternative approaches discussed.

4.1 Problem Definition

The CMM returns the probe center coordinates at the point of contact. A method is required to relate this point to the design surface and determine the error vector measured between the two. This distance, less the probe radius, represents the estimated error between the part surface and the design surface. This error is only an estimate of the measured error vector, since it is based on the assumption that the differences in the normal between the part surface and the design surface are minimal. With errors expected in the range 4 to 4000 microns, and surface roughness significantly below that, this assumption is reasonable.

A method is required to determine the point on the design surface which is nearest the probe center. This point will be called the theoretical contact point or the minimum distance point (MDP). Since this point is *nearest* to the measured point, the normal to the surface at the minimum distance point must also pass through the measured point. This surface normal vector then defines the direction of the error vector. It can immediately be noticed that all error vectors will be normal to the design surface.

As reported in Chapter 2, a variety of analytic approaches to determining the minimum distance point have been proposed, but few results presented. There are two significant problems to overcome in determining the MDP analytically: multiple local minima, and the difficulty of computing the roots of the algebraic equation describing the distance to the surface. The problem of local minima is shown in Figure 7. The second problem can be described by briefly investigating the analytic approach.

Sculptured surfaces are typically represented as bi-cubic splines surface patch in two dimensions (U,V) as shown in Figure 15. Such a surface description provides position (C^0), tangency (C^1) and surface normal (direction) continuity at patch boundaries. The function describing the coordinates of a point on the surface involves 16 terms and has maximum order $U^3 \times V^3$. The function describing the distance between any measured point (P_1), is then the length of a vector from the measured point to a point on the part surface.

$$D(u,v) = \sqrt{(F_x(u,v) - X_1)^2 + (F_y(u,v) - Y_1)^2 + (F_z(u,v) - Z_1)^2}$$

Where F_x, F_y, F_z are functions used to describe the surface contours
 X_1, Y_1, Z_1 are the coordinates of a measured point

To solve algebraically for the minimum distance point on the surface,

the derivative of this equation must be evaluated (WRT U , and V) and the resulting equations set to zero (for a minimum). This results in two algebraic equations of combined order 11, which must be solved for roots, among which the local minima can be found by calculating the distance to the measured point. Since CAD surfaces are defined usually as a union of patch elements, this solution would have to be carried out for each patch. Note some of these patches could be eliminated without solution if the patch could be tested to ensure it was *away* from the measured point. Although significant performance improvements might be expected over an iterative interpolating approach, the development effort for an algebraic solution would be significant higher, and difficult to apply to different surface types. Duffie 22 describes a Newton-Raphson (iterative) solution to the minimum distance problem for surfaces made up of multiple bi-cubic spline surface patches. This approach is an alternative to the method implemented below and may offer better performance but at the cost of a more extensive development and maintenance effort.

The nature and type of surfaces used in different CAD systems are significant factors in the method used to determine the minimum distance point. The Unigraphics CAD/CAM system supports nine different types of surfaces, including ruled surfaces, tabulated surfaces, and a cubic spline based sculptured surface. Any of the nine surface types can be used to design and manufacture a part. For the development effort of the thesis it was felt useful to use a common interface to all these surface types. This also has the advantage of making software developed for the MDP function more easily portable by having a clear and common interface to any surface type.

4.2 Tools Available

Before developing the solution, it would be useful to describe the tools available in the implementation. The interactive CAD/CAM system, and the interactive programming language, includes a function to determine the line (vector) which passes through a given point and is normal to a given surface. Unfortunately this function cannot distinguish between multiple normal points on surfaces even though it takes as input a point *near* the surface-normal point. In subsequent releases of the CAD/CAM software these functions may perform more predictably and then can be used in place of much of the code developed. Until then, a method is required to determine the surface MDP.

Two possible development environments are available when developing the analysis software with the CAD/CAM system. The host computer (VAX 780 under VMS) provides a complete program development environment, including screen editors, linkers, and a sophisticated debugger. The CAD/CAM system provides a Graphics Interactive Programming language (GRIP), a line editor, linker, and rudimentary compiler. The GRIP programs are executed interactively by an interpreter. This has the advantage of providing *instant* viewing of program results, at the expense of execution speed. The Fortran interface has a significant performance advantage over GRIP, at the cost of a more *batch* user interface (graphical results can be viewed only after exiting the measurement program). A Fortran developed analysis system is more portable: the analysis program can be modified to run with other CAD/CAM systems, or even ported to run on a CMM computer. Based on the above reasons, it was decided to implement the system in Fortran.

Two possible levels of routines are supplied with the CAD/CAM system. The lower level functions extract the basic surface definition data from the CAD/CAM database. From the parameters defining the surface, special purpose representations of the surface could be developed, and a solution similar to that developed by Duffie [22] could be developed. Such an approach would be fast, at the expense of a reduction in the portability of the code, and would require significantly more coding effort (each surface type must be treated separately) to develop and maintain.

The second level of routines provides a higher level interface to the surface data. The CAD/CAM system provides two routines which calculate positions, tangents and normals at a surface position. The routines take as input a unique surface entity identifier, and the U,V parameters on the surface which uniquely define the position (fig 15), positions, tangents, and normal given a surface identifier and parameterized surface position (U,V). It was decided to use the higher level routines. This approach provided a common interface to all types of surfaces and required less development effort. As well, since it can be expected that other CAD/CAM systems may suffer a weakness similar to Unigraphics (concerning lines constructed normal to a surface through a given point), this approach would make the resulting function easier to implement on other CAD/CAM systems.

4.3 Algorithm for Minimum Distance Point Determination

Positions on the surfaces in the CAD/CAM system are defined using two normalized parameters U and V. As described above, Fortran callable routines are supplied which return surface position, tangents, and normal

on a surface given a unique surface identifier and two parameter values. The problem then translates into determining the U and V parameters of the point on the surface which is nearest the measurement point. The solution has been broken down into a four steps: initialization, locating, rough binary search, and normal point determination. An overview of the solution method is shown in Figure 16. Briefly, the first step is to develop an approximate representation to the surface which eliminates the possibility of finding local minima. Building this surface representation need be done only once for each surface. For each measured point, the nearest element's corner node is located. The distance of the measured point to the adjacent nodes is used as an estimate of the parameter position on the surface for the MDP. The final section interpolates to find the actual position of the MDP. The solution method is expanded below.

4.3.1 Initialization

In the initialization section, a mesh of points is placed on the surface such that the length of the sides of all grid elements is less than a specified distance, and the difference between the corresponding surface vectors (tangent along U, tangent along V, and surface normal) at adjacent grid element corners is less than a user specified angle. This effectively breaks the surface into a set of variable size rectangular elements (rectangular in U,V). The algorithm uses a divide and conquer approach to the problem, much like an Oct-tree solid modeller.

The elements are smaller in regions of higher curvature, and larger in regions of lower curvature. The airfoil section used for system evaluation has approximately 2200 elements with a tolerance angle specified as 15 de-

degrees (no attention has been paid to determining the optimum tolerance angle). Figure 17 shows a mesh of points created with a much larger tolerance angle. The user must use a tolerance angle low enough to ensure that grid elements do not contain multiple normal points, or significant changes in slope.

The data stored for each grid point are: position (X,Y,Z) normal (I,J,K), and surface tangents (along U and V as vectors). This mesh is created once for the surface and is stored in a datafile for subsequent analysis involving that surface.

4.3.2 Locating

For each measurement point, the analysis system first locates the nearest section of the grid surface. At present the routine finds the surface mesh point nearest the measured point, and then checks that there are no elements between the nearest point and the measured point. With the nearest point calculated, the routine then calculates an initial estimate of the U,V parameters at the minimum distance point (the method is shown in Figure 18). With an initial estimate of the MDP calculated, a rectangular grid (in terms of parameter values) on the design surface containing this estimated MDP must be calculated. The grid is sized according to the degree of correlation between the three estimates of the MDP parameter values:

$$Du_i = (MAX(U_l, U_r, U_n) - MIN(U_l, U_r, U_n)) \cdot 2$$

Where U_l is the U MDP parameter value from point to left of the i^{th} near point

U_r is the U MDP parameter value from point to right of the i^{th} near point

U_n is the U MDP parameter value from nearest point to the measured point

DU_i is estimate of surface patch parameter length

(SIMILAR FOR ESTIMATE OF DV)

The maximum size of the grid is limited by the minimum parameter length of the smallest adjacent element. The minimum size is limited to a specified percentage of the minimum adjacent parameter length.

This section of the algorithm avoids local minima which are not nearest the MDP. It also reduces the size of the surface region which must be interpolated over to find the actual MDP and thus increases the performance of the final interpolating strategy.

4.3.3 Final Interpolating Search

The interpolating search algorithm assumes that the surface segment passed to it by the rough search, is sufficiently small that it can be considered *almost* flat. The interpolating search attempts to move the MDP estimate point so that its surface normal passes through the measured point. To start the algorithm, the positions of each corner of the grid segment are obtained, and the surface vector data and position for the center point is obtained. Then:

1. The measured point is mapped into the coordinate system defined by the surface normal and one of the tangent vectors (Figure 15). The

X,Y distance of the measured point from the Z axis, corresponds to the distance of the measured point from the surface normal. Based on the projection of this distance along the U tangent, and along the V tangent, and the current size of the grid, the U,V estimate of the MDP is modified:

2. If the distance of the measured point from the current surface normal is less than some specified fraction of the grid segment's maximum side length, then the grid is scaled down around the current estimate of the MDP.
3. If the U,V estimate of the MDP falls outside the current patch, then the grid is re-centered.
4. If the distance of the measured point from the local Z axis is less than a system tolerance (currently E-06 units), then the current estimate of the MDP is deemed correct.
5. If the U,V estimate moves outside the parameter values defining the surface ($0 \leq U, V \leq 1$), then the routine returns to the calling routine with an error status. In this case the rough locating routine increases the size of the grid and restarts the final interpolation routine.
6. If this fails, then each element for which the *nearest point* was a corner node is evaluated by the final interpolating routine.
7. A point failing all these strategies is defined as off the grid.

When a MDP point has been obtained, its U,V parameters, X,Y,Z coordinates and surface normal vector are stored for use in the quality assurance routines.

4.3.4 Evaluation of Current Algorithm

The algorithm successfully avoids the problem of multiple minimum distance points (local minima). To date it has been used successfully on the plane, sphere, and airfoil shape shown in the Figures (19-26). Although a possible fatal bug is discussed below, the bug has not yet been observed in the measurement results. The routine has performance problems, and in

view of the critical requirement for speed in an integrated quality assurance and manufacturing control information system, performance improvements are required.

The MDP algorithm has not been tested for measurement points located over the surface edge. This is not envisaged to be a major problem, but has been avoided due to time constraints.

Bugs

The current MDP locating method is successful but has limitations and performance problems. The rough search algorithm currently is entirely functional, but a case has been envisaged which would cause it to fail (Figure 27).

The locating algorithm first finds the nearest surface mesh point, and then checks that there are no mesh facets between the nearest point and the measured point. However, it may be possible to have a measured point inside a closed surface that is selected as over a mesh node on one side, but actually is closer to the surface on the opposite side. In this case the locating section would pass the incorrect surface segment to the interpolating search routine, resulting in a local, but not global MDP being found. As well as this possibly fatal error, the locating function estimates the location of the initial U,V parameter of the MDP using the approximation that the grid is rectangular (i.e. U tangent is orthogonal to V tangent). This results in less than ideal location of the initial grid element size. This can be easily corrected, which would improve the execution time.

Performance

The algorithm speed is heavily dependent on the size and type of surface stored in the CAD/CAM system, and the number of times the surface position and vector data must be calculated.

The functions used to determine the surface positions, tangents and normal data requires in excess of 90% of the execution time of a typical analysis run. As can be expected, this function (written by the CAD/CAM vendor), requires more computing resources as the surface complexity increases. At present no effort has been made to improve the execution speed of the function. The MDP function takes from less than a second (for the plane and sphere of revolution) to in the neighbourhood of 5 seconds per measured point for the airfoil surface.

4.3.5 Alternative Minimum Distance Point Solutions

The approach presented above has proven accurate and general although slow. Since the MDP routine is the current bottleneck in the analysis system, other methods should be considered to improve the speed of the feature fitting speed function.

The fitting requirements can be broken down into two levels: coarse and fine-tuning. For coarse fitting, the transformations calculated are comparable to the characteristic dimensions of the feature. This type of fitting is important for parts without an easily referenced datum. Usually, only fine-tuning fitting is required (i.e. the part is precisely aligned before measurement). The fine tuning fit calculates movements that are small relative to the surface geometry, and thus approximations to the surface geometry such as suggested by Bourdet [11], can be applied.

Bourdet has presented a method whereby the surface is modelled as a set of planes, one tangent to the surface at each MDP. For this model to work, the plane must model the design surface in the region that the transformation moves the MDP. The MDP on a simple geometric feature (like a plane) can be calculated directly giving a significant performance advantage. For small changes in the MDP, the planes model quite well the feature surface. For larger changes in the MDP, higher order approximations (i.e. quadratic surfaces) might be used to model the surface at the MDP. For these quadratic surfaces, the MDP point should be easily obtained. It is clear that the accuracy of the approximated minimum distance points must be verified when the feature has been optimally *fit*. These MDP approximation methods have not been implemented or tested yet.

Chapter 5

Integrated Surface Measurement and Analysis System

In the previous three chapters, the analysis of measurements on sculptured surfaces for tolerance evaluation and dimensional manufacturing control was investigated. The study has included the development of analysis algorithms for sculptured surfaces. To gain further knowledge on the problems in analysis methods for quality and manufacturing control, some of the algorithms developed have been implemented as part of an integrated manufacturing facility under development at the National Research Council. The ideal performance of the inspection system and its current performance are described in this chapter.

5.1 The Quality Assurance Problem

A basic problem in manufacturing is to ensure the efficient production of functional, valuable products. Tolerance criteria have been developed to

define the domain of acceptable functional parts.

In some discrete part manufacturing environments, flexible manufacturing cells are being developed to improve the productivity of expensive machine tools. By grouping machines in cells according to the type of object they produce, parts spend less time being transported between machines, increasing the machine usage and reducing the total part manufacturing time. By reducing the throughput time, a new problem has appeared. The time required to inspect a finished or semi-finished part is often longer than the time it takes to machine the part. Thus, a method is required which improves the efficiency of tolerance status inspection.

The CMM's recent arrival on the manufacturing scene has been spurred by this need for a fast flexible quality assurance tool, and by the decreasing cost of computer equipment. The combination of a CMM for part measurement, and a CAD/CAM system for measurement programming and analysis provides the opportunity to develop an effective quality control tool inspection for sculptured parts in flexible manufacturing environments.

5.1.1 The specific Problem

Existing quality assurance methods for precision air-foil parts are labour intensive and expensive, requiring special machines and/or gauges. Computer assistance to design, manufacture, and measurement has lead to islands of automation, and information processing bottlenecks.

This chapter deals with the problem of developing a computer integrated inspection system in the context of a modern flexible manufacturing environment. The system is intended to provide precise measurement data on sculptured surface features, and feed manufacturing control informa-

tion back to the flexible manufacturing facility with a minimum of human interaction.

5.1.2 The Approach

Modern manufacturing methods are developing around the use of computers to integrate information flow. Typical discrete part manufacturing facilities include a computer aided design and manufacturing system, numerically controlled machines, and local area networks to allow communication between electronic computing devices. In a computer integrated manufacturing environment, the CAD system is responsible for creating and storing the geometric definition of the objects to be produced. Thus the CAD database should be used for measurement programming and for analysis of measurement results. The CAD database should be used by measurement programs to evaluate measurement analysis data for non-prismatic shapes. To this end, the functions provided in the CAD system need to be enhanced to include measurement programming functions (much like NC programming functions), and quality analysis functions, (similar to analysis functions implemented in CMM analysis software). The NBS 31.32 is developing an inspection system which combines features of a CAD system and a CMM programming and analysis system in one computer system.

In the section which follows, features of an ideal system are described to guide the development and evaluation of an integrated surface measurement and analysis system. These requirements are divided into three sections, corresponding to the measurement programming tool, the measurement tool, and quality analysis tool.

5.1.3 Requirements of Measurement Programming Method

Features of an ideal measurement programming system would include:

- the ability to measure specific points in the design surface (often the points used to define the surface)
- ability to use different measurement strategies (point distribution)
- automatic programming of user selected features
- automatic feature recognition and programming
- transportable measurement programs (useful on different makes and types of CMMs)
- ability to create programs for different probe configurations (i.e. to take advantage of motorized probe heads and multiple tip configurations)
- ability to create programs for various probe technologies (contact, contouring, laser scanning, optical, acoustic)
- graphical animation of measurement sequences
- collision detection and avoidance
- compact measurement program size since most CMM computers are small
- minimum workstation cost and operator training requirements

Measurement program creation methods have received some attention to date, and a variety of solutions exist. In the future more of these features will be appearing on more of the programming systems.

5.1.4 Requirements of the Measurement System

Based on the quality assurance requirements for sculptured surface parts and the problem definition, features of an ideal measurement tool can be defined. They include:

- ability to precisely measure points on the part surface (not at some given offset distance from the part surface)
- ability to measure a wide variety of materials unaffected by physical properties such as: strength, reflectivity, and conductance
- ability to measure many points on surface quickly
- minimal part setup, calibration, and operator interaction requirements
- high accuracy and repeatability
- minimal cost of equipment
- transparent communication with other computer equipment
- open system design suited to system integration

Although these features represent a wish-list of features, the measurement technology is approaching these goals much quicker than the analysis technology, leading to the possibility of a bottleneck in the analysis system.

5.1.5 Requirements of the analysis System

Chapter 2 reviewed the state of current surface measurement analysis tools. The review showed that this is an area of ongoing research, in which few commercial tools are immediately available. Chapter 3 is devoted to understanding and developing the analysis problems associated with sculptured surfaces in the context of dimensional tolerances and geometric process control feedback. The current chapter describes some of the system objectives of a computer integrated quality assurance system for sculptured surfaces. The analysis tool developed will be briefly evaluated here.

Based on the problem definition, the ideal sculptured surface measurement analysis and evaluation tool should have the following features:

- accept coordinate measurements on sculptured surfaces as input
- be able to evaluate form orientation and position tolerances for sculpture surface parts (including compensation for probe radius offset as required)
- provide graphical display of position and form errors with colour coding of quality assurance status (pass fail, gouge, stock).
- extract position and form error data in a form suitable for a cell controller
- execute analysis quickly

5.2 Tools Available

The system objectives described above provide goals to aim for in the implementation. The tools available for developing the solution form the other part of the development environment. In the following paragraphs, these tools are described to provide a better understanding of the details of the system implementation which follows.

5.2.1 The Technical Environment

The Manufacturing Technology Center is a section of the National Research Council which manufactures experimental equipment for researchers at the Council using a wide variety of sophisticated equipment and techniques. As well as having manufacturing responsibilities, the MTC also investigates and develops manufacturing techniques useful to Canadian industry. It is against this background that an adaptive manufacturing cell is being developed by the MTC. The cell is acting as a test bed for new and innovative manufacturing ideas, and as a productive environment for pro-

ducing small lots of high precision objects. Typical parts being produced in the cell involve airfoil shapes and have lot sizes less than fifty.

The cell includes a multi-axis machining center, a 4-axis lathe and a CMM. All the machines are computer driven and are being integrated to run under a cell controller being developed in-house. A CAD/CAM system supports the activities of the cell. The CMM and the CAD/CAM system are the key tools used to implement the quality assurance system for surfaces and are described in more detail below.

5.2.2 CAD/CAM System

A Unigraphics CAD/CAM system is used at the MTC to design, analyze and manufacture some of the parts produced. The system includes three-dimensional surfaces, a link to a finite element analysis package and an advanced machining package. As well as these interactive facilities, the system is equipped with keystroke macros, (for often repeated commands), an interactive CAD/CAM programming language, and a Fortran/callable interface to the Unigraphic database. Both the programming languages above allow user *tailoring* of the CAD/CAM system to suit particular needs.

The NC machining functions of the CAD/CAM system provides an easy partial answer to the problem of developing a method for offline measurement motion programs for CMMs. The interactive CAD/CAM language and the Fortran interface provide programming access to the CAD database and high level geometric functions. The graphics ability of the CAD/CAM system provides an excellent method of presenting a graphical display of the results of the measurement analysis.

The CAD/CAM system runs on a VAX 11/780 minicomputer under

the VMS operating system. The computer is linked via DECnet to several other machines but not the CMM control computer. The CMM computer is currently linked by the communications program Kermit. It is planned to implement a DECnet link in the very near future.

5.2.3 CMM

The CMM is a Brown and Sharpe model 8202 (with components in Figure 1). Equipped with a Renishaw ph9 probe, the CMM has a measurement envelope of 720 X 880 X 730 mm and a repeatability of 8 microns. Unfortunately, though our CMM is a very accurate measurement device, the servo-control system has a significant following error, and poor dynamic control of the machine's axis, preventing the machine from moving along an arbitrary vector in space. Precise movement is only available by moving the probe parallel to one of the principle axis at a time.

The CMM is controlled by VALMES measurement software residing in a PDP 11 23 computer under the RSX-11M plus operating system. The CMM is also equipped with a library of Fortran callable subroutines which can be used to control the CMM from a user's application program. The CMM software is menu-driven, allowing inspection, analysis and on-line programming of regular geometric features.

The analysis package of the CMM has evaluation functions for vertices, edges, planes, arcs, spheres and cylinders. Any geometry which cannot be described using the geometry mentioned above, must be evaluated using other analysis software (possibly user written). The measurement results can be output to a file or a printer. The CMM is not equipped with a graphics output device, or graphics software.

5.3 Current Implementation

Given the requirements and tools presented, a surface inspection system has been designed and is being implemented.

In the following sections, the current solution is described. A discussion of alternatives, improvements and directions for future work is also presented.

5.3.1 Measurement Programming Implementation

Measurement programming currently is done manually or from the CAD/CAM system. With the CMM installed in October 1984, valuable experience is being gained by comparing the manual programming against the CAD/CAM based approach.

Manual Surface Programming

In the manual mode, the operator moves the CMM through the inspection sequence by keying in coordinates, selecting functions from the menu-based system or using the joysticks to control motion.

The typical sequence for measuring a single point on a surface involves seven distinct operator actions. The sequence is recorded and can be edited and later replayed to repeat the measurement program.

CMM-Based Surface Programming

Using the CAD/CAM system, an operator creates a NC toolpath with the probe normal to the measured surface, and a rectangular mesh of points.

The rectangular mesh of points (constant number of measurement points)

in each row) is currently required by the analysis software. The NC program (a text file) is modified by a program which inserts positioning moves above each measurement point (Figure 28) a distance specified by the user. To provide compatibility with our CMM these position points are placed along the principle axis of the machine, from the measurement point or at forty-five degrees to the axis. The modified NC program is then translated into a text version form of the Brown and Sharpe measurement program and transferred to the CMM computer. The transferred file is translated into its binary equivalent to reduce its size by approximately two-thirds. This file is now compatible with the Brown and Sharpe measurement software and can be edited and executed. The operator often adds a sequence of measurements to the beginning of the program to align the coordinate system of the machine to the part. This establishes a reference to the part, and allows quality control data to be calculated.

5.3.2 Part Measurement

The CMM uses a touch trigger probe which measures contact with the part surface. The machine returns the probe center coordinates at the instant of contact with the surface. The measurement program is executed by the Brown and Sharpe VALMES-11 software, and the results are output to a file or a printer.

5.3.3 Measurement Analysis

Measurement data to be compared against the CAD database must be saved to a disk file. The file is transferred to the CAD CAM computer for analysis. The operation of the analysis program is shown in Figure 29 and

its principles developed in Chapter 3.

Briefly, the point measurements are read from the inspection report file and fit to the design surface feature. The fit is limited to rigid body movements: translation and rotation. The transformation determined to fit the measurements is used to determine the position and/or orientation tolerance status, while the minimum distance from the measured points to the fitted surface feature is used to evaluate the form tolerance on the feature. The fitting transformation also indicates global manufacturing control information for the part (as was noted in Chapter 3, if no position or orientation tolerance is specified on the feature, the feature fitting procedure must be repeated to allow creation of the rigid body fitting transformation). Four possible fitting criteria are investigated in Chapter 3, and algorithms for two have been described. From the fitting transformation, a translation and rotation can be extracted which indicate how to change the placement of the part, or the tool to correct errors which are global to the inspected feature. In some cases the corrections to the part position or the tool characteristics can be fed automatically back to the cell controller, while in others, the manufacturing process must be modified at a more fundamental level. From the graphical display of measurement results produced by the analysis system, the user can obtain better understanding of the nature of local errors. A listing file of the results of the analysis provides hardcopy of the measurement results, including measured errors at specified points.

To perform the analysis a variety of data are required. These are listed below to indicate the initial user input required.

- the name of the measurement file.
- the name of the design part file.

2

OF/DE

2

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

- the maximum allowed stock.
- the minimum allowed stock.
- the layers to put the error mesh geometry on.
- the colours to be used to create the error mesh geometry.
- the error mesh scaling factor.
- the dimensions of the measurement grid.
- the layer location of the surface in the design part database.
- the type of surface to be inspected (only used to locate the surface).
- the name of the file containing the rough search point data
- the tolerance angle used to create this set of points.
- the surface mesh point maximum linear spacing (optional)
- the MDP calculation tolerance (optional)
- the name of the listing file used to audit the analysis (optional)
- the probe radius used to measure the part
- the coordinates of a point above the surface on the *outside*

5.4 Testing, Evaluation, and Future Directions

In the previous section the current system design was outlined. In this section the current implementation is evaluated, alternatives are discussed and directions for future work are indicated.

5.4.1 Programming Method

The manual programming method has proven to be labor intensive and hard to modify. The manual approach produces a measurement sequence which conforms to the data input requirements of the CAD system (ie. a mesh of measurement points). However, manual programming remains a viable means of developing measurement programs for surfaces due to the flexibility of the human operator.

In both the manual method and the CAD/CAM based method, it is common for several iterations to be made through the programming process before an acceptable program is produced.

Features and Advantages of Offline Surface Inspection Programming

The offline programming using the CAD/CAM system has proven to be viable. The approach used is flexible, fast, and easy to develop. It reduces CMM down time due to inspection program development and provides an ability to semi-automatically measure sculptured surfaces (much as the CMM software now allows automatic circle measurement).

Weaknesses

The offline programming system has demonstrated several weaknesses.

The current analysis software requires that measurement points be in a rectangular grid. Thus, only CAD/CAM functions which are capable of producing such a grid of points are suitable for producing N/C programs to be converted to measurement programs.

The CAD/CAM based offline programming requires more training to

use since knowledge of both the CMM and the CAD/CAM system is required.

The offline programming system has no collision avoidance strategies, and relies on the graphical verification of the tool path by the operator to ensure a collision-free sequence of motions. The system also does not make any attempt to orient the motorized probe head (of the CMM) so that the probe flank does not collide with the part before the tip.

One alternative to the CAM-based offline approach taken would be to generate measurement programs directly from the CAD/CAM database. This avoids the requirement of user knowledge of the CAM functions in Unigraphics. However this approach significantly restricts the flexibility in the offline program created and requires significantly more development effort.

A possible improvement to the method implemented, might be to develop a program based on the CAD/CAM programming language (GRIP) which contains NC functions to generate tool motions. The application program could contain all these functions and modify the NC programs created to include the CMM probe positioning sequences (prior to measurement). The CMM program could then be animated for user verification. This implementation would eliminate the creation of N/C programs, thus reducing the number of files produced (the current method results in at least five files being produced for each measurement program developed). However a significant development effort would have to be undertaken for this solution, something that will only be practical if CAD/CAM based offline CMM programming receives strong user response.

In summary the current method developed for offline programming is

suitable but should be further developed. More attention should be placed on creating measurement programs that allow the user to control which regions of the surface (or features) receive the most measurement points.

5.4.2 Measurement

In this section the measurement tool (CMM) used to obtain coordinate information on sculptured surface parts is evaluated.

It would appear that the CMM is at present the most suitable tool to solve the problem of precisely measuring sculptured surface parts. However the type of CMM, along with the probes, and the control software used to execute the inspection sequence should be evaluated.

CMM Evaluation

The CMM available can be used as a device to measure sculptured surfaces but has severe limitations. The probe system is limited by the a probe radius error, and measurement speed. The probe radius error requires significant software to provide probe radius compensation.

The CMM requires approximately 1 to 20 seconds for each measurement. For sculptured surfaces, a relatively even distribution of measurement points is required to accurately determine the quality status of the part (possibly several hundred points). Contouring probes are much better suited to the measurement of free-form surfaces, with their high data acquisition rates and contour following ability. Normal sensing probes (as described in the literature survey) should reduce the need for software probe radius compensation, and allow more meaningful data to be produced by the measurement machine.

The control system is one of the weakest parts of our CMM. The servo control system has such a serious following error that the machine cannot move along a vector in free space. A precise servo-control system is required to allow measurements to be made normal to the theoretical surface (to minimize measurement errors) and increase the flexibility of offline programming. The Brown and Sharpe 8202 is more suited to manual programming, and the measurement of prismatic parts than the cell-computer-controlled, free-form surface measurement that is required. Since this CMM can move accurately only along certain directions, the part (and or part fixture) must be aligned very precisely to the machine coordinate system. This eliminates one of the advantages of a CMM: the ability to place the part randomly and allowing the CMM to compensate for the positioning of the part. It would appear that CMMs are still evolving into NC machine tools, and the next generation of motion controllers should have acceptable accuracy.

Alternative Coordinate Measurement Devices

Alternatives to a CMM as a measurement tool currently include: laser scanning devices, and special purpose measurement machines. Their capabilities are described in the review section of this thesis.

Briefly, the laser scanner is limited by reflective surfaces and the laser spot size, and may require calibration for each surface type measured. Laser scanners feature fast data acquisition rates and no probe compensation requirements.

Special purpose measurement machines are built for measurement in high production environments and for special purpose applications where

existing technology is not sufficient. The high production inspection machines (typically the automobile industry) use a variety of special sensors, with customized control and analysis. The special purpose measurement machine environment has produced laser scanners, and can be expected to develop technology which may find application in the measurement of small batches of precision parts.

Measurement Execution Software

Despite the limitations mentioned above, a CMM equipped with a touch trigger probe appears to be a viable tool for measuring parts in a flexible manufacturing environment.

The CMM used by MTC has a flexible, open computer control and as such is a machine well suited for integration into an experimental manufacturing cell. The integration ability is largely based on the library of Fortran subroutines supplied with the CMM, and the PDP 11 computer used to drive the measurement system.

Two methods of controlling the CMM are possible: the interactive package VALMES, and secondly via a user-created program which accesses the library of CMM control functions. VALMES is currently used to execute the measurement programs. It is a good tool for inspecting prismatic shapes in a manual mode, but it is not suitable for inspecting sculptured surfaced parts in a computer controlled adaptive manufacturing cell. VALMES cannot be easily controlled by an external computer, and the measurement programs required for surface measurement are not suited to measuring sculptured surface parts.

Proposed Measurement Control Software

The author is not aware of any commercially available system which can be used directly to replace the VALMES control program. Rather it would appear necessary to develop in-house a CMM control system from the supplied library functions to provide the control method required.

The program required should interface to the offline programming system at the CAD/CAM system, the cell control computer, and the analysis software. As well it should accommodate for some of the weaknesses of the CMM in measuring sculptured surfaces. From these requirements, and experience with the existing CMM control system, some aspects of the CMM control program requirements can be defined.

The control program should receive a measurement program from the CAD/CAM system in the form of an APT-like program, with probe orientation and positioning moves already included. The control program should interpret this program, and compensate the movements for minor mis-alignment between the part and its expected position. As well as being more suited to measuring as part of a cell, and measuring sculptured surfaces, the above method should reduce significantly the size and number of files produced in the CMM programming cycle.

The control program interface to the cell control is less well defined and is not a focus of this thesis. Currently the inspection system is not well integrated, and requires significant manual input.

The control program interface to the analysis software is not clearly defined. Some of the interface requirements can be defined. The analysis software must reside on the CAD/CAM computer to access the database, and the CAD/CAM library routines. The CMM must pass probe center

coordinates to the analysis software. One issue is the frequency of data transfer. One alternative is to pass each point to the analysis system individually, while alternatively a set of data points could be passed at once. If the points are passed individually, pass/fail status for individual points can be quickly determined, while if the data is passed as a set, less communication is required and manufacturing information (translations, scaling factors, trends) can be established.

Summary of Measurement Method Evaluation

In summary, the use of a CMM to measure free-form surfaces is viable. However the particular CMM, probe, and CMM measurement control software are not ideally suited for the job.

Introduction To Analysis Evaluation

The analysis system must produce two types of information: firstly, it must provide pass/fail quality information on the part feature measured. Secondly it must provide manufacturing feedback to the cell controller to ensure the production of acceptable parts.

The quality assurance function has been broken down into two sections: fitting the data to the design surface, and secondly evaluating the dimensional errors of the measured part. The manufacturing control information function extracts global error information from the fitting transformation used for the quality assurance function.

In the sections which follow, the system will be evaluated. The analysis system has been tested using synthesized data on a plane, sphere, and an experimental airfoil shape. The use of synthesized data allows individual

fitting transformation algorithms to be more easily demonstrated. A significant difference exists between synthesized and *actual* data when attempting to fit the measurements to the design surface since the noise inherent in actual data may affect the ability of the analysis (depending on the noise level).

Quality Assurance Function Evaluation

Finding the error between the measured point and design surface involves two steps: determining the rigid body transformation between the measurements and the feature (which best matches the two according to a norm), and secondly evaluating the geometric tolerancing status.

The Fitting Function

The fitting function has been implemented with a linear fitting criteria. Fitting functions have been developed for translation and a deforming scaling. The results are presented in Figures 19-26. In general the results are encouraging. The function is able to reduce the vector sum of the residuals but significant improvements are required.

Area weighting of the residuals is currently done using the area represented by the facets between MDPs. The accuracy of this estimate of the surface area increases with the number of measured points, but in general, this area is less representative of the actual surface area than the area calculated using the surface mesh used for the rough locating search. Thus a better approximation of the surface area between measured points would be to use the locating search surface mesh (Figure 17). Another alternative would be to use the surface parameter (U,V) values for area weighting.

In the test examples used, the measured points were evenly spaced. This meant that area weighting was in some cases less accurate than the same calculations made without area weighting. An effective area weighting strategy is important in accurately predicting improvements to the fit.

Manufacturing Control Information Evaluation

The manufacturing control information can be separated into information describing local errors (extracted from the individual error residuals), and information describing global errors (feature position, orientation, and scaling errors).

No effort has been made to extract manufacturing control information about local errors.

The algorithm for extracting the rotations and translations contained in the transformation matrix has not yet been implemented.

General Evaluation of the Analysis System

The analysis system shows promise and has produced encouraging results. Several improvements can be made to the analysis system.

The analysis currently requires that the measurement points form a rectangular grid (for area weighting and the error display mesh).

This limits the CMM programming methods that can be employed, and may result in more measurements being made than necessary. To overcome this limitation, a method is required which will link measurement points with their nearest neighbours (in terms of U,V parameters), so as to create a mesh of triangular facets. This will allow the analysis of measurements which are not distributed in a grid pattern. One benefit of free distribu-

tion of measurement points is increased compatibility (for benchmarking) with current hard-gauging methods where measurements are made only at specific *gauge* points.

The analysis is only capable of dealing with point measurements made relative to one design surface. The system was originally intended to provide analysis of parts where the majority of the exterior was described by one design surface. However, the system can be expanded to multiple surfaced parts, and may see application in providing quality assurance and manufacturing control information for prismatic shapes described by multiple surfaces.

There is no provision to store the current state of the analysis data so that it can be resumed or *restarted* at a later date. This feature will be implemented.

As well as the above general improvements, the analysis software should be tightened up, and made more user friendly (on line help, better menus, etc.)

Graphical Display of Error Information

The graphical display is functional and useful. The colour coding of the vectors quickly identifies trouble spots on the surface.

Improvements to the graphical display are: the automatic scaling of the error vectors so that the maximum error vector is a given length, allowing error meshes for interim transformation states to be produced, and highlighting the maximum stock and undercut error vectors.

Analysis Listing File

The analysis listing file currently tracks the analysis, includes the listing of: the input parameters used in the analysis, the measured point coordinates as input, the calculated error vectors, and a summary of the analysis results.

✓ The listing currently reports the coordinate data in world coordinates where local coordinates might be more useful, and reports on the error vectors after each *fitting* operation. At this date, the listing also outputs all the error vector data after each transformation, resulting in large files. In general the listing is useful, but needs polishing.

Chapter 6

Conclusions and Future Work

6.1 Summary and Conclusions

The state of measurement devices used for coordinate measurement has been summarized in chapter 2. The literature review showed that sensors are being developed which are capable of measuring points on a part surface at high data rates, without a probe radius error. This new technology will require that analysis methods be capable of handling increasing quantities of measurement data.

Dimensions of sculptured surface parts are specified with form, position, and/or orientation tolerances. These tolerances indicate allowed deviations between the design surface feature and the manufactured part feature.

This thesis developed an analysis method for evaluating all three tolerances from a set of measured points. The analysis extracts three types of error vectors from the measurements which can be related to each of the tolerances directly.

The position error vector is evaluated as the three-space vector which best fits the design surface to the measured points. The orientation error

vector indicates the rotation in space which best fits the measurements onto the design surface feature. The length of this vector indicates the magnitude of a rotation angle, while the direction indicates an axis of rotation (which can be used to decompose the rotation into three orthogonal rotations).

The form error vector is the maximum of the set of shortest normal vectors between each measured point and the design surface after the surface has been fit to the measured points according to the position and rotation tolerancing requirements. The magnitude of the form error at each measured point is compared against the form tolerance requirements. If any form error exceeds the form tolerance then the measured item fails the inspection.

It is proposed that a rigid body motion of the design surface be used when fitting the sculptured surface to the measurements. This preserves the shape of the surface, which allows the tolerances specified on the design surface to be used in conjunction with the fitted surface.

The thesis has investigated the criteria used to fit the measured points to the design surface. Four criteria have been considered: linear, least squares, Minimum Zone (MZ), and Maximum Material Condition (MMC). Although the MMC criteria is required by ISO standards, few analysis methods conform to it. Most industrial dimensional analysis systems apply a least squares criteria for fitting prismatic shapes. In the thesis it is concluded that an averaging fit criteria (linear, least squares or MZ) may be more suitable for most sculptured surface tolerance evaluation. The thesis developed detailed algorithms for the linear and MZ fit, and a sample implementation using a linear fit is described.

A major problem in the analysis of measurements on sculptured sur-

faces is the evaluation of the error vector between each measured point and the surface. This thesis developed an algorithm for determining this error vector. Although a possible situation has been envisaged which will cause the algorithm to fail, the implementation has proven successful for all testing to date. The algorithm requires that a point mesh representation be developed for each design surface. The algorithm developed in Chapter 4 is limited by the fact that the point mesh representation is slow to create, and further, the error vector algorithm is inefficient.

The different surface types used within, and between CAD databases complicates the approach used to analyze inspection measurements on sculptured surface parts. The use of a common interface to CAD surface representations has the advantage of a clear separation between CAD functions and database functions, and makes for more portable program code. The common surface interface has the disadvantage of lower performance (higher system overhead), and results in a complex numerical solution being used on all surface types, including for surface types where simple analytic solutions are possible.

6.2 Future Work

Methods for improving the performance of the error vector algorithm have been investigated. Approaches which model the region of each MDP as a simple geometric element show promise. The use of MDP algorithms created for each surface representation (as demonstrated by Duffie 22) is another means of improving the MDP function performance.

The current solution implementation requires that measured points form a rectangular grid (equal numbers of points in each row). This limita-

tion can be eliminated by developing an algorithm for determining non-overlapping facets that pass between all the measured points. Existing work in tessellation (making facets) might be applied here.

The algorithms for translational and rotation fitting are primitive. Alternative algorithms and improvements are suggested below.

- application of algorithms developed for matching two dimensional shapes (developed in mapping and vision)
- recognition and extrapolation of trends in the iterative fitting methods used

FIGURES

(SERVO CONTROL CABINET NOT SHOWN)

COMPONENTS OF A
COORDINATE MEASURING MACHINE

FIGURE 1

-- 101 --

TOUCH TRIGGER PROBE

CONTOURING PROBE

LASER SCANNING PROBE

PROBE TYPES

FIGURE 2

PROBE RADIUS OFFSET ERROR
FIGURE 3

FRICTION AND NORMAL FORCE
ON SLIDING PROBE TIP

FIGURE 4

INACCURACY CAUSED BY
APPROACH OFF SURFACE NORMAL
FIGURE 5

- MINIMUM MATERIAL FIT
- MAXIMUM MATERIAL FIT
- MMC FIT: THE FEATURE WHICH COMPLETELY ENCOMPASSES ALL THE MEASUREMENT DATA (INSIDE OR OUTSIDE)

MINIMUM MATERIAL CONDITION VS MINIMUM ZONE FIT (EXAMPLES)

FIGURE 6A

L2 FIT: THE AVERAGE OF THE SUM OF
ERROR VECTORS MAGNITUDES
SQUARED IS MINIMIZED

L1 FIT: THE AVERAGE OF THE SUM OF
THE MAGNITUDE OF THE ERROR
VECTORS IS MINIMIZED

L1 AND L2 FIT METHODS
(EXAMPLES)

FIGURE 6B

FOUR POSSIBLE NORMAL VECTORS
TO MEASURED POINT.
NOTE THAT TWO VECTORS ARE ALSO
LOCAL MINIMUMS

MEASURED POINT

THE MINIMUM DISTANCE PROBLEM
FIGURE 7

++ INDICATE MEASURED POINTS
CURVES INDICATE THEORETICAL SHAPE

COMMON SCULPTURED SURFACE
TOLERANCES

FIGURE 8

BEFORE ROTATION

INDUCED TRANSLATION ERROR

AFTER ROTATION

TRANSLATION INDUCED BY
INEXACT ROTATION POINT SELECTION

FIGURE 9

FITTING ALGORITHM (OVERVIEW)

FIGURE 10

⊕ - MINIMUM DISTANCE POINTS

DASHED LINES INDICATED TRIANGULAR
FACET EDGES

AREA USED TO WEIGHT CENTER
M.D.P. IS INDICATED BY CROSSHATCHING

AREA WEIGHTING METHOD BASED
ON MINIMUM DISTANCE POINT FACETS

FIGURE 11

B_i — THE ANGLE BETWEEN THE i^{th} RESIDUAL VECTOR AND THE MAXIMUM RESIDUAL VECTOR

GEOMETRY FOR ITERATIVE
DETERMINATION OF
MINIMUM ZONE TRANSLATION FIT

FIGURE 12

WHERE P_c = CALCULATED PART CENTROID
 P_i = MEASURED POINT COORDINATES
 $M D P_i$ = CALCULATED MINIMUM DISTANCE POINT
 A_i = CALCULATED ROTATION ANGLE
 $O P_i$ = MEASURED POINT OFFSET VECTOR
 $O M D P_i$ = MINIMUM DISTANCE POINT OFFSET VECTOR
 R_i = RESIDUAL OF POINT

GEOMETRY FOR ROTATION MOMENT CALCULATION

FIGURE 13

(OUT OF PHASE BY 90 DEGREES)

PHASE SHIFT
LOCAL MINIMUMS

FIGURE 14

PARAMETRIC SURFACE DESCRIPTION

FIGURE 15

MINIMUM DISTANCE POINT ALGORITHM

FIGURE 16

EXAMPLE: EXPERIMENTAL AIRFOIL
SHAPE

MESH CREATED WITH TOLERANCE ANGLE OF 45 DEGREES
MAXIMUM GRID ELEMENT SIZED TO 10% OF SURFACE EDGE
THE MESH ABOVE CONTAINS 501 POINTS

SURFACE POINT MESH FOR
ROUGH SEARCH

FIGURE 17

GIVEN: SURFACE PARAMETER AND X,Y,Z COORDINATES OF PL,PN,PR
 X_1, Y_1, Z_1 AT MEASURED POINT P_1

PN - INITIAL M.D.P. ESTIMATE NEAR POINT
 PL - POINT ON SURFACE MESH TO LEFT OF PN
 PR - POINT ON SURFACE MESH TO RIGHT OF PN

PN, PL, PR ARE ALL ON ONE SURFACE PARAMETER LINE

THIS GEOMETRY DESCRIBES THE METHOD USED TO CALCULATE THE MINIMUM DISTANCE POINT SURFACE PARAMETERS (U AND V) TO DEMONSTRATE, WE WILL SHOW THE METHOD USED TO ESTIMATE THE U PARAMETER VALUE (UM)

$$UM = \frac{D \cdot \cos(\text{ALPHA2})}{UR - UN}$$

$$D = \text{SQRT}((XN - X1)^2 + (YN - Y1)^2 + (ZN - Z1)^2)$$

$$E^2 = D^2 + B^2 - D \cdot B \cdot \cos(\text{ALPHA2}) \quad \dots \text{COSINE LAW}$$

$$B^2 = (XN - XR)^2 + (YN - YR)^2 + (ZN - ZR)^2$$

$$\cos(\text{ALPHA2}) = \frac{(D^2 + B^2 - E^2)}{2 \cdot D \cdot B}$$

THE GEOMETRY OF TRIANGLE CDA CAN ALSO BE USED TO ESTIMATE THE PARAMETER VALUE

GEOMETRY FOR MINIMUM DISTANCE POINT
 PARAMETER ESTIMATION

FIGURE 18

SAMPLE GRAPHICAL OUTPUT FROM
MEASUREMENT ANALYSIS SOFTWARE

FIGURE 19

GRAPHICAL DISPLAY OF MEASUREMENT ANALYSIS OUTPUT
(AFTER APPLYING TRANSLATION TO MINIMIZE
NET ERROR VECTOR)

FIGURE 20

NOTE RESULTS ARE INDENTICAL TO
THOSE PRODUCED BY TRANSLATE
'FITTING' FUNCTION
(FIGURE 18)

SAMPLE RESULT OBTAINED FROM APPLYING
'SCALE TO REDUCE STOCK/UNDERCUT'

FIGURE 21

SAMPLE OUTPUT FOR SPHERE
(POINT DATA AS INPUT)

FIGURE 22

TRANSLATION WAS APPLIED 5 TIMES
AVERAGE ERROR VECTOR WENT FROM
.0399 INCHES BEFORE TRANSLATION
TO .0011 INCHES AFTER TRANSLATION

SAMPLE OUTPUT - SPHERE
(AFTER 5 TRANSLATIONS)

FIGURE 23

MESH SHOWN IS OF DATA
AFTER 'SCALING TO REDUCE STOCK'

AVERAGE ERROR BEFORE SCALING = .0399
AVERAGE ERROR AFTER SCALING = .0011

SAMPLE DATA - SPHERE
(SCALING TO REDUCE STOCK)

FIGURE 24

THIS FIGURE SHOWS A 'SHIFT'
IN THE MEASURED DATA WITH RESPECT
TO THE PART SURFACE (VECTOR SIZE
SHOWN ABOVE
THE MEASURED PART DATA HAS
.05 INCHES EXCESS MATERIAL

NOTE: COLOURS INDICATE QUALITY
CONTROL STATUS OF MEASURED POINTS

GRAPHICAL OUTPUT FOR SCULPTURED PART
(WITH PART SHIFTED)

FIGURE 25

NOTE: PART MOVED AS PER
PRECEEDING FIGURE

.0058 STOCK ON ALL POINTS

RESULTS PRODUCED BY AREA
WEIGHTING DATA

SURFACE MESH
(AFTER 'FITTING')

PART SURFACE

GRAPHICAL OUTPUT - SHOWING COMPENSATION
(AFTER TRANSLATION FIT AND SCALING STOCK FIT).

FIGURE 26

SITUATION WHICH COULD CAUSE
M.D.P. FUNCTION TO FAIL

FIGURE 27

TOOL PATH CREATED USING CAM FUNCTIONS
(TOOL SIZE .05 INCHES DIAMETER)

CMM PROGRAM OUTPUT FROM INPUT SHOWN ABOVE
(RETRACT DISTANCE = .2 INCHES)
NOTE: PROBE APPROACHES TO PART ARE PARALLEL
OR AT 45 DEGREES TO COORDINATE SYSTEM

CAD/CAM BASED METHOD FOR
OFFLINE CMM PROGRAMMING

FIGURE 28

ANALYSIS FLOWCHART
FIGURE 29

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