2001

CAD model construction from CMM and laser scanning data for reverse engineering.

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CAD MODEL CONSTRUCTION FROM CMM AND LASER SCANNING DATA FOR REVERSE ENGINEERING

by

Christopher J. Rolls

A Thesis
Submitted to the Faculty of Graduate Studies and Research through Industrial and Manufacturing Systems Engineering in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada
2001

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0-612-62276-2
ACKNOWLEDGEMENTS

I would like to extend sincere appreciation to my advisor Professor Waguih H. ElMaraghy, and co-advisor Professor Hoda A. ElMaraghy, for affording me the opportunity and ongoing support necessary in completing this work. I would also like to recognize my other committee members, Dr. Fillipo Salustri, for his rigorous examination, and Dr. Robert Kent, for his review, of this work. It is fair to say that my time spent at the University of Windsor over the past few years, was quite fruitful, and that the experience was enhanced by the assistance I received from several members of the university staff. Most notable from this group are the Industrial and Manufacturing Systems Engineering technicians Dave McKenzie and Ram Barakat, secretary Jacquie Mummery, and Mark Enns and the late Dieter Liebsche of the Technical Support Centre.

On a more personal note, I would like to thank my mother Linda McAuley for her support and understanding during several years of university study. I would also like to thank my wife Shan for her assistance in preparing this dissertation, as well as for numerous nights spent alone while I was working in the lab. Finally, I must express my deepest gratitude to my grandmother June Vandenberghe for a lifetime of encouragement and belief, which is at the core of all that I have accomplished.
ABSTRACT

In reverse engineering, computer-aided design (CAD) models are constructed from existing production or prototype parts. Until the introduction of high-speed digitization technologies, in the early 1990s, coordinate measuring machines (CMMs) were the primary means of reverse engineering data collection. Today, CMM use is largely reserved for precision projects. Often, however, it is the accuracy requirements of only a few critical part features that inhibit the use of high-speed digitizers for many of these applications. In this work, the strengths and weaknesses of constructing CAD models from CMM and laser scanned data are examined, through case studies, and shown to be the complement of one another. This justifies the development of a reverse engineering system that combines CMM and laser scanning data in efficiently accommodating a much wider range of applications. Such a system definition is contained herein for a DEA Mistral CMM and Hymarc Hyscan 45C laser scanner.

In a combined approach, data collected using CMM and laser scanning must be transformed into a common coordinate system. This data set combination, or registration, is facilitated by digitizing prismatic datum artifacts along with the part. The dominant uncertainty in this process lies in determining the location and orientation of these artifacts, relative to the part, for each data set. A new approach was developed to control this uncertainty in the CMM sampling of manufactured primitives. Focusing on planes, a series of fractional factorial experiments were conducted. The results confirm the feasibility of developing manufacturing process specific prediction relationships linking significant measurement factor effects and form error magnitude to the level of location and orientation uncertainty, the key enabler. In the case of laser scanning, similar uncertainties were assessed for spheres and cylinders, an area not previously considered in literature. Using the resultant trends, an artifact-based compensation technique was devised, yielding a 74% decrease in the laser scanner systematic registration error. This, in tandem with the CMM approach, enables the precise combination of both forms of data.
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CHAPTER 1 – OVERVIEW AND LITERATURE SURVEY

1.0: INTRODUCTION

In modern practice, and for the scope of this work, reverse engineering may be defined as the process of generating a computer-aided design (CAD) model from an existing part or prototype. The general reverse engineering process, which has changed from a skilled manual process to one incorporating sophisticated computer software and measuring instruments, has four main phases.

![Diagram showing the stages of reverse engineering]

**Figure 1.1:** Stages in the general reverse engineering process.

While reverse engineering has been used for many years in industry, particularly in the automotive and aerospace sectors [103], it has recently shown a marked increase in implementation. This is primarily due to the introduction of rapid part digitization technologies, and the availability of inexpensive computers. With these, the product design and manufacturing cycle has shown time reductions of as much as 40 to 90% [35, 51, 53, 105, 121].

In the late 1980’s and early 1990’s, Coordinate Measuring Machines (CMMs) were the most common method for digitizing surfaces [67]. Today, due to the need for faster cycle times and the development of high speed digitization technologies, their use has declined greatly. However, in cases where high accuracy and the availability of, or access to, a machine are of primary concern, CMMs are still in use.
1.1: APPLICATIONS OF REVERSE ENGINEERING AND DIGITIZATION

There is a wide array of applications for reverse engineering technologies, many of which have emerged in recent years. This section describes several areas of major and increasing use.

1.1.1: Importing Artisan and Prototype Geometry into CAD

In the automotive industry sculpted clay models are, and have in the past been, used extensively for car body design, trim: panels, components, and so on [51, 64]. Currently, clay prototypes are scanned, often using laser-based technologies, and the data is imported into CAD software for Class A surfacing and subsequent tooling manufacture. The use of rapid digitizing technologies has lead to significant time savings, and better surface modeling visualization due to increased data densities.

In another example, a major eyeglass manufacturer has switched from copy-milling frames from hand sculpted prototypes, to using reverse engineering and rapid prototyping technologies in generating production tooling [28]. Not only is the process significantly faster, but the constructed CAD model can be scaled to accommodate variations in a particular frame style. Moreover, perfect symmetry between the right and left sides of a particular frame is obtained by mirroring the model of one side. This reduces the reverse engineering cycle time, and leads to improved product quality.

1.1.2: Generating Custom Fit Surfaces

In this area, reverse engineering is generally used to enhance performance and ergonomics. Applications include custom fit gloves and clothing for NASA astronauts, the development of gas and medical masks to fit the contours of the human face [100], product packaging, and precisely sculpted surgical implants, tools, and prostheses [31]. The significance of this application in certain industries has led to the creation of human features databases, used in subsequent product design. Work by the Intelligent Manufacturing Systems Centre, at the University of Windsor, has included the production of a custom fit holder for an ultrasound probe used at the John Robarts Institute, London, Ontario [45].
1.1.3: Updating CAD Models Due to Production or Prototype Design Changes

Reverse engineering has become an effective tool for producing parts when design data is partially missing, or non-existent [105]. It is also helpful in updating design intent CAD models when prototype-based functional improvements or downstream manufacturability enhancements are made.

In a particular case, engineers at a Detroit automotive company used reverse engineering to capture the redesign geometry of a side-view mirror prototype. The original design prototype was found to vibrate beyond specifications in wind tunnel testing. Engineers experimented with various contours in clay until a shape that met both functional and aesthetic requirements resulted. This geometry was then digitized, and the data imported to the CAD system to facilitate design model changes [93].

1.1.4: Rapid Tooling

While several reverse engineering applications involving rapid prototyping have been discussed, it is important to note the specific impact on production tooling. In the past, the duplication of prototype tooling was accomplished using manual tracing or copy-milling. Automated scanning can produce tooling in 30% to 90% less time, depending on the complexity and detail of the data [51]. Several companies have emerged that specialize in this area, particularly in replacing worn production tooling, and in generating new tooling by reverse extraction of prototype surfaces [95].

1.1.5: Replacing Parts with Lost Supply Lines

Mechanical breakdown of machinery often occurs while spare parts are not available, as in the case of old machinery [1]. It may, therefore, be necessary to reverse engineer a worn or broken part in order to remedy the situation. In India, for example, 3D digitizers are used to reverse engineer aerospace and automotive parts from the former Soviet Union, as supply lines have been lost [100].

1.1.6: Medical Pre-Operation Planning

Combined with rapid prototyping, this is a growing application of reverse engineering digitization. CT scanning is used to digitize an operable area on a patient.
From this data, a rapid prototype part (generally SLA) is produced which aids surgeons in planning complicated surgery [28, 74, 122].

1.1.7: Quality Control

In many areas of production, more thorough, rapid and on-line inspection is required [51]. The advent of high speed digitizers, and software with the capability to handle large amounts of data, has led to an ability to automatically and quickly compare scan clouds from manufactured parts directly to CAD master files. The system can then accept or reject a part based on comparative calculations.

1.1.8: Engineering Analysis

An important, and recently acquired, capability is the automatic generation of meshes for finite element analysis (FEA) from the voxel data of CT scanners. Engineers from the Ford Motor Company have used CT scan data, in conjunction with commercially available software, to reduce the turnaround time in performing FEA on complex automotive structures by as much as 97% [53].

An interesting application, geared towards hand held digitizers, is accident reconstruction and analysis. Digitizing technologies have been used to measure crash vehicles and scenes for later reconstruction as CAD images and entities [31].

1.2: REVERSE ENGINEERING DIGITIZATION METHODS

Methods employed in digitizing physical parts can be classified as contact, non-contact, or a combination of the two. Inherently, non-contact methods are not destructive to the part, and generally provide much faster data collection rates. Due to this, a large number of non-contact techniques have evolved. Figure 1.2 shows a classification of the various methods.

1.2.1: Non-Contact Methods

The most accurate, and widespread, non-contact data collection methods are based on those of the radiography and optical categories. Optical methods are capable of high digitization rates and are cost effective in many applications. Computed
tomographic (CT) scanning tends to be a much higher cost solution, but is material independent, and can capture internal/occluded geometry and material flaws.

**Digitization Methods and Techniques**

- Non-Contact Methods
  - X-Ray
  - Optical
  - Computed Tomography
  - Triangulation
  - Interferometry
  - Structured Lighting
- Contact Methods
  - Acoustic Magnetic
  - Robot Manipulators
  - CMMs
- Combined Techniques
  - Milling and Scanning
  - Laser Trackers

*Figure 1.2:* Reverse engineering digitization methods (modified from [112]).

1.2.1.1: **Optical Methods**

1.2.1.1.1: **Active Triangulation**

Optical triangulation, incorporating laser beams, is the basis of operation of many reverse engineering data acquisition devices on the market today. In active triangulation by spot sensing, shown in Figure 1.3, a beam of light originating at A, is projected at a known angle (α) onto a part surface. The reflected beam is focused by a lens, of focal length f, and detected by a photosensitive device at point P. Knowing the center to center distance (d) between the beam projector and lens, the projection angle, the focal distance, and the beam detection point (δ), the range (R) can be calculated using Equation 1.1. To generate 3D range data, a rotating mirror is usually incorporated in the beam projection mechanism, and the scanner is moved by a suitable transport mechanism.

Stripe sensing, an extension of spot sensing, generally incorporates the use of a beam splitter to widen a single beam of laser light into a plane, as shown in Figure 1.4 (a). The instantaneous intersection of the plane of light with the object surface is detected as a curve of finite thickness, by a photosensitive device. This is shown in Figure 1.4 (b). The image is analyzed to determine the mid-profile of the curve, and triangulation is used to calculate the locations of sample locations along the mid-profile.
Figure 1.3: The active triangulation of a laser beam [50].

\[ R = \frac{D \sin(\alpha)}{\sin[180 - (\alpha + \theta)]} \]
\[ \theta = \tan^{-1}\left(\frac{f}{\delta}\right) \]  \hspace{1cm} (1.1)

Triangulation using laser beams can collect data at high rates (greater than 10000 points per second). The accuracy of the method is primarily based on the detector resolution and systems optics, the distance from the scanner to the surface, scanner axis alignment with the surface normal, and part surface conditions [96, 112, 121].

Figure 1.4: a) Stripe sensing triangulation of planar light [72].
b) Image capture and mid-profile sampling.
1.2.1.1.2: Time of Flight

Two approaches fall into this category. Laser radar uses a direct measurement of the time of flight of a light beam projected to, and returning from, an object [79]. This information, in conjunction with the speed of light in a given medium, is used to calculate the distance of flight. Interferometry, on the other hand, determines distance based on the phase difference between two interfering beams of light. A beam splitter is used to divide an emitted laser beam. One beam is routed directly to an interferometer, and the second is projected onto a part surface, as shown in Figure 1.5.

![Diagram of beam splitter and interferometry setup]

**Figure 1.5**: Distance measurement utilizing interferometry methods [43].

The projected beam returns, and enters the interferometer coaxial with the first. The resultant phase shift is directly proportional to the object distance, and is calculated using Equation 1.2.

\[ D = \frac{\theta \lambda}{360 \times 2} \]  

(1.2)

where: \( \theta \) is phase shift between projected and non-projected beams \( (0 < \theta < 360) \). \( \lambda \) is the wavelength light for the beams \( (2D < \lambda) \).

1.2.1.1.3: Patterned Structured Lighting

Part digitization using patterned structured lighting involves projecting a fringe (interference) pattern onto a part surface. The distortion of the fringe pattern is proportional to the distance to the object. The most widespread technique in use is the Moiré technique, in which the projected fringe pattern is composed of alternating light and dark bands. Images of the distorted pattern(s) are captured by a photosensitive
device, and analyzed using complicated algorithms [116]. The distance between the
distorted contours is proportional to the height of the scanner above the object, and
thus, part coordinates are determined. Digitization rates easily exceeding 50000 pts/s
are possible using this technique [40].

1.2.1.1.4: Photogrammetry

In photogrammetry, multiple images of an object are captured using 2 or more
vision cameras. The cameras are placed in accurately known, fixed positions and
landmarks are typically placed in the scene. The positions of the landmarks form the
basis for registering the data in a common coordinate system. The most difficult aspect
involves the mathematical complexity in accurately correlating the views [112].

1.2.1.2: Radiography

1.2.1.2.1: Computed Tomographic (CT) Scanning

Computed tomographic (CT) scanning, is a non-destructive means of digitizing
physical objects. Since CT scans are densiometrically accurate, complete dimensional,
morphological, and part characterization information can be obtained [36]. In this
approach, high energy collimated x-rays are projected through an object, and captured
by a radiation detector array. The object is scanned in “2D slices,” which are
sequentially stacked to generate a 3D density map of the part. Figures 1.6 (a) and (b)
give the general scanning setup and representative data slices respectively.

![Diagram](image)

**Figure 1.6:** a) Schematic of CT scanning configuration [35].
b) Representative CT scanning image slices.
Each slice is an image consisting of voxels with density values ranging from 0 to 255 [6, 53]. A density gradient threshold is applied, and the voxels representing different materials and spatial regions within the scanned slice are identified [53]. A 3D voxel map of the component is generated, and smoothed, to reduce noise. A point cloud representing the part boundaries and edges is then output.

The machine accuracy and resolution determines the overall digitization accuracy. The resolution is increased by decreasing the slice thickness, leading to an increase in the number of scanned slices, and overall scanning time. Further, the scanning time depends on the energy and intensity of the x-ray source, and the part size and composition [122].

1.2.1.3: Magnetic and Acoustic Methods

Magnetic and acoustic techniques have been developed, but these cannot generally compete with the accuracy and digitization rates of other non-contact methods. Acoustic methods use time of flight to triangulate probe position, and must be “acoustically visible” to sonic sensors at all measurement locations. Thus, noise and interference are problematic. Magnetic methods generally employ a stylus whose position is monitored within a magnetic field, or that interprets magnetic signals from transmitters. Such methods do not perform well when digitizing metal parts, and are affected by the presence of metal objects in the surroundings [106, 112].

1.2.2: Contact Methods

1.2.2.1: Coordinate Measuring Machines (CMM)

The major difficulty in digitizing part surfaces with a CMM is accurate probe tip compensation [25, 76]. In operation, the CMM tracks the position of the center of the probe tip, which has a finite radius. Upon contact with the part, as shown in Figure 1.7, the actual location of contact is displaced \( \mathbf{R} \) from the probe tip center. In calculating the part coordinate, the probe center location is offset by a distance \( \mathbf{R} \), in the direction opposite to the surface normal \( \mathbf{N} \). However, determining the direction of the surface normal at the contact point for a general measurement on unknown geometry is difficult. The uncertainty in estimating this vector leads to compensation error \( \mathbf{E} \),
which is a function of the angle (θ) between the approach/estimated vector (A) and the surface normal.

![Diagram of CMM probe tip compensation error](image)

**Figure 1.7:** CMM probe tip compensation error.

This problem is largely alleviated in inspection by using a CAD model of the part. However, a critical issue in the accuracy of inspection is the alignment of the physical part on the CMM, with the CAD coordinate system. This relies on imperfectly manufactured surfaces, and remains a difficult problem when dealing with complex surfaces [55].

### 1.2.2.2: Robot Manipulator Arms

Robot manipulator arms provide a solution for part digitization where portability is paramount. These are counterbalanced, temperature compensated devices incorporating precision bearings and optical encoders at each joint to constrain motion and provide probe location and trajectory information. Generally, custom or kinematic touch trigger probes comprise the end effector, but laser scanners or similar digitizers may also be incorporated [42].

### 1.2.3: Combined Techniques

Combined techniques incorporate both contact and non-contact methods into a single digitization process. The result is a combination of the advantages and disadvantages attributed to the individual methods.
1.2.3.1: Milling and Scanning

This process couples the cost effectiveness of optical scanning with the ability to digitize internal geometry. A part is encased in a hardenable material, which provides support and high contrast with the part material. The part is then machined in extremely thin layers. As each layer is machined, the surface is digitized. Each scan is processed, using advanced image processing techniques, to generate points at the part boundaries. Ultimately, a 3D data cloud results. The major drawback of the process is that it is destructive to the part [23].

1.2.3.2: Laser Trackers

Laser trackers use time of flight methods to measure the distance to a target, which is manually maneuvered in contact with the part surfaces. A beam projector, typically having two angular degrees of freedom in a spherical coordinate system, projects a laser beam to a retroreflective target at an orientation monitored by angular encoders. The beam reflected from the target re-enters the projector at the same position in which it left. Three dimensional part coordinates are calculated based on the orientation of the projector, and the determined flight distance of the beam. This digitization technique addresses the needs of very large parts, and provides digitizer portability [13, 65].

1.3: CMM PART DATA COLLECTION

Primitive geometry may be digitized using manual probing directly, or through the creation of approximate geometry by manual probing, and subsequent inspection. In this process, analytical models employing best fit algorithms to calculate feature parameters, are used to generate substitute geometry, and to handle tip compensation automatically [79].

For complex surfaces, a number of techniques have been developed, all of which involve some form of surface normal approximation at the measurement point. The simplest entails the uncompensated measurement of a surface using a small diameter probe, followed by the subsequent offset of a CAD created surface, by the probe tip radius. Alternatively, the uncompensated CAD surface may be used to generate inspection based probe paths. A variation on this theme is derived from the copy
milling process, which in the late 1980s and early 1990s was used in 80 to 90% of surface machining for tool and mold manufacture [119]. Here, the probe is dragged along the part surface while a controller samples its location at a given frequency. This is referred to as "scanning", and is the product of improved controller performance in recent times [102]. A further innovation is the development of analog scanning heads whereby the distance and deflection of the probe tip can be calculated [19].

For surfaces displaying low degrees of inflection and curvature variation, the global surface normal may be estimated by probing an approximate plane, or other applicable primitive. This information is then used to generate a new point set with improved compensation. Where the surface is more complex, the same principle may be applied on a local scale to generate small groups of compensated points [96]. This technique has been automated by Aoyama and Insaki [5].

As shown in Figure 1.8, a single point from a sculptured surface is digitized by probing 3 uncompensated points removed from a target point (P'). The location at P' is then calculated by offsetting for the magnitude of the dynamic tip radius (R), along the plane normal (N). An advantage to this approach is that it collects both point and surface normal information. This may be used to automatically segment the data, based on curvature variation, and directly generate mathematical surfaces.

**Figure 1.8:** Point and normal vector acquisition on free-form surfaces [5].
Several methods for the automatic digitization of planar curves on surfaces have also been developed. The most well implemented method is based on the linear prediction. This approach uses the normal to the line segment joining the two previously measured points to approximate the compensation vector for the next measurement point. The measurement location is estimated by linear extrapolation, and the probed point is compared to the linearly predicted point. If the error is greater than a given threshold, an intermediate point is introduced, and the process repeated.

Polynomial prediction and spline interpolation variants have also been discussed [25]. Polynomial prediction is similar to linear prediction, but uses a second-degree curve to follow the contours of a complex surface more closely. The premise of the spline interpolation method is somewhat different. It surmises that the error associated with interpolation is less than that of extrapolation. An initial set of 5 points is collected by linear prediction, and a cubic spline constructed, as shown in Figure 1.9.

A new set of sample points is calculated on the interpolated spline, and probing occurs along the normal to the curve tangent at these locations. These newly probed locations are used to update the spline model, and if the error threshold is surpassed at a given point, two new points, mid-way between the target point and each of the previous and following points, are probed. This process is repeated until all measurements are within the given tolerance. Reportedly, this technique yields greater accuracy from a fewer number of sample locations.

![Figure 1.9: Spline interpolation method of planar curve digitization [25.](image)](image)

1.4: SAMPLING OF PRIMITIVES

1.4.1: Measurement Error and Uncertainty in Coordinate Metrology

Measurement error is defined as the difference between the true and measured values. However, in CMM measurement, the true value is generally not known.
Performance evaluation procedures typically employ well-calibrated artifacts [4] whereby the object uncertainty is negligible. In practice, the measured value is taken as the true value, which has been accepted in production environments, where the gauge tolerance is stipulated to be an order of magnitude less than the part tolerance (dubbed the gauge-maker's rule). However, even well calibrated artifacts lead to different results for a given series of measurements.

Measurement uncertainty is the term used to describe the collection of all measurement errors. It reflects the unknown systematic and random measurement errors, and reproducibility. For the one-dimensional case, the relationship between measurement uncertainty, the measured value, and the true value is shown in Figure 1.10 (a). In coordinate metrology, the uncertainty region describes a volume about the measured point, as shown in Figure 1.10 (b). The size and shape of this region is generally anisotropic with respect to direction, and depends on the CMM error sources [89].

Characteristics of the uncertainty clouds change dynamically with time due to [89]:

- temperature variations;
- structural distortion of the CMM under loading; and
- machine damage and wear.

**Figure 1.10:** a) The relationship between measurement error and uncertainty. b) The 3-D uncertainty zone in CMM measurement [89].
Uncertainty also depends on measurement specific factors such as [89]:

- tip radius;
- stylus length;
- probe approach direction;
- probe approach distance;
- probe velocity; and
- probe contact force.

In 1988, the Government-Industry Data Exchange Program (GIDEP) sent out an alert to CMM manufacturers and industrial users. The accompanying report indicated that, on the basis of tests performed on CMMs from four different CMM manufacturers, algorithms were reporting larger than actual errors 37% of the time, and smaller than actual errors 50% of the time [49]. This translated directly to a large number of parts being incorrectly accepted or rejected by inspection processes. Subsequent research has determined that the results of fitting algorithms show a dependence on several factors [52, 114]. The relationship between these factors is summarized in Figure 1.11. Given that systematic and random errors will always exist, emphasis is placed on understanding the uncertainty propagation in substitute geometry generation due to sampling strategy, part form error, and algorithm issues.

![Diagram](image)

**Figure 1.11:** Factors affecting CMM based substitute geometry creation [89].

The generation of substitute geometry is an important factor for both inspection and reverse engineering. Since primitives generally represent functional design features, and are widely used in establishing datums, high accuracy in their digitization is desired. Although Figure 1.11 was constructed with CMM data collection in mind, it is quite relevant to other digitization methods. In fact, very few references to uncertainties and uncertainty trends associated with high speed digitizers are found in literature. For this reason, and in the development of compensation schema,
uncertainties involved in data collection with the Hymarc Hyscan 45C laser scanner, used in this study, are investigated in Chapter 6.

1.4.2: CMM Hardware Errors

1.4.2.1: CMM Geometric Errors

In the design of CMMs, the moving components are considered as rigid bodies with all but one degree of freedom eliminated. Motion errors of these elements, known as parametric errors, exist and may be generally classified as linear, rotational, or orthogonality errors. Since, it would be difficult, and expensive, to design and manufacture CMMs that provide micron measurement accuracy using purely mechanical means, error compensation techniques have been developed and implemented. These approaches use a mathematical model based on rigid body assumptions and first order approximations for thermal expansions to calculate theoretical positions. Laser interferometry measurements [17, 38] are then compared to the theoretical positions, and an error map generated. The error map is linearly interpolated in compensating actual measurement data [16, 127].

Another major class of CMM geometric error, of more recent concern, deals with dynamic affects. Such effects were found to play an increasing role in CMM systematic measurement error as machine operational speeds increase, in response to the demand for shorter measurement cycles. Work on assessing and compensating for CMM component deformation due to inertial forces has been performed by Weekers et. al [118]. In this work, sensors were attached to the CMM carriages and on-line measurements of the deformations during single-axis motion were taken. A kinematic model was generated, relating the measured deformations to the parametric errors. This model was then used as a compensation tool with reportedly good success.

1.4.2.2: CMM Probe Errors

Most CMMs are fitted with electromechanical probes, known as kinematic touch trigger probes. An example is shown in Figure 1.12. A small pre-travel of the probe tip is required to break the electrical contact at one of the three supporting seats, which signals the recording of a coordinate. The pre-travel reduces the effective magnitude of the compensation vector slightly. The new value is referred to as the dynamic tip
radius, as it has been shown to depend on the dynamics of the probe on contact. To determine this quantity, a highly accurate sphere of known diameter is placed in the measuring volume of the CMM. It is manually probed without compensation, and a least squares fit is applied to the data. The difference between the fit and known radii is the average dynamic tip radius.

![Figure 1.12: Schematic of a kinematic touch trigger probe [94].](image)

The displacement of the tip is resisted by a compression spring. The moment required to trigger the probe varies with direction, reaching a maximum at mid-angle between any two seats. This leads to pre-travel variation, also known as "probe lobing", which depends significantly on the stylus length and probe tip diameter [7]. Probe lobing can be a dominant source of systematic error in highly repeatable machines, leading to significant error [90]. It is estimated to account for as much as 60% of measurement errors, excluding machine geometric errors [18].

Several authors have identified, modeled, and proposed compensation schemes for dealing with probe lobing. Nawara and Kowalski generated an analytical model relating lobing error and measuring force, and used simulation to investigate its effect on measured profiles [78]. Pahk and Kim described the use of a computer in assessing 2D lobing error from ring gauges, with error compensation based on raw measurements [84]. Yang et al. modeled pre-travel variation using neural network approaches [124]. Mayer et al. used experimental error characterization to define a 3D empirical model for pre-travel behavior based on sliding contact between the probe and part [71]. Estler et
al. described a simplified mechanical model for the pre-travel variation of kinematic touch trigger probes, and provide considerable data on the lobing behavior of the Renishaw TP-2 probe [41].

In order to decrease inspection times, through the development of faster CMMs and measurement capability, Johnson et al. have identified the need for the characterization of dynamic probing errors. Their work examines the dynamic effect of a number of factors, such as measurement speed, stylus length, approach distance and angle, probe orientation, and pre-load spring force, on probe pre-travel [61].

A more frequent approach to reducing the measurement errors due to lobing, is the development of alternative probe construction technologies. Continuous scanning probes, which are servoed in constant contact over the part surface, eliminate most of the problems associated with probe lobing, and have tremendously higher data collection rates. However, precise control of the contact force, which is monitored by strain transducers, is required for accuracy [47].

The use of active piezoelectric (PZT) probes has also been discussed. PZT actuators provided higher stiffness, and potentially higher accuracy at faster measurement speeds. Bittle and Kurfess have developed a prototype PZT probe, and experimentally verified its performance [12]. Also, mechanical probing systems which better address the dynamics of probing have recently been developed [111].

1.4.3: Part Form Error

Manufacturing processes leave characteristic trace marks of varying frequency and amplitude on part surfaces. The high, medium, and low frequency components are generally referred to as surface roughness, waviness, and form error, respectively. These imperfections can have a pronounced effect on CMM measurements of size and in the fitting for substitute geometry, especially in the case of form error. Typical form error due to tooling marks in precision milling is approximately 10μm [22]. Work in determining the influence of surface roughness and probe ball radius on the accuracy of the actual size in mechanical probing has been reported by Anbari et al. [3]. In the case of manufacturing form error, considerably more work is needed. Published research deals mainly with form errors of cylindrical features from various
manufacturing operations \cite{62, 63, 83, 120}. This is not surprising since cylinders are the most common manufactured feature \cite{9}.

### 1.4.4: Sampling Strategies

The largest numbers of publications on this subject have dealt with sampling methods, and generally report on results using simulation. Sampling strategies applicable to primitives include uniform, random, randomized grid (stratified), and Hammersley.

#### 1.4.4.1: Lines and Planes

Uniform sampling of lines in the presence of simulated sinusoidal form and random errors has been studied. Results indicate that high point densities are required to achieve stable parameterization \cite{85}. The need for high data densities was also expressed in similar studies on planes using uniform and stratified sampling strategies \cite{69, 104}, and is well known in general \cite{126}.

#### 1.4.4.2: Circles

The most work in establishing reliable sampling patterns for geometric entities has been performed on circles. Odayappan used computer simulation to ascertain the effect of random, uniform, and stratified sampling strategies, as well as sampling density, on the radius value and center point location of lobed circles, indicative of modern manufacturing processes \cite{81}. The lobe frequency, amplitude, and random noise level was varied in the analysis. Uniform sampling was found to be the most appropriate for detecting form error, and stratified sampling was reported to give erratic results for low sample densities. This was experimentally verified by Wilson Jr \cite{120}.

Phillips et al. used experimental methods and a theoretical model to examine the effect of sampling strategy on the measurement uncertainty of circular geometry \cite{90}. The form error and algorithm dependencies were deemed irrelevant to the analysis due to the use of a precision ring gauge (0.2 \textmu m form error), and a 3 point sampling strategy. The start point and angular spacing of the measured points were varied independently over the ranges 0° to 360° and 1° to 120°, in 10° and 1° increments respectively. A steady reduction in the variation of the fit radius and center point was observed, as the
angular spacing of the measured points increased. This led to the conclusion that measurement uncertainty varies by four orders of magnitude as a function of the angular spacing of the points. Similar experimental work involving the least squares fitting of circles to larger data sets collected on ring gauges has also been recently carried out [24].

Other work in the sampling of circles and arcs has generated further insight. Wu suggested non-uniform sampling on arcs of less than 180°, with a greater number of points being taken near the two ends [123]. The efficiency of equidistant sampling is described, relative to optimal sampling on the same arcs, in Table 1.1. The notion of prime number sampling, and its ability to detect periodic manufacturing errors in circular features was also discussed [123]. It was advised that prime number sample sets of greater than 10 points will detect part form error, as in most cylinder manufacturing processes the dominant lobing is of low order (2 to 9 lobes) [120].

**Table 1.1: Efficiency of Uniform Versus Optimal Sampling on Circular Arcs**

<table>
<thead>
<tr>
<th>Angle</th>
<th>360°</th>
<th>270°</th>
<th>180°</th>
<th>90°</th>
<th>45°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>1.00</td>
<td>0.91</td>
<td>0.59</td>
<td>0.38</td>
<td>0.34</td>
</tr>
</tbody>
</table>

1.4.4.3: Cylinders

For cylinders, part form error in both the axial and radial directions affect the resultant substitute geometry. Babu et al., researchers from the same group as Odayappan, published results from a similar computer simulation study based on cylinders [9]. The number of points about the cylinder circumference, and number of sampled cross sections were varied, with 100 data sets being generated for each sampling pattern. The study concluded that, in the presence of random errors, the fit parameters converge to stable values only at large sampling densities. It was determined that uniform sampling of 17 to 19 points about the circumference was able to detect the radial form error for 2 to 9 lobed cylinder. Also, in the absence of any prior information about the feature, a good starting point is 17 points per section at 17 sections. Software, which takes user input specifying tolerances, an educated guess at the form error, and a CMM uncertainty estimate, is being developed to aid the operator in selecting an appropriate sampling method [8].
Zhang et al. have proposed the use of a back-propagation neural network approach in approximating the relationship between sample size, manufacturing process, tolerance specification, and substitute geometry confidence level for manufactured holes [128]. The work focused on the sampling of drilled, bored, reamed, and milled holes using data sets ranging in size from 4 to 50 points. The authors suggest this as an adaptive approach that may be applied to other primitives.

1.4.4.4: Spheres

Very little work has been discussed with regard to the sampling of spheres. Phillips et al. performed an investigation of the interaction of a variety of symmetrical form errors and sampling strategies on the resulting fit parameters of sphere generated using the Least Squares Method [88]. The study suggested that the choice of certain strategies may reduce the effects of form error on size and location variation.

1.4.5: Fitting Algorithms

It might seem reasonable to expect that fitting the same primitive to the same data set using various software packages would yield the same result, this is not always the case. One main reason is algorithm implementation. In order to reduce solution times, mathematical approximations are typically used. The degree of conformity of the approximate solution, to the mathematical one, depends on the nature of the approximations, and on the characteristics of the particular data set [89]. Algorithm implementation is also influenced by coding errors and the computer platform (e.g., internal precision). All of these effects lead to variations in the solutions obtained from software to software, as discussed by Wäldele et al. [114] and Hopp [54].

The second major reason for noticeable variations in substitute geometry is in algorithm selection. While the least squares algorithm is by far the most widely implemented, other algorithms, such as minimum zone, also exist. In least squares, the aim is to minimize the sum of the squares of the residuals to the fit geometry. In contrast, the minimum zone criterion minimizes the maximum residual. The difference in criteria yields slightly different results, which are again a function of the implementation [89].
Research in comparing orthogonal least squares and minimum zone methods for straightness and flatness tolerances has been performed by Dowling et al. [34], Wang [117], and by Murthy et al. [77], in work which also extends to circularity and sphericity. Gass et al. compare a linear programming approach for solving the algebraic minimum zone problem to the popular algebraic least-squares solution, suggesting that better performance is obtained [48].

1.5: REGISTRATION OF REVERSE ENGINEERING DATA SETS

For the majority of digitization technologies, obtaining a complete data set for a particular object requires several changes in the orientation of the object itself, or in the digitizing device. As such, the generation of a full object point cloud involves two stages: single view data set acquisition and multiple view registration, which by definition, is the process of transforming all single views into a common coordinate system.

1.5.1: Physically-Aided Multiple View Registration

In industrial environments, physically-aided data set registration is a common practice. In fact, many digitizing systems use some degree of physically-aided registration in their calibration procedures. While this may represent a final registration result, the accuracy is sometimes insufficient for various applications [46], at reasonable cost. Thus, software refinement, based on this coarse registration result, is often used.

Physically-aided registration usually takes one of two forms. The first is the use of a highly precise positioning and fixturing system that changes the relative position and orientation of the scanner and part, within known configurations. The most common example is a turntable, which is incorporated in several current commercial technologies, and has been discussed in literature by Bhanu [11].

The main alternative to positioning systems involves the use of high precision, primitives, visible to the scanner from all orientations, as the basis for establishing view transformations [95, 112]. These typically take the form of spheres, whereby three fit centers are sufficient to constrain all degrees of freedom. The obvious advantage of this approach, compared to precision positioning, is lower cost.
1.5.2: Software-Based Multiple View Registration

Several approaches have emerged for software-based multiple view registration. The main objectives are generally to improve the level of registration accuracy, and to automate the process.

One of the first and most popular techniques is the Iterative Closest Point (ICP) algorithm, developed by Besl and McKay [10]. As a starting point, the ICP algorithm requires a rough estimate of the overall registration transformation, generally provided by the digitizer calibration procedure. Then, under the current transformation, ICP compares a point in the base view to the closest point in the view to be transformed. It then calculates and applies an incremental transformation, which further aligns the two points. This process is repeated until the selected convergence criterion is met.

Two major drawbacks of the base algorithm exist. First, it will properly converge only if one of the data sets is a subset of the other. Moreover, it only addresses the problem of registering two views, not multiple views. Some authors have attempted to use the consecutive registration of view pairs in sequence to generate a multiple view registration [33, 91]. However, this approach is highly susceptible to error accumulation, leading to poor registration results between the first and last views.

Chen and Medioni [26] developed a method to incrementally register data from successive views into a combined data set, based on modifying the ICP algorithm to do point-to-estimated surface correlation. The method begins by selecting base view “control” point grids from smooth regions of overlap between two views. It then proceeds to determine the point, in the view to be transformed, that is closest to the estimated surface normal through each of the control points. This point is then projected onto the tangent plane at the control point, which yields the new position for the chosen point after incremental transformation.

Gagnon et al. [46] developed several improvements on the technique of Chen and Medioni. Further, similar techniques that generate estimated polygonal [15, 70, 110], or parametric surfaces [15, 92] have also been developed. It should be noted, however, that the accuracy of several such techniques depends highly on feature recognition abilities.
Eggert et al. have proposed an approach for the simultaneous registration of multiple range views without reliance on pairwise correlation [37]. The technique regards the data sets as connected by groups of springs, with individual view motions computed using force-based optimization methods.

1.6: GEOMETRIC MODELING

1.6.1: The Parametric Representation of CAD Entities

In CAD software, geometric entities are mathematically represented in the parametric space. This [73, 125]:

- allows the representation of closed, multivalued, and bounded geometry;
- avoids computational difficulties associated with curve and surface slopes that approach horizontal or vertical;
- enhances the ability to evaluate orderly sequences of points on a geometric entity;
- generally offers more degrees of freedom in controlling the shape of curves and surfaces; and
- accommodates the intrinsic independence that many engineering shapes exhibit with respect to specific coordinate systems.

In the parametric representation, the Cartesian x, y, and z coordinate components of locations on an entity are expressed in terms of one or more independent parameters \( \mathbf{p}(u) = [x(u), y(u), z(u)]^T \) for curves), as shown in Figure 1.13. The parameter values themselves indicate relative position on the entity. The parametric curves define the absolute, and unique, position of every point on the entity as a function of the parameter [58].

1.6.2: Parametric Representations of Curves

1.6.2.1: Parametric Cubic Polynomials

The most popular form of parametric curve representation is the cubic polynomial. It is the lowest order polynomial able to represent non-planar curves without unnecessary undulation, and in a computationally efficient manner. The cubic polynomial may be defined using the Lagrange interpolation of four points, as given by
Figure 1.13: Parametric representation of a general curve and surface in space.

Equation 1.3, or from two points and two endslopes. The latter formulation, known as the Hermite interpolation, has been widely adopted due to its close control of the curve slope, and its amenability as a basis for piecewise curves [73].

\[
p(u) = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} a_1 & b_1 & c_1 & d_1 \\ a_2 & b_2 & c_2 & d_2 \\ a_3 & b_3 & c_3 & d_3 \end{bmatrix} \begin{bmatrix} 1 \\ u \\ u^2 \\ u^3 \end{bmatrix} = \sum_{n=0}^{3} k_n u^n
\]  

(1.3)

where: \( k_n \) are the unknown coefficient vectors.

1.6.2.2: The Hermite Equation

Given the curve endpoints \( p_0 \) and \( p_1 \), and the end slopes \( p_0' \) and \( p_1' \) as boundary conditions, the general form for a Hermite cubic polynomial can be derived from Equation 1.3. This result is expressed equivalently by Equations 1.4 (a) and (b).

\[
p(u) = p_0(1 - 3u^2 + 2u^3) + p_1(3u^2 - 2u^3) + p_0'(u - 2u^2 + u^3) + p_1'(-u^2 + u^3) \quad (1.4a)
\]

\[
p(u) = \begin{bmatrix} 1 & u & u^2 & u^3 \end{bmatrix} \times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -3 & 3 & -2 & -1 \\ 2 & -2 & 1 & 1 \end{bmatrix} \times \begin{bmatrix} p_0 \\ p_1 \\ p_0' \\ p_1' \end{bmatrix} \quad (1.4b)
\]

The location of the curve for any value of the parameter \( u \) is defined by the sum of the four functions of \( u \) from Equation 1.4. These functions are referred to as
blending (or basis) functions, which, in conjunction with the boundary conditions, describe the shape of any Hermite cubic polynomial. Normally such blending functions are designed so that the sum of their relative contributions is unity [58].

![Hermite cubic blending functions](image)

**Figure 1.14:** Hermite cubic blending functions [73].

### 1.6.2.3: Bézier Curves

The difficulty in applying the Hermite formulation to real world engineering design is that the boundary conditions are not intuitive to the end user. Thus, Paul Bézier developed the concept of a control polygon to take the place of specifying the point and tangent boundary conditions. This provided an easier way to control the curve shape. The control polygon, as shown in Figure 1.15, is approximated by a curve of order equal to the number of control points.

![Cubic Bézier curve with control points labeled](image)

**Figure 1.15:** Cubic Bézier curve with control points labeled.
Figure 1.16: Bernstein blending functions.

Similar to Hermite curves, Bézier polynomials interpolate the first and last control points of the control polygon. In the case of a the cubic Bézier polynomial, the mid vertices are located 1/3 of the distance (1/degree) along the tangent vector at each of the curve ends. The general Bézier representation applies the polynomial approximation developed by Bernstein, and is provided in Equation 1.5. The blending functions for a cubic Bézier curve are shown in Figure 1.16.

\[ p(u) = \sum_{i=0}^{n} B_{i,n}(u)p_i \quad 0 \leq u \leq 1 \]  

\[ B_{i,n}(u) = \frac{n!}{i!(n-i)!} u^i (1-u)^{n-i} \]  

(1.5a)

(1.5b)

where: \( p_0, p_1, \ldots, p_n \) are the control points of the control polygon with \( n+1 \) vertices; 
\( n \) is the curve degree.

Since the blending functions sum to unity for all values of the parameter, the Bezier curve lies within the convex hull (polyhedral region enclosed by linearly
connecting the endpoints) of the control polygon. This results in mathematical simplicity and predictability. However, curve modifications have a global, although diminishing, effect and the high degree curves required to represent surfaces with multiple inflections lead to higher degree basis functions and increased processing times [58, 73].

1.6.2.4: B-Spline Curves

The limitations of global modifiability make Bézier curves unattractive for modeling complex shapes. The B-spline formulation was developed in order to increase efficiency in this venue. It is a generalization of Bézier whereby the B-spline curve is generated from blending functions which are themselves splines.

Splines are piecewise continuous parametric curves. Each separate segment is referred to as a span, and each span is joined at a particular value of the parameter, referred to as a parametric knot. The use of spline blending functions allows the construction of curves having larger numbers of control points, while maintaining independence in the curve degree. For B-splines, as with Bézier curves, a minimum number of control points is required to construct the curve, which is equal to the curve order (k). In this minimal case, the B-spline and Bézier representations are equivalent single span curves. For a given degree B-spline, with the addition of each new control point, a new span is generated.

The curve segmentation is governed by the knot vector, which is a non-decreasing, real numbered sequence that records the knot values. For B-splines, the parametric length of all spans is uniform. The knot vector is then formulated with k leading zeros, k trailing ones, and the uniformly spaced knot values between. For example, in the case of a cubic B-spline curve with 7 control points, the knot vector is formulated as: \( U = \{0, 0, 0, 0.25, 0.5, 0.75, 1, 1, 1, 1\} \).

The mathematical definition of the B-spline curve, and its recursive blending functions, is given in Equation 1.6 [73]. Figure 1.17 provides a plot of B-spline blending functions for various curve orders. For a valid B-spline representation, the relationship
between the number of control points, knots, and the curve order, is governed by Equation 1.7.

\[ p(u) = \sum_{i=0}^{n} N_{i,k}(u)p_i \]  

\[ N_{i,k}(u) = \frac{(u-U_{i+k})}{(U_i-U_{i+k})} N_{i-1,k-1}(u) + \frac{(U_{i+k}-u)}{(U_{i+k}-U_{i-k})} N_{i,k-1}(u) \]  

(1.6b)

where: \( 0/0 = 0 \), for the limiting condition of \( k = 1 \),

\[ N_{i,k}(u) = \begin{cases} 
1 & \text{if } U_i \leq u \leq U_{i+1} \\
0 & \text{otherwise}
\end{cases} \]  

(1.6c)

and, \( k \) is the curve order; \( U_i \) are the knot values; and \( p_i \) are the control points.

\[ \# \text{ Control Points} = \# \text{ Knots} + \text{Curve Order} \]  

(1.7)

**Figure 1.17:** Plot of cubic B-spline blending functions.
Since each span of the blending functions is defined by a number of control points equal to the curve order, when traversing from one span to the next, a new control point is introduced while another is no longer needed. Thus, when evaluating the curve, the blending functions are applied to the control points for each span, resulting in a locally modifiable curve with reduced mathematical complexity.

The level of continuity between the spans is equal to the curve degree minus one. For a cubic curve, this equates to curvature continuity between spans. An equivalent representation under the Bézier scheme would require the careful construction of several independent curves.

1.6.2.5: Non-Uniform Rational B-Splines (NURBS)

A rational curve is defined by the algebraic ratio of two polynomials [125], and is represented in the homogeneous space. A coordinate in Cartesian space maps to the homogeneous space as: \((x, y, z) \rightarrow (x', y', z', w)\), where \(w\) is a scaling factor. The NURBS curve, a generalization of the B-spline form, is a piecewise continuous, rational polynomial function of the form shown in Equation 1.8 [87].

\[
p(u) = \frac{\sum_{i=0}^{n} w_i N_{i,k}(u)p_i}{\sum_{i=0}^{n} w_i N_{i,k}(u)}
\]

(1.8)

where: \(w_i\) are the control point weighting factors; \(N_{i,k}(u)\) are the B-spline blending functions; and \(p_i\) are the control points.

The NURBS formulation has become popular due to its ability to represent both a wider range of arbitrary shapes, and mathematically exact primitives [115]. The use of a non-uniform knot vector allows freedom in span length, and the rational basis allows weighting of the influence of individual control points in generating the curve. Figure 1.18 illustrates the affect of weighting the contribution of the same set of control points differently.
Figure 1.18: The effect of changing control point weight on a B-spline curve.

The non-uniform knot vector provides tremendously more flexibility in representing local curve features, without the need to generate an unnecessary number of control points along the entire curve length. The rational nature allows NURBS curves to represent exact mathematical primitives. Other advantages include [87, 115]:

- representing analytical and free-from shapes in a unified form;
- evaluating curves relatively quickly, and with computational stability; and
- invariance under affine transformations.

1.6.2.6: Curve Continuity

The term continuity is used to describe the smoothness across the junction of two curve segments or surface patches, pieced together to form a more complex shape. Continuity has both a geometric and parametric interpretation. Geometric continuity is of most concern to a typical user, since parametric continuity is trivial to establish once geometric continuity exists [58].

In geometric terms, there are three types of continuity between entities. Figures 1.19 (a) to (c) illustrate these for the simplified case of 2D curves. As shown, positional continuity (G0) is satisfied when the two curve endpoints are coincident in space. In geometric tangent continuity (G1), the additional constraint of parallel tangent vectors at the curve endpoints must also be met. Mathematically, this requires that the tangent
vectors across the junction be represented by continuous functions. Curvature continuity (G2) is satisfied for the additional condition that the magnitudes of the radii of curvature at the two curve endpoints are equal, which requires a continuous second derivative function.

Figure 1.19: a) Positional continuity (G0). b) Tangent continuity (G1). c) Curvature continuity (G2) [125].

1.6.3: Parametric Representations of Surfaces

The most common surfacing techniques in CAD are biparametric extensions of many of the polynomial curve approaches described in the preceding sections \( \mathbf{p}(u,v) = [x, y, z]^T = [x(u,v), y(u,v), z(u,v)]^T \). Thus, surface representations share the same strengths and weaknesses that are associated with their counterpart curves. Fundamentally, these surfaces are composed of patches, which are analogous to spans in piecewise continuous parametric curves. Holding one of the two parameters constant defines an isoparametric curve in terms of the other variable. Patches may then be viewed as an intersecting mesh of isoparametric curves.

1.6.3.1: The Bicubic Patch

The mathematical definition of the bicubic patch is provided by Equation 1.9 [73].
\[ p(u, v) = \sum_{i=0}^{3} \sum_{j=0}^{3} k_{ij} u^i v^j \] (1.9)

The surface may be constructed through the Lagrange interpolation of 16 points, or by using Hermite interpolation, in a fashion similar to that of Section 1.6.2.2. In the latter case, however, the use of 4 corner points and 8 accompanying tangent vectors are not sufficient to fully define the surface. The 4 additional constraints which are required, are generally derived from the cross derivative, or twist, vectors at each corner point \( \partial^2 p / \partial u \partial v \). However, this method tends to be even less intuitive to the user than in the case of Hermite curve tangent definition.

### 1.6.3.2: Bézier Surfaces

The Bézier surface, formulated using Equation 1.10, is generated through the blending of a control polyhedron, in a process similar to that for Bézier curves [73]. Figure 1.20 illustrates a Bézier surface and control polyhedron.

\[ p(u, v) = \sum_{i=0}^{m} \sum_{j=0}^{n} B_{i,m}(u) B_{j,n}(v) p_{ij} \quad u, v \in [0,1] \] (1.10)

where: \( p_{ij} \) are the control polyhedron vertices; and 
\( m \) & \( n \) are the curve degrees in the \( u \) & \( v \) directions respectively.

**Figure 1.20:** Bi-cubic Bézier surface with defining control polygon.
Bézier surfaces share characteristics similar to those of Bézier curves, namely:

- interpolation of the 4 control polyhedron corner points;
- convex hull and variation diminishing properties; and
- edge curves tangential to the edges of the control polyhedron.

1.6.3.3: B-spline and NURBS Surfaces

The straightforward extension of B-spline and NURBS curves to surfaces yields Equations 1.11 and 1.12 respectively [87].

\[
\mathbf{p}(u,v) = \sum_{i=0}^{m} \sum_{j=0}^{n} N_{i,k}(u)N_{j,l}(v) \mathbf{p}_j
\]

(1.11)

\[
\mathbf{p}(u,v) = \frac{\sum_{i=0}^{m} \sum_{j=0}^{n} N_{i,k}(u)N_{j,l}(v)w_j \mathbf{p}_j}{\sum_{i=0}^{m} \sum_{j=0}^{n} N_{i,k}(u)N_{j,l}(v)w_j}
\]

(1.12)

where: \( m \) & \( n \) are the curve degrees in the \( u \) & \( v \) directions respectively;
\( k \) & \( l \) are the curve orders in the \( u \) & \( v \) directions respectively;
\( w_j \) are the control point weights; and
\( \mathbf{p}_j \) are the control points.

These formulations, as with curves, allow local control over the surface shape, and exhibit a strong convex hull property, with variation diminishing influence in the control points defining each patch. The distinct advantages of the NURBS surface parallel those of its curve counterpart, namely non-uniformity in parametric patch size, and the ability to use varying control point weights.

1.7: RESEARCH OBJECTIVES

In this chapter, several topics relevant to reverse engineering were reviewed. These include general reverse engineering applications, various digitization methods, uncertainties involved in substitute geometry generation from CMM data, techniques for the CMM digitization of free-form surfaces, and the multiple view registration of reverse engineering data sets.
Each of the digitization methods described in Section 1.2, has several advantages and limitations, with no single method being applicable in all situations. However, combining methods of data collection in certain cases, has the potential to reap significant benefits in process time and data set characteristics. Despite this, very few publications have dealt with the issue. In this work, the merits and concerns with accurately combining CMM and laser scanning data collection are explored, with the goal of defining a reverse engineering system that addresses a wider range of applications than the two techniques alone.

At the core of any system that combines CMM and laser scanning data collection, must be an accurate registration of both types of data into a common coordinate system, a process that will rely on the use of geometric primitives as datum artifacts. This, along with the fact that primitives typically represent critical functional design features, makes the uncertainty in representing such artifacts from both CMM and laser scan data a primary consideration. In the CMM case, the 1988 GIDEP alert initiated considerable research into the generation of substitute geometry from CMM data. However, few guidelines for reducing the uncertainty associated with substitute geometry generation have resulted to date, for a given algorithm implementation and general form error. As far as high speed digitizers go, most research work related to registration has focused on software-based approaches, as discussed in Section 1.5.2. This leads to several concerns, which include the:

- limited ability to combine sparse and dense data (eg. CMM with laser scan data);
- reliance on the overlap between views, which may occur where digitization error is high (eg. at fillets);
- overall accuracy obtainable; and
- additional cost of registration algorithms/software.

For these reasons, and since software-based registration methods typically rely on artifact-based methods for a starting estimate of the registration transformation, it is advantageous to reduce artifact-based registration error in support of a system that combines both CMM and laser scanning data.
With the above considerations in mind, several objectives have been defined for the work of Chapters 3 through 8. These are:

1. To compare the strengths and weaknesses in generating reverse engineered CAD models using CMM and laser scanning digitization, in tandem with the abilities of several CAD software packages to support the reverse engineering process;

2. To identify and characterize the major uncertainties, most relevant to reverse engineering, associated with CMM and laser scanning data collection;

3. To develop techniques, guidelines, and compensation schema for reducing the effects of these major uncertainties in generating data sets comprised of multiple laser scanned views, or a combination of laser scanned and CMM data; and

4. To create the conceptual framework for an integrated reverse engineering system, which makes use of existing and newly developed techniques, in generating combined data sets that exploit the advantages of both CMM and laser scanning data collection.
CHAPTER 2 - EXPERIMENTAL EQUIPMENT

2.0: INTRODUCTION

A wide range of experimental equipment was employed in the work of Chapters 3 through 8. All major software and hardware resources involved are described here.

2.1: HARDWARE

2.1.1: DEA Mistral Coordinate Measuring Machine

All digitization data was collected using the DEA (Digital Electronics Automation Inc.) Mistral, a Cartesian bridge configuration, computer numerically controlled (CNC) CMM. The DEA Mistral is shown in Figure 2.1. For mechanical probing, a Renishaw PH9/TP2 probe arrangement was used.

![Figure 2.1: Renishaw PH9 probe, DEA Mistral CMM, & Hymarc Hyscan 45C scanner.](image)

The CMM software interface is Tutor for Windows™ ver 2.02, running on a 486 DX2/66 PC under Windows 3.11. All DEA Part Programming Language (DEAPPL) programs, as provided in Appendix D, were compiled using the Tutor for Windows (TWF) Compiler Environment version 1.0. DMIS programs, as discussed in Section
2.2.5, were translated using the DMSDOSTUT-94304x release DMIS Translator, and subsequently compiled.

2.1.2: Hymarc Hyscan 45C Laser Scanner

The Hymarc Hyscan 45C laser scanner computes 3D coordinates on the surface of an object through the active triangulation of a 25 μm diameter infrared beam. The beam projection onto the object surface, and detection on a linear CCD array, are synchronized as it simultaneously reflects from the front and back of an oscillating mirror. Figure 2.2 shows the general configuration of the laser scanner. From the position of the beam on the CCD array, and the angular orientation of the scanning mirror, the coordinates of a point on the object surface are determined.

![Diagram of Hymarc Hyscan 45C Laser Scanner](image)

**Figure 2.2:** Active triangulation using synchronized scanning [56].

This scanning configuration is referred to as auto-synchronous. In contrast to conventional triangulation, as discussed in Section 1.2.1.1.1, synchronous triangulation uses an additional rotational axis (oscillating mirror) to significantly reduce the size of the capture plane (CCD array), shown as the difference between positions P and P' in Figure 2.3. The Hymarc configuration is deemed auto-synchronous since it uses both sides of the added oscillating mirror to simultaneously direct the projection and return of the laser beam.
Figure 2.3: Synchronous scanning geometry.

The relationships describing the position of the synchronized spot (P') on the data capture plane are provided below [68]:

\[ u = d \times P \sqrt{P - \frac{fh(d - 2h \tan \theta)}{(1 - f)(d \tan \theta + 2h)}} \]  
\[ v = -d \sqrt{\frac{P(h - f)}{fh} - \frac{d - 2h \tan \theta}{d \tan \theta + 2h}} \]  
\[ P = P' - \frac{fh \tan \theta}{h - f} \sqrt{\frac{P'(h - f) \tan \theta}{fh}} \]

As the mirror rotates, the beam sweeps back and forth, within the scan plane, on the surface of the object. Data is collected in scan lines, with each point being recorded at the instantaneous intersection of the scan plane and object surface. The scanner only acquires data within its field of view (FOV), located at the stand-off distance from the end of the scanner (see Figure 2.4 (a)).

The Hymarc 45C scanner is mounted as a retrofit on the CMM. The manual trunnion (mounting fixture) allows the acquisition of data from views at 15° increments within the scan plane, as shown in Figure 2.4 (b). The scanner may also be rotated in 90° increments, about the axis of the mounting arm.
Points must be transformed from the 2D scanner space \((u-v)\) in order to generate 3D coordinates \((x-y-z)\). This requires knowledge of the:

- instantaneous position of the machine axes;
- scanner orientation with respect to the machine arm; and
- relationship between CMM and scanner coordinates [56].

**Figure 2.4:** a) The Hymarc Hyscan 45C laser scanner operating configuration. 
   b) Rotation of the manual trunnion [56].

The instantaneous position of the machine axes is provided through continuous interpretation of the CMM axis encoder signals. The orientation of the scanner axis \((v)\) of Figure 2.4 (b) is estimated by the relevant component of the angle between the CMM arm, and the normal to a plane fitted from scan data collected on a calibrated plane. It is assumed that the fixturing ensures orthogonality with respect to the two other machine axes.

Since several viewing angles are generally required to digitize a part, a common datum for each view is needed to establish a 3D coordinate transformation from the scanner space to the CMM space. The fit center to a large alignment sphere serves this purpose, and each view is “aligned” in this manner. The complete transformation for the registration of the individual views is then defined.
The user interface for the scanner runs on an SGI Indy (IRIX 5.3 O/S), and is composed of the Hyscan Console Interface v1.56s and the Hyscan Viewer version 1.0.

2.2: SOFTWARE

2.2.1: SDRC I-DEAS Master Series™ [101]

SDRC (Structural Dynamics Research Corporation) I-DEAS (Integrated Design Engineering Analysis Software) Master Series™ 6 is a high-end, integrated package of mechanical engineering software tools designed to support a concurrent engineering methodology. Such tools include, but are not restricted to, solid modeling, drafting and detailing, kinematic and dynamic mechanism analysis, finite element modeling (FEM), tolerance analysis, and CNC toolpath generation. During this work, application of the software was primarily limited to the construction of solid models from CMM and laser scanned data, as discussed in Chapter 3.

![Image](image.jpg)

**Figure 2.5:** SDRC I-DEAS Master Series™ displaying a solid model of a hip prosthesis.

2.2.2: Imageware Surfacer [59]

Imageware Surfacer 8 is a reverse engineering software package designed specifically for efficient CAD surface model construction, and the handling of large data sets. A wide range of tools for point cloud editing, filtering and manipulation, curve and
surface construction, curve and surface quality diagnosis, and data set registration are provided. Surfacer meets the requirements of a capable reverse engineering software as set forth in Section 3.7. Moreover, it was used to construct the bulk of the CAD models in this work, as well as to facilitate data analysis.

![Image of Surfacer software displaying a surface model of an automotive piston.](image_url)

**Figure 2.6:** The Imageware Surfacer software displaying a surface model of an automotive piston.

### 2.2.3: CADKEY® [20]

CADKEY® 7 is a CAD wireframe modeling software, with limited to no surface and solid model construction abilities. As such, models constructed using the software have limits in their downstream applicability. However, while the software lacks much of the high end modeling functionality of a package like SDRC I-DEAS Master Series™, its extremely low cost makes it a viable, and popular, option when dealing with parts having low to moderate design feature complexity.

### 2.2.4: DEA Surfer™ [29]

The Surfer™ system is an on-line inspection and reverse engineering software package, developed by Digital Electronics Automation Incorporated (DEA). During reverse engineering, Surfer™ guides the CMM in measuring points on a part surface. From these, the software generates Beziér surface patches.
Initially, the part surface is divided into four sided patches, as shown in Figure 2.7. This maps out a network of patch boundaries for manual probing. The goal in constructing this network, is to minimize the curvature variation within each patch. Since Bezier surfaces cannot be locally modified, regions of high curvature or form variation require the use of several small patches to maintain accuracy [44].

![Automotive BIW bracket displaying network of patch boundaries.](image)

**Figure 2.7:** Automotive BIW bracket displaying network of patch boundaries.

The network of patch boundaries is subdivided, and then manually probed. The system uses this information to automatically probe the patch boundaries, producing curves of user specified degree. From these curves, surface patches are manually created. Surfer™ then automatically probes these patches, and builds "minimum energy" surfaces through approximation. Once complete, the accuracy may be verified by inspection, which returns measurement deviations based on a 100 point isoparametric grid of target points.

Properly constructed patches can display average errors close to the systematic measurement level of the machine, depending on the condition of the part surfaces. The complete CAD model is typically comprised of many discontinuous surfaces. This does not present a great difficulty for some applications, particularly in machining where gaps are considerably less than the tool radius. In general, however, significant rework may be necessary to establish improved continuity between surfaces.

The DEA Surfer™ System version 7.2 is running on a VAX 4000-60MHz machine, under DEC Windows Motif version 1.2 for OpenVMS. Communication with the CMM is facilitated by a serial link to the Tutor for Windows™ PC, and the Tutor-Surfer version 1.2 communications software. Kermit Terminal is used to transfer files.
2.2.5: Origin Checkmate [82]

Origin Checkmate is a graphical, offline inspection programming and simulation software package. The software, depicted in Figure 2.8, was used to generate CMM probe paths for studies involving the inspection of normal approximating surfaces created from uncompensated CMM, or laser scanned data, as discussed in Chapter 4. The probe path information was conveyed to the CMM using DMIS (Dimensional Measuring Interface Standard), which is the standard for bi-directional communication of inspection data between inspection systems [21].

![Image of Origin Checkmate software](image)

**Figure 2.8:** The Origin Checkmate software used to generate CMM probe paths.

2.3: DISCUSSION

While the choice of data collection hardware was based entirely on availability, software resources were selected to fulfill specific needs. Imageware Surfacer 8 was selected as the main off-line surface modeling and data analysis software due to its wide range of tools, open architecture, and reputation as the most accurate on the market. To assess the capabilities and limitations of CAD software packages in the construction of reverse engineered surface models, CADkey® 7 and SDRC I-DEAS Master Series™ 5 were also chosen. Together, these three packages represent a wide range of cost,
function, and CAD modeling methodology, specifically wireframe, solid, and surface modeling.

The precision of DEA Surfer™, in the on-line construction and verification of reverse engineered surfaces, was instrumental in comparing the digitization accuracy of various CMM and laser scanning techniques. Origin Checkmate was used to efficiently generate CMM probe paths in digitizing free-form surfaces, particularly in Section 4.2.
CHAPTER 3 - REVERSE ENGINEERING CAD MODEL CONSTRUCTION

3.0: OBJECTIVES

The climax of a reverse engineering project is the generation of a CAD model that meets the needs of the intended downstream process. Such applications may include computer numerical control (CNC) machining, rapid prototyping, computer-aided engineering (CAE) analysis and optimization, and many others. As a result, the characteristics of the CAD model, namely shape, surface quality, continuity, accuracy, construction time, and so on, vary with the downstream process in addition to design intent. CNC machining applications, for instance, are often capable of handling position discontinuous surface models where the magnitudes of the discontinuities, are sufficiently small in comparison to the tool radius. By contrast, the aesthetic and aerodynamic requirements of high quality exterior automotive surfaces place more emphasis on the continuity between surface patches, and less on accuracy (typically \pm 0.5mm to the scan data). Table 3.1 provides an overview of some typical downstream process requirements.

With this in mind, the following goals have been identified for this chapter:

- discuss the relationship between scan data characteristics and surface model attributes and construction techniques;
- illustrate the reverse engineering methodology for parts of varied design function;
- compare the advantages and disadvantages of CMM and laser scanning data collection in the reverse engineering process;
- discuss the functionality required of software tools in working with dense scan data, and briefly describe a number of packages available commercially;
- compare a number of commercially available digitization technologies.

3.1: REVERSE ENGINEERING CURVE CONSTRUCTION TECHNIQUES

In classical CAD design applications, interpolation dominates curve and surface construction methods. However, in reverse engineering, curve construction by approximation plays a much larger role, due primarily to uncertainty levels in the measured data, and to the large number of control points required in interpolating dense data sets.
<table>
<thead>
<tr>
<th>Downstream Process</th>
<th>Continuity Requirements</th>
<th>Other Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Modeling</td>
<td>• Totally closed, watertight volume required.</td>
<td>• Design intent may have large effect on req'd continuity (eg. aerodynamics).</td>
</tr>
<tr>
<td></td>
<td>• Position continuity may be as tight as ±12.7μm.</td>
<td>• Use of trimmed surfaces may have restrictions.</td>
</tr>
<tr>
<td></td>
<td>• High degrees of tangent or curvature continuity may be req'd for appearance or</td>
<td></td>
</tr>
<tr>
<td></td>
<td>performance.</td>
<td></td>
</tr>
<tr>
<td>Computer-Aided Machining</td>
<td>• Modern CAM software can handle small position discontinuities (much less than tool</td>
<td>• Concerns include gouging and smooth gap traversal.</td>
</tr>
<tr>
<td>(CAM)</td>
<td>radius up to ~0.127mm).</td>
<td>• Low # of control points leads to more efficient machining.</td>
</tr>
<tr>
<td></td>
<td>• Typical tangent continuity req'd is ±0.5°.</td>
<td>• Some CAM systems may not accept trimmed surfaces.</td>
</tr>
<tr>
<td>Rapid Prototyping</td>
<td>• Watertight, closed model req'd for production of STL file from solid model.</td>
<td>• May produce STL file from polygonal model of scan data if solid model not req'd.</td>
</tr>
<tr>
<td>Finite Element Analysis</td>
<td>• Model should be position continuous to ~0.05mm.</td>
<td>• May produce FE mesh from polygonal model of scan data if solid model not req'd.</td>
</tr>
<tr>
<td>Packaging, Concept</td>
<td>• Watertight, closed model may be req'd with less stringent tangent or curvature</td>
<td>• May use or convert to polygonal representation to increase data handling speed</td>
</tr>
<tr>
<td>Visualization</td>
<td>tolerances.</td>
<td>within software.</td>
</tr>
<tr>
<td>Animation</td>
<td>• Mathematical continuity is not req'd, only &quot;visually&quot; continuous.</td>
<td>• Most software packages only support four sided patches, and most do not allow</td>
</tr>
<tr>
<td></td>
<td></td>
<td>trimmed surfaces.</td>
</tr>
</tbody>
</table>

An alternative approach is tolerance based fitting, which uses the full flexibility of NURBS curves in optimizing the number and placements of knots and control points in defining the smoothest curve that lies within an accuracy tolerance band.
Several advantages, disadvantages, and characteristics of the three techniques are summarized in Table 3.2.

**Table 3.2: Characteristics and Reverse Engineering Curve Construction Techniques**

<table>
<thead>
<tr>
<th>Curve Construction Technique</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Parameterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpolation</td>
<td>• Curve passes through all data points (zero error).</td>
<td>• High number of control points (mathematical complexity).</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Poor smoothness, high degree of inflection.</td>
<td>• Non-uniform.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Number of control points equals the number of data points.</td>
</tr>
<tr>
<td>Approximation</td>
<td>• Control tradeoff of smoothness for accuracy.</td>
<td>• Less accurate than interpolation, error directly varies with the number of control points.</td>
<td>• Typically is uniform.</td>
</tr>
<tr>
<td></td>
<td>• Significantly fewer control points.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tolerance-Based Fitting</td>
<td>• Relatively low error.</td>
<td>• Result depends on optimization algorithm performance (very little control by user except to set tolerance band).</td>
<td>• Non-uniform.</td>
</tr>
<tr>
<td></td>
<td>• Optimizes tradeoff between accuracy and smoothness automatically.</td>
<td></td>
<td>• Optimal number of knots and control points.</td>
</tr>
</tbody>
</table>

**3.2: REVERSE ENGINEERING SURFACE CONSTRUCTION TECHNIQUES**

In cases where surfaces are generated directly from scan data, approximation is nearly always used. However, it is considerably more common for surfaces to interpolate a well-formed network of curves. In some cases, a hybrid approach is taken, whereby boundary curves are interpolated, and a tolerance is set for the deviation between the included data and the constructed surface. This section describes the most common surface construction techniques in use today.

**3.2.1: Free-Form Fitting**

As with curves, this technique typically generates a uniformly parameterized surface with a specified number of control points. Accuracy can be improved by increasing the number of control points.
3.2.2: Fitting of Geometric Primitives

Where applicable, least squares fitting is the most popular technique used to generate geometric primitives from scan data. Stepped linear optimization techniques are currently the most common, due to the added time and computational intensity of non-linear optimization. The rational nature of NURBs allows a common mathematical representation with free-form parametric surfaces.

3.2.3: Lofted Surfaces

Lofting, depicted in Figure 3.1 (a), interpolates a surface from a set of parallel, or nearly parallel, curves that define the surface topology normal to the flow direction. As is the case for all surfacing operations, the curves must be non-self intersecting, and may form an open or closed path. For a 3rd degree NURBs surface, the number of control points in the u-direction is equal to that of the curve with the largest number of control points, deemed the “heaviest curve.” In the v-direction, the number of surface control points is equal to the number of curves plus two. Generally, continuity at the beginning and end curves can be specified. In some implementations, continuity can also be specified at the boundaries parallel with the flow direction, which are formed by interpolation through the curve endpoints.

3.2.4: Boundary Curve Blended Surfaces

In cases where four curves define a closed loop, as shown in Figure 3.1 (b), curve blending can be used to interpolate a surface that is bounded by these curves. The surface degree and control points in the u- and v-directions are controlled by the heaviest curve of the pair in the given direction. Continuity can generally be specified at each boundary.

3.2.5: Boundary Curve Blending with Points

While this technique is functionally similar to boundary curve blending, it automatically generates an approximated surface that interpolates, and is trimmed at, the bounding curves. The data points must lie within the closed loop of the curves in the fitting direction. This technique may also be applied using a deviation tolerance, and with specified continuity at the edges.
3.2.6: Curve Network Blended Surfaces

This technique generates a surface completely defined by a set of \( u \) and \( v \) curves, as shown in Figure 3.1 (c), and is similar to lofting in two parametric directions simultaneously. The degree of the surface in each parametric direction is determined from the highest degree curve in the respective direction. The number of control points is defined from the heaviest curves in either direction. Continuity may be specified at the surface boundaries.
3.2.7: Sweep Surfaces

In sweeping, a surface is typically generated by interpolating a curve, which defines the surface topology, swept along a coincident path curve, as illustrated in Figure 3.1 (d). The surface degree and number of control points in the parametric directions are defined by those of the swept and path curves. In the particular case of a linear path curve, the term extrusion is often applied.

Some implementations of sweeping allow rail curves to be incorporated, which define the surface boundaries along the parametric direction associated with the path curve. The swept curve is held coincident with the rail curves as part of a variational constraint network that defines its shape. As the curve is swept along the rails, its shape varies in accordance with the solution of the constraint network at a given location. This technique is commonly referred to as a variational sweep, and finds only minor use in reverse engineering since it is difficult to extrapolate enough information from scan data to generate a reliable rail, sweeping curve, and constraint network.

3.2.8: Surfaces of Revolution

A surface of revolution is generated by the rotation of a non-self intersecting curve about an axis. The parametric u-direction runs along the axis of revolution, while the v-direction encircles it. The parameter v is defined by the angle of rotation, falling between 0 and 2π. The resulting surface is typically 2nd degree in u, and of degree equal to the revolved curve in v.

3.3: ACCURACY/SMOOTHNESS TRADEOFF IN SURFACE CONSTRUCTION

Data generated by all digitization devices has associated uncertainty levels, comprised of random, environmental, and systematic components. The level and distribution of these uncertainties has a direct effect on the characteristics of resultant CAD surfaces, which takes the form of an accuracy/smoothness tradeoff. This impacts the techniques employed in surface creation, and must be balanced against design and downstream requirements. Essentially, this amounts to establishing a satisfactory position between interpolated surfaces of high inflection, and smoothly approximated surfaces having greater deviation from the scan data.
A study relating curve accuracy and smoothness to number of control points, was conducted using the algorithms included in the Imageware Surfacer 8.0 software. All functions were employed using default settings. The primary goals of the study were to explore the accuracy/smoothness tradeoff characteristics, and to evaluate any performance gains offered by the tolerance-based fitting technique. The relationship between the number of control points, accuracy, and the number of curve inflection points, a harsh indicator of smoothness, is described by the plots of Figures 3.2 through 3.4.

**Figure 3.2: Simple Curve Accuracy vs. Smoothness**

<table>
<thead>
<tr>
<th>Number of Control Points</th>
<th>Approx Error</th>
<th>Tol-Based Error</th>
<th>Approx IPs</th>
<th>Tol-Based IPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>14</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>18</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>22</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Data Set #1
The plots substantiate that the accuracy of the curve in representing the data, and the number of inflection points, increases with the number of control points. In the case of tolerance-based fitting, the only noticeable performance gain exists for the complex curve of Figure 3.4, in the region between 14 and 24 control points. Here, the non-uniform span length generates a curve better suited to following the areas of high
local curvature. Overall, however, the performance advantage is observed to be minimal.

A starting point in optimizing the accuracy/smoothness tradeoff for a particular application may begin by estimating the number of inflection points on the design curve. After determining this, the curve having the greatest number of control points with the same, or closely similar, number of inflection points is generated. The number of control points is then reduced until the maximum acceptable error in representing the scan data is reached.

The general results of this study may be extended to surfaces. However, it may require considerably more effort to establish the simultaneous maximum number of control points in both parametric directions, and/or the design surface inflection characteristics. In this case, a good approximation of the minimum pragmatic deviation between scan data and reverse engineered surfaces can be obtained by fitting to data collected on a well formed planar surface of the part, or similar artifact. The deviation levels resulting between the fitted plane and scan data mark the practical accuracy limits, in light of the uncertainty of the digitization device. Figure 3.5 illustrates this for the Hymarc Hyscan 45C laser scanner, using scan data acquired on the well-calibrated alignment plate.

![Image](image_url)

**Figure 3.5:** Typical deviations of alignment plate scan data to least squares plane.
3.4: REVERSE ENGINEERING CASE STUDIES

The aim of this section is to identify, qualitatively, major advantages, disadvantages, and considerations in generating reverse engineered CAD models from CMM and laser scanned data, using CAD software packages having varied capabilities. The issues encountered in the following case studies, which involve an injection molded part, hip prosthesis, piston, and automotive fender, form the basis for the quantitative work contained in Chapters 4 through 8.

3.4.1: Case Study #1 - The Injection Molded Automotive Part [96]

3.4.1.1: Purpose

To compare the process advantages and disadvantages of constructing a reverse engineering CAD model of a primarily prismatic part, from CMM and laser scan data, using the CADkey 7 and SDRC I-DEAS Master Series 5 software packages. 

Figure 3.6: Injection molded automotive part.

3.4.1.2: Data Collection

The part was fastened squarely on the CMM, which aligned many of its surfaces with the principal planes of the machine coordinate system. For CMM data collection, it was necessary to formulate a measurement strategy that would support the construction of wireframe geometry, by defining the intersection and edge lines of the part. Once this was complete, target measurement positions were marked on the relevant surfaces. These locations were then probed, while compensating along the major axis of approach. The data cloud generated is shown in Figure 3.7 (a).

The collection of laser-scanned data, on the other hand, was a much quicker process, requiring very little in the way of pre-planning. Since the part surfaces were black, however, it was necessary to coat the part for reliable data capture, which adds to the overall error in representing the part. Figure 3.7 (b) shows the resulting laser scan data cloud.
Figure 3.7: Data clouds used in reverse engineering the automotive part.
a) CMM data points; and b) laser scanned data cloud.

3.4.1.3: CAD Model Construction and Software Comparison

An attempt was made to construct CAD models from both types of data, using CADkey 7 and SDRC I-DEAS Master Series 5. The major issues involved are summarized in Table 3.3, while Figure 3.8 (a) depicts the wireframe modeling process from CMM data, and Figure 3.8 (b) shows the wireframe model created from laser scan data. The role of CADkey 7 in reverse engineering is considered to be limited to simple, primarily prismatic parts due to the limited CAD entity construction tools, awkward viewing capabilities, and downstream process requirements.

In Figure 3.8 (c) the wireframe models generated using the CMM data and CADkey, and the laser scanned data and SDRC I-DEAS, are overlaid. The major discrepancies between the models are found in areas where the angle between the part surface normal and probe approach direction is high, most notably the bottom center and bottom right areas of Figure 3.8 (c). A further contributor was the sparse nature of the CMM data, which limits shape control over free-form entities. Evidence of this can be found in the bottom right corner of Figure 3.8 (c).
### Table 3.3: CAD Model Construction Issues for Injection Molded Automotive Part

<table>
<thead>
<tr>
<th>CADkey 7</th>
<th>CMM Digitization</th>
<th>Laser Scanning Digitization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Satisfactory wireframe model.</td>
<td>• Software incapable of handling large data set generated by laser scanning.</td>
</tr>
<tr>
<td></td>
<td>• Inavailability of dynamic viewing (pan and rotate) significantly increased modeling time and visualization difficulty, which was further diminished by the sparse CMM data set.</td>
<td>• No CAD model was constructed.</td>
</tr>
<tr>
<td></td>
<td>• Lack of fitting and surface construction techniques limited modeling flexibility, and overall approach.</td>
<td>• Lack of surface fitting tools would have impeded surface model construction.</td>
</tr>
<tr>
<td>I-DEAS MS 5</td>
<td>• Satisfactory wireframe model.</td>
<td>• Satisfactory wireframe and surface models constructed.</td>
</tr>
<tr>
<td></td>
<td>• Dynamic viewing significantly decreased modeling time.</td>
<td>• Dynamic viewing, modeling flexibility, and visualization were strong advantages.</td>
</tr>
<tr>
<td></td>
<td>• Wide range of surface fitting and construction techniques provided good modeling flexibility within constraints of sparse data set.</td>
<td>• Tools to segment dense data for individual surface construction were very awkward.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Data set caused noticeable decrease in system performance, although the it was relatively small by laser scanning standards.</td>
</tr>
</tbody>
</table>
a) CMM wireframe model construction.  
b) Wireframe model from laser scan data.

c) Comparative overlay of both models.

**Figure 3.8:** Reverse engineering CAD model construction of the automotive part.

### 3.4.2: Case Study #2 - The Hip Prosthesis [96]

#### 3.4.2.1: Purpose

The primary objective of this study is to compare the advantages and disadvantages involved in reverse engineering a part, having both prismatic and free-form design features, using both CMM and laser scanned data. A further aim is to compare the reverse engineering capabilities of the SDRC I-DEAS Master Series 5 and Imageware 8 software packages.
3.4.2.2: Data Collection

Data was collected on only one half of the part, due to the inherent design intent symmetry. The symmetry plane was established using the fit center and centerline of the spherical and cylindrical features respectively, and a point at the mid-thickness of the tip. The remaining half of the data was generated by reflecting the captured half. The effective use of symmetry lead to a reduction in digitization time, and fewer difficulties in collecting the data, since 360° access to the part after fixturing was troublesome. A more detailed summary of issues involved in collecting the data is provided in Table 3.4.

Figure 3.10: a) Partial CMM data set collected from curved section of hip prosthesis. b) Laser scanned data set of hip prosthesis.

3.4.2.3: CAD Model Construction

In generating CAD surfaces from both types of data, prismatic features were created by either fitting or revolving, and free-form features were constructed using lofted surfaces. Figure 3.11 (a) provides a representation of the point distribution in the CMM cross-sections, and the curves generated from them for lofting. Figure 3.11
(b) shows a complete set of lofting curves, generated from the laser scan data, immediately prior to reflection about the plane of symmetry.

**Table 3.4:** Data Collection Issues Involved with the Hip Prosthesis

<table>
<thead>
<tr>
<th>CMM Digitization</th>
<th>Laser Scanning Digitization</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Tedious and lengthy process.</td>
<td>• Relatively quick and simple process.</td>
</tr>
<tr>
<td>• Sparse data set generated.</td>
<td>• Dense data set with full part coverage.</td>
</tr>
<tr>
<td>• Software routines used for automatic tip compensation on prismatic features.</td>
<td>• Reflectivity of part required that coating be applied for reliable data capture.</td>
</tr>
<tr>
<td>• Data collection on free-form surfaces required a strategic plan for the sampling distribution, since tip compensation significantly affects process time.</td>
<td></td>
</tr>
<tr>
<td>• Data collected in cross-sections minimized process time while keeping compatibility with surface construction techniques.</td>
<td></td>
</tr>
<tr>
<td>• Finite probe size made data collection near part tip difficult due to the slimming and blending of meeting surfaces.</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 3.11:** a) Schematic of lofting sections created from CMM data points.  
b) Lofting sections constructed from laser scan data.

The most significant differences in generating a CAD model from the two types of data were modeling flexibility, and detail resolution. In both cases, the laser-
scanned data was far superior. The density of the data provided excellent flexibility in choosing the number, placement, and construction techniques for the lofted curves, considerably increasing the control over the resulting surface characteristics. Further, the sheer number of points made it much easier to envision the entire part, understand how mating surfaces blended, and judge the conformity of the generated surfaces with respect to the part shape. The CMM surface construction, by contrast, was highly constrained by the number and placement of the measured points. Figures 3.12 (a) and 3.12 (b) show the finished CAD models for each data type.

![Figure 3.12: SDRC I-DEAS reverse engineered surface models constructed from: a) CMM data; and b) laser scanned data.](image)

3.4.2.4: Comparison of Modeling Capabilities of SDRC I-DEAS Master Series 5 and Imageware Surfacer 8 for Reverse Engineering

A comparison of the Imageware Surfacer 8 and the SDRC I-DEAS Master Series 5 software packages was made for the generation of reverse engineered CAD models of the hip prosthesis from laser scanned data. From the comparison, the superiority of the Imageware software was immediately obvious. The fundamental issues involved are contrasted in Table 3.5, grouped in accordance with the major stages of the reverse engineering process, as defined in Figure 1.1.
<table>
<thead>
<tr>
<th>Data Editing, Manipulation, &amp; Segmentation</th>
<th>SDRC I-DEAS Master Series 5</th>
<th>Imageware Surfer 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Treats every data point as a separate entity, resulting in slow performance and an inability to handle large data sets.</td>
<td>• Treats entire point cloud as a single entity, yielding efficient performance and the capacity to handle large data sets.</td>
<td></td>
</tr>
<tr>
<td>• Significant lack of tools for segmenting data.</td>
<td>• Good data segmentation tools (i.e. cross-sectioning, area point selection, angular, chordal, and curvature-based segmentation).</td>
<td></td>
</tr>
<tr>
<td>• Insufficient number of tools to efficiently manipulate data points and enhance visualization.</td>
<td>• Excellent point display and visualization tools (i.e. point size, display decimation, color, and polygonalization).</td>
<td></td>
</tr>
<tr>
<td><strong>Curve &amp; Surface Construction</strong></td>
<td><strong>Curve &amp; surface construction is almost entirely based on interpolation, with limited approximation for surfaces.</strong></td>
<td><strong>Curve interpolation, tolerance-based interpolation, and approximation are supported.</strong></td>
</tr>
<tr>
<td>• Shape manipulation tools are decent for curves, but limited for surfaces.</td>
<td>• Surfaces may be interpolated or approximated.</td>
<td></td>
</tr>
<tr>
<td><strong>CAD Model Construction</strong></td>
<td>• Continuity management tools are decent for curves, but limited for surfaces.</td>
<td><strong>Ability to manage curve and surface continuity is good.</strong></td>
</tr>
<tr>
<td>• Shortage of diagnostic tools to gauge suitability of curves and surfaces created.</td>
<td>• Several diagnostic tools help gauge entity accuracy with respect to the data points, and smoothness.</td>
<td></td>
</tr>
<tr>
<td>• Supports solid model creation when all position discontinuity is below software tolerances.</td>
<td>• Software supports surface surface models only.</td>
<td></td>
</tr>
</tbody>
</table>
3.4.3: Case Study #3 - The Automotive Fender

3.4.3.1: Purpose

To generate a laser scan data based reverse engineering CAD model of a part, specifically the automotive fender of Figure 3.13, that is too large to be fully placed within the machine working volume.

Figure 3.13: Automotive fender under study.

3.4.3.2: Data Collection

Parts that are too large for the machine working volume, must be scanned in multiple positions and orientations, and then the scan data combined and aligned (registered). In digitizing the automotive fender, two small rectangular blocks, which always remained within the machine working volume, were fastened on the surface of the part. The fender was then repositioned and scanned, as required, generating a point cloud encompassing all part surfaces. Prior to scanning, wooden supports were fastened to the fender to minimize distortion of the part under the varied loading conditions arising from each position. Further, the fender and block surfaces were coated to enhance data capture. The data acquired from each of the four main positions of the fender is shown in Figure 3.14.

3.4.3.3: CAD Model Construction

All view data was imported into SDRC I-DEAS Master Series 5. Before surface construction could begin, it was necessary to assemble the various view data sets, forming a complete part point cloud. In accomplishing this, the two small rectangular blocks were reconstructed within each view, via plane fitting and trimming as shown in Figure 3.15 (a), and used as datums in the reorientation and combination of the multiple views. The complete part point cloud is depicted in Figure 3.15 (b).
Figure 3.14: Multiple scan views of the automotive fender.

Figure 3.15: a) Reconstruction of rectangular block view datums.  
b) Complete part point cloud for automotive fender.
Once the complete part point cloud was fully assembled, a curve network was generated, and lofted surfaces were constructed. Since I-DEAS does not provide approximation tools with which to generate smooth curves for lofting, new points were manually placed, using the laser scanned data cloud as a reference, from which the interpolated curves were created. Figure 3.16 (a) shows the set of manually placed points used to generate the lofting curve network, while Figure 3.16 (b) depicts a large portion of the curve network created from these points. Figure 3.17 illustrates the portion of the surface model constructed from the curve network illustrated in Figure 3.16 (b).

![Figure 3.16: a) Points used to create network of lofting curves for automotive fender. b) Curve network defining reverse engineered surface model of fender.](image)

A major issue in the reverse engineering of this part was the accuracy associated with assembly of the multiple view data sets. For a large part, such as the automotive fender, small angularity errors in representing the faces of the datum blocks, led to significant discrepancies in data alignment for part features located at large distances from them. An example of this is provided in Figure 3.18. The solution to this problem lies in the choice of datum artifacts, the precision of their manufacture, their location on the part, and in developing a repeatable process that minimizes digitization uncertainty. Further work on this topic, known as view registration, is provided in Chapter 7.
3.4.4: Case Study #4 - The Automotive Piston

3.4.4.1: Purpose

The objective in this study was to construct a CAD model of the automotive piston, shown in Figure 3.19, using the method considered most appropriate, and in doing so, to illustrate and examine the reverse engineering decision-making process.
### 3.4.4.2: Part Characteristics and CAD Model Requirements

Prior to the start or any reverse engineering project, a description of the part characteristics, and resultant CAD model requirements, is imperative. This provides important information for both data collection and CAD modeling decision-making. For the particular case of the automotive piston, and the choice of CMM or laser scanning digitization, Table 3.6 provides a categorical description of these characteristics and requirements, as identified in the initial stages of the project.

**Table 3.6: Automotive Piston Part Characteristics and CAD Model Requirements**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Description / Requirement</th>
<th>Justification / Implication</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD Model Accuracy</td>
<td>High (within 0.050mm of part).</td>
<td>• Functional requirements of part features.</td>
</tr>
<tr>
<td>Downstream Process</td>
<td>Solid Model</td>
<td>• 0.5° tangent continuity.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• 0.025mm position continuity.</td>
</tr>
<tr>
<td>Critical Part Features</td>
<td>Overall Diameter, Rng Grooves, Piston Pin Hole.</td>
<td>• Functional design requirements.</td>
</tr>
<tr>
<td>Feature Accessibility</td>
<td>Primarily Accessible. Piston Pin Hole Partially Occluded.</td>
<td>• Unlikely that piston pin hole feature can be reliably digitized using laser scanning.</td>
</tr>
<tr>
<td>Topology of Surfaces</td>
<td>Functional Features are Prismatic. Free-Form Around Pin Hole.</td>
<td>• Model construction by surface fitting, intersection, &amp; trimming.</td>
</tr>
<tr>
<td>Part Symmetry</td>
<td>Two Planes of Symmetry.</td>
<td>• Reduces data collection needs on free-form surfaces to 1/4 of part.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• CAD model symmetry preserves part balance (design intent).</td>
</tr>
</tbody>
</table>
3.4.4.3: Data Collection

The size, position, and orientation of many of the design features comprising the automotive piston, as noted in Table 3.6, are critical to its operation. Due to this, along with the manufacturers' accuracy specifications, the need to coat the part surfaces for laser scanning, and the partially occluded piston pin hole, CMM digitization was deemed the most appropriate data collection method.

Due to symmetry, it was not necessary to collect data on the entire part. The overall diameter, and piston pin hole, were probed, and least squares cylinders generated. The axes of these cylinders were used as datums in defining the part symmetry. Since the basic part shape is axis-symmetric, a planar profile of data points was sufficient to define the overall topology.

A surface patch network and target points, shown in Figure 3.20 (a), were marked on free-form regions of the piston. A data set, sufficient to define each surface patch individually, was collected. Tip compensation was achieved through the inspection of surfaces constructed from uncompensated measurement points, a method discussed in Section 1.3. The major difficulty involved in this process was resolving blending surface details near the bottom of the piston pin hole, due to the finite probe diameter. The complete CMM point cloud for the automotive piston is shown in Figure 3.20 (b).

Figure 3.20: a) Surface patch network marked on free-form regions of the piston. b) Complete CMM data set collected in reverse engineering the piston.
3.4.4.4: CAD Model Construction

The surfaces representing the overall cylindrical shape of the piston, including the piston ring grooves, were created by revolving a section of curves, constructed from the profile measurement points. In the free-form regions surrounding the piston pin hole, smooth surfaces were created by approximation. These were then extended, intersected, and trimmed at their mutual intersections. This process is known as "slab surface" construction. The recessed feature on the top of the piston was constructed in a similar manner with the chamfer wall being a lofted surface.

Due to the sparse data and poor detail resolution in the proximity of the piston pin hole, surface construction in this area was a time consuming process. Significant gains in surface construction efficiency would have been realized, had the region been digitized using laser scanning. Since the features in this region, aside from the pin hole, are not particularly critical to design intent and function, combining both CMM and laser scanned data would lead to a more optimal combination of functional accuracy and process time. Accommodating this depends entirely on the ability to accurately and reliably align, or register, both types of data.

3.5: COMPARATIVE STRENGTHS AND WEAKNESSES OF CMM AND LASER SCANNING DIGITIZATION

Based on the case studies of Section 3.4 and, to a lesser extent, the literature survey, several advantages and disadvantages of CMM and laser scanning digitization have been identified. These are provided in Table 3.7.

From Table 3.7, it is clear that the strengths and weaknesses of each digitization technology are in high contrast. A union of the two technologies would offer significant flexibility in engineering the characteristics of a given part point cloud, and as such, would be highly beneficial.

3.6: REVERSE ENGINEERING CAD MODEL CONSTRUCTION PROCESS

More specific definition of the reverse engineering CAD model construction process has resulted, due largely to the case studies of Section 3.4. Figure 3.21 illustrates the key aspects of this decision making process.
<table>
<thead>
<tr>
<th></th>
<th><strong>CMM Data Collection</strong></th>
<th><strong>Laser Scanning Data Collection</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pros</strong></td>
<td>• High accuracy potential.</td>
<td>• Rapid digitization rates and low overall process times.</td>
</tr>
<tr>
<td></td>
<td>• Technology widely available.</td>
<td>• Dense data improves modeling visualization &amp; detail resolution.</td>
</tr>
<tr>
<td></td>
<td>• Ability to collect data in some cases of occlusion.</td>
<td>• Pre-planning of data collection process is held to a minimum.</td>
</tr>
<tr>
<td></td>
<td>• Sparse data set easily handled by CAD software packages.</td>
<td>• Non-destructive to the part.</td>
</tr>
<tr>
<td></td>
<td>• Non-destructive to the part.</td>
<td>• Non-contact nature allows data collection on soft or fragile parts.</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td>• Process times are high and tip compensation is tedious.</td>
<td>• Highly reflective or diffuse part surfaces typically require coating to allow reliable data collection.</td>
</tr>
<tr>
<td></td>
<td>• Cannot digitize internal geometry.</td>
<td>• Cannot digitize internal or occluded geometry.</td>
</tr>
<tr>
<td></td>
<td>• Limited ability to digitize soft or fragile parts (contact process).</td>
<td>• Dense data not easily handled by many CAD software packages.</td>
</tr>
<tr>
<td></td>
<td>• Pre-measurement planning and strategy is essential and involved.</td>
<td>• Non-destructive to the part.</td>
</tr>
<tr>
<td></td>
<td>• Finite probe tip radius limits ability to resolve fine details on part.</td>
<td>• Much higher cost technology.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Scanner stand-off distance decreases machine work volume.</td>
</tr>
</tbody>
</table>
Figure 3.21: The reverse engineering CAD model construction process.
3.7: SOFTWARE REQUIREMENTS FOR REVERSE ENGINEERING SURFACE
MODEL CONSTRUCTION

The use of digitizing technologies, such as laser scanning and CT scanning, having data collection rates upwards of 10000 pts/s, demands software packages with the capacity to handle files up to several gigabytes in size. With most digitization systems, software for performing basic point cloud manipulation, such as data viewing, thinning, and output in various formats (eg. STL, IGES, ASCII, and CAD specific) is provided by the manufacturer. Vendor or third party solutions exist for many downstream applications, such as machining, rapid prototyping, and FEM, which provide direct tool-path or mesh generation from point cloud data.

Where a CAD model is required, most classical CAD software packages cannot handle the large data files generated by commercial digitizers. Further, data cloud manipulation, curve and surface construction, and curve and surface editing tools typically fall short of those needed to efficiently generate high quality surface models. In meeting this need, various software solutions, have been developed. A brief survey of these is included in Section 3.9.

3.7.1: Software Selection Criteria [14]

There are several issues of importance when selecting a particular reverse engineering software package. This section summarizes a number of primary considerations, as well as identifies several areas where improvement is needed.

3.7.1.1: Data Import and Export

Several import and export file formats must be supported in order to maintain compatibility and integration with CAD and manufacturing software packages. At a bare minimum, these must include IGES, ASCII, and the digitizer specific format. To be robust, flexible IGES and ASCII translators, several digitizer and rapid prototyping formats, and direct translators for classical CAD software packages must also be included in the list.
3.7.1.2: Data Handling, Manipulation, and Visualization Capabilities

The ability to efficiently handle and process the tremendously large data sets output by many commercial digitizers is paramount in keeping the reverse engineering cycle time to a minimum. The required software capabilities are:

- efficient and responsive dynamic viewing of large data sets;
- point size, shape, color, polygonalization, and display decimation control;
- data reduction tools such as cloud sampling, sectioning, and filtering; and
- data segmentation tools such as cloud sectioning, extraction by area or volume, trimming, curvature-based extraction, and feature extraction;

3.7.1.3: Curve and Surfacing Capabilities

The successful construction of high quality surfaces from data clouds representing complex parts is not an automated process. As such, the surfacing tools and continuity management capabilities of the software package significantly impact the model quality and reverse engineering cycle time. The ability of NURBS curves and surfaces to be locally modified, and to represent free-form shapes with fewer individual patches, generally gives them a slight advantage over their Bezier counterparts. This is of particular importance where tangent or curvature continuity between surface patches is required.

A large variety of curve and surface construction and editing tools contribute significantly to the ease and efficiency of the modeling process. Better software packages will provide flexible curve creation through interpolation, approximation, and combined approaches, reinforcing the importance of curves in achieving high quality surfaces. Surface construction techniques should include those described in Section 3.2. Important curve and surface modification tools are:

- smoothing, cleaning, and inflection removal;
- control point editing (weights, distribution, number, and position);
- flexible trimming/extension, intersection, and filleting; and
- curve/normal reversal, and curve network harmonization;
3.7.1.4: Diagnostic Tools

A good set of tools for diagnosing the accuracy, smoothness, and continuity of the curves and surfaces constructed is of the utmost importance in selecting a reverse engineering CAD modeling software package. These tools can greatly assist in forming the surface construction methodology, correcting surface quality problems, and modifying the nature of the transition between adjoining surfaces. As an example, Figure 3.22 illustrates the use of a radius of curvature plot in diagnosing curve inflection. This condition would lead to a dip in a surface created from such a curve.

![Radius of curvature plot](image)

**Figure 3.22:** Radius of curvature plot used in diagnosing inflections, which lead to aesthetic surface flaws.

Invaluable diagnostic tools include:
- point cloud flatness and curvature plots;
- point cloud to curve or surface distance deviation plots;
- curve and surface control, normal, curvature, and continuity plots;
- highlight line, specular, and reflectance plots;
- tool radius, draft angle, and parting line plots; and
- dynamic cross-sectioning.

3.8: SURVEY AND COMPARISON OF EXISTING DIGITIZATION TECHNOLOGIES

A large number of digitizers are available on the market, each offering a different blend of accuracy, price, data collection rate, portability, and other characteristics. In this section a number of commercially available digitizers, representative of the overall state of the industry, are described. A comparison of their process characteristics is provided in Table 3.8.
Table 3.8: Process Characteristics of Several Reverse Engineering Digitization Technologies

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Digibotics</th>
<th>Hymarc</th>
<th>SMX</th>
<th>LDI</th>
<th>CGI</th>
<th>EOIS</th>
<th>SMS</th>
<th>FaroArm</th>
<th>CMM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range Accuracy</td>
<td>--</td>
<td>12.7</td>
<td>--</td>
<td>12.7</td>
<td>--</td>
<td>50 to 300</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Positional Accuracy</td>
<td>--</td>
<td>MD</td>
<td>--</td>
<td>12.7 per axis</td>
<td>--</td>
<td>MD</td>
<td>--</td>
<td>25 to 168</td>
<td>3 to 25</td>
</tr>
<tr>
<td>Process Accuracy</td>
<td>50</td>
<td>MD</td>
<td>2±0.8/m (radial) 2±5/m (transverse)</td>
<td>--</td>
<td>±25</td>
<td>MD</td>
<td>25 to 50</td>
<td>DD</td>
<td>DD</td>
</tr>
<tr>
<td>Dedicated (D) or Retrofit (R)</td>
<td>D</td>
<td>R</td>
<td>D</td>
<td>D</td>
<td>D</td>
<td>R</td>
<td>D</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Working Volume (m³)</td>
<td>Up to 1.2</td>
<td>MD</td>
<td>&gt; 40000 radial slice</td>
<td>Up to 1.8</td>
<td>0.0156</td>
<td>MD</td>
<td>Up to 3.2</td>
<td>Up to 7.8</td>
<td>&gt; 24</td>
</tr>
<tr>
<td>Approximate Cost (USD)</td>
<td>$60k</td>
<td>$75k</td>
<td>$200k</td>
<td>$80k to $500k</td>
<td>$175k</td>
<td>$19k to $40k</td>
<td>&gt; $400k</td>
<td>$25k to $50k</td>
<td>$50k to $300k</td>
</tr>
<tr>
<td>Data Collection Rate</td>
<td>20 pts/s</td>
<td>10000 pts/s</td>
<td>50 pts/s</td>
<td>14400 pts/s</td>
<td>--</td>
<td>300000 pts/image</td>
<td>--</td>
<td>DD</td>
<td>DD</td>
</tr>
<tr>
<td>Process Time</td>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Contact Process</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>DD</td>
<td>DD</td>
</tr>
<tr>
<td>Destructive Process</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Internal Geometry</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
</tr>
<tr>
<td>Portable</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>Y/N</td>
<td>N</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Feature Resolution</td>
<td>Moderate</td>
<td>High</td>
<td>Moderate</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>DD</td>
<td>DD</td>
</tr>
<tr>
<td>Part Coating Req’d</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>DD</td>
<td>DD</td>
</tr>
</tbody>
</table>

Key: MD – Motion System Dependent, DD – Digitizer Dependent.
3.8.1: Digibotics Incorporated [32]

Digibotics, Inc. manufactures a portable four-axis laser scanning device which integrates workpiece rotation with laser scanner translation. The Digitbot II™ uses a remote ranging method, which does not require imaging optics or sophisticated detector array processors.

![a) Digibot II Desktop](image1.png) ![b) Digibot III](image2.png)

**Figure 3.23:** Two configurations of the Digibotics technology.

A laser projector is mounted between two triangulation sensors on a horizontal rail. The viewing direction of each sensor is at 30° to the laser beam, as described by Figures 3.23 (a) to (c). Points the object surface are measured by rotating the object so that the surface normal, at the point of interest, approaches collinearity with the laser beam. The sensors then adjust their positions until one of the viewing directions intersects the point. Coordinates on the part surface are calculated knowing the horizontal and vertical position of the sensor, and its viewing angle.

![Sensor](image3.png) ![Beam](image4.png) ![Part](image5.png)

**Figure 3.24:** Digibotics laser beam projection/sensing configuration.
3.8.2: The Hymarc Hyscan 45C Laser Scanner

The Hymarc Hyscan 45C laser scanner, discussed in detail in Chapter 2, is a retrofit implementation for a CMM or CNC machine. It was originally developed at the National Research Council of Canada (NRC). The scanner employs auto-synchronous triangulation with data collection rates of up to 10000 points per second (pts/s). Hymarc also offers the Colorscan digitizer, which uses a trichromatic laser beam to capture both the color and geometry of an object.

3.8.3: Laser Design Incorporated [66]

LDI markets the 3D Surveyor® RPS (Rapid Profiling Sensor) family of laser scanners, which use stripe sensing triangulation to digitize a part surface. LDI 3D Surveyor® RPS systems, an example of which is shown in Figure 3.25, are typically dedicated digitization systems that operate in a similar manner to a CMM.

![Figure 3.25: The LDI Surveyor Model DS-2016.](image)

3.8.4: Spatial MetriX Corporation [108]

SMX markets a portable, tripod mounted laser digitization system which uses ranging methods, rather than triangulation, to record part coordinates. In incremental mode, interferometry is employed, while in absolute mode, time of flight techniques are applied. In either case, the system unit rests on a tripod, and projects an infrared beam to an SMR (spherical mounted retroreflector), which is guided by hand over the part surface. The SMX Laser Tracker 4500 system is shown in Figure 3.26 (a).
A frequency stabilized HeNe (helium-neon) laser beam is split into two beams in incremental distance measurement mode. One beam enters an interferometer directly, while the other travels to and from the SMR before entering. While in the interferometer, the two beams interact coaxially. A change in the position of the SMR is indicated by a phase shift in the interference pattern of the coaxial beams. Conversely, absolute distance measurement mode uses the time of flight of the beam to and from the SMR, in conjunction with the speed of light in air, to calculate the distance between the Tracker and the SMR center. The system is temperature and pressure compensated, to improve performance in real world manufacturing environments.

As the SMR is repositioned, the beam emitter rotates about the horizontal and vertical axes, keeping the beam focused on its center. Angular axis encoders monitor the position of the emitter. This information, along with the distance measurement, is used to track the 3D coordinates of the SMR. The part surface coordinates are then calculated by offsetting the SMR center coordinates by the sphere radius, for the given size of SMR chosen.

The huge working volume of the device is ideal for the measurement of large objects, such as a 31 foot, 45000 lb Caterpillar backhoe boom (Figure 3.26 (b)), or for tooling certification as at the Chrysler Pillette Road Truck Plant in Windsor, Ontario.
3.8.5: Capture Geometry Inside [23]

The CGI\textsuperscript{®} system also offers the ability to digitize internal geometry, however, it is a process destructive to the part. In this implementation, the part is encased in a hardenable material, and vacuum pressure is applied to ensure full coverage. Once hardened, the part is secured to a mill table, as shown in Figure 3.27 (b), where it is successively flycut and scanned in cross sections spaced from 12.7\textmu m to 250\textmu m.

The encasing material provides a high contrast background for digitization, in addition to supporting the part. After each layer is milled, the surface is optically scanned, the data filtered, and the part boundaries identified using intensity thresholding. This generates a series of 2D cross sections that are then output as an aggregate scan cloud.

![Figure 3.27: The CGI\textsuperscript{®} CSS-1000 reverse engineering system.](image)

3.8.6: Electro-Optical Information Systems [40]

EOIS produces several configurations of a Moiré Interferometry based LCD sensor, capable of collecting up to 300000 points per image. The Mini-Moiré sensor, shown in Figure 3.28 (a), is a retrofit device for motion systems, and is the only Moiré based technology light enough to be mounted on a Renishaw CMM articulating head, used by the majority of CMM customers.
Figure 3.28: Two configurations of EOIS digitizers.

A second, hand-held configuration, known as "The Handy", combines a digital camera with the EOIS sensor. Software is included to register the captured views after downloading from the camera to a PC. "The Handy" is shown in Figure 3.28 (b).

3.8.7: Faro Technologies Incorporated [42]

Faro Technologies manufactures a portable robot manipulator arm that is counterbalanced, temperature compensated, and portable. The Faro Gold version of the product is shown in Figure 3.29 (a). The device incorporates six joints, and is manually maneuvered. Optical encoders at each joint track the position of the arm. Several measuring devices may be fastened to the end of the arm, including the EOIS Mini-Moiré sensor, touch trigger probes, laser scanners, and hard probes.

3.8.8: Scientific Measurement Systems [107]

SMS is the leading producer, from a group of very few, of Computed Tomographic (CT) scan based systems for reverse engineering. The CT scanning process, described in Section 1.2.1.2.1, is often the only valid solution for non-destructively digitizing internal part geometry, and is most widely used in the aerospace industry. SMS offers two main systems, differing significantly in capacity (work volume and maximum part weight). These are shown in Figures 3.30 (a) and (b).
3.9: COMMERCIALY AVAILABLE SCAN DATA PROCESSING SOFTWARE

It is possible, to some degree, to process scan data and create representations of the form required for many downstream processes, using conventional CAD software packages. However, as was discussed in Section 3.4, this may place significant constraints on the process of constructing such representations, as well as lead to large reductions in productivity. For these reasons, many software packages and capabilities have emerged, which are streamlined for working with scan data. In this section, the functionality of such software packages is discussed with respect to several
downstream processes. While some of these packages may have cross-functional capabilities, here they are organized by their main historical application.

3.9.1: Surface Model Construction

The timely construction of high quality parametric surface models from scan data requires a software package having tools which support all steps of the reverse engineering process, as outlined in Figure 3.21. The three most prevalent packages on the market are ICEM Surf™ [57], Alias|Wavefront™ [2] and Imageware Surfacer™ [59], all of which meet or exceed the requirements of reverse engineering software packages as discussed in Section 3.7. ICEM Surf™ and Alias|wavefront™ both existed before the introduction of rapid 3D digitization technologies, while Imageware Surfacer™, on the other hand, has emerged and developed alongside these technologies.

While all three software packages have a wide range of capabilities, some differences are notable. ICEM Surf™ is regarded as the best implementation for automotive Class A surfacing applications, and offers selective global surface modification, real-time diagnostic plots, and triangular/tetrahedral mesh generation for computational fluid dynamics (CFD) applications. Alias|Wavefront™ provides the ability to generate 2D concept sketches, used to guide the 3D model construction process, a considerable number of rendering tools, and artistic, inverse kinematics, or dynamics based animation. Imageware Surfacer™ has the most well rounded tool set for supporting the overall reverse engineering process. It offers global surface modification tools, real-time diagnostic plots, file format support of nearly all 3D digitizers, and most significantly, a number of artifact-based registration algorithms to assist in multiple view registration, combining data types, and inspection.

3.9.2: Rapid Prototyping and Tooling

For rapid prototyping or tooling, polygonal surface models may be generated directly from 3D scan data. InnovMetric PolyWorks [60] and Raindrop Geomagic® [92] are two well known software packages in this arena, each offering a number of applicable tools. Among these are:
- Point cloud editing, filtering, sampling, and manipulation.
- Automated polygonal surface generation.
- Polygon reduction, editing, and feature repair/reconstruction.
- Automated parametric surface generation from polygonal surfaces.
- Real-time point cloud to surface accuracy verification.
- Variety of file format read and write abilities.

The above software packages have a number of functional similarities, however, several differences are notable. PolyWorks includes software-based multiple view registration abilities, and point cloud to surface registration, making it suitable for inspection applications. Although Geomagic® does not offer these capabilities, it yields NURBS, rather than Bezier, surfaces during automated parametric surface generation from polygonal surfaces.

3.9.3: Quality Control

Quality control is an application of 3D digitizing that is growing rapidly with the accuracy and number of variants of the technology, particularly for parts where dimensional tolerances are loose (e.g. 0.5mm or higher), as in stampings and castings. Many scanner manufacturers and reverse engineering software packages provide functions to register scan data to the design intent CAD model, and provide diagnostic distance deviation plots. Such packages include Imageware Surfacer, InnovMetric Polyworks, Alias Wavefront, Delcam, and Cimatron [27, 30]. Further, Open Architecture software implementations, such as Imageware Surfacer, offer significant flexibility in creating automated and on-line inspection systems.

3.9.4: Finite Element Analysis

Due to the growing popularity of reverse engineering digitization technologies and rapid prototyping, "meshless" finite element analysis techniques and software have emerged. In this approach, voxel models are generated from STL or CT scan data, which are used to define the finite element mesh. This approach is excellent for complex parts, such as large castings, where mesh generation from a surface or solid model could take weeks or even months. One software package, available on the market, which supports this type of analysis is called VoxelCon [113].
This method offers dramatic strengths, with further research being focused on two main areas. Firstly, the number of degrees of freedom associated with the voxel model tends to be very large, which results in high computational costs in the analysis. Secondly, stress levels may be reported as artificially high around boundaries due to zigzag shaping resulting from the mesh generation. One method of dealing with these issues is to use multi-scale voxel data, which increases resolution at the boundaries, and decreases resolution in the interior of the volume, where it is not needed [109].

3.10: DISCUSSION

In this chapter, many key aspects of the reverse engineering CAD model construction and decision-making process were qualitatively discussed. In Section 3.3, the resulting smoothness and accuracy in the construction of CAD entities from scan data were shown as inversely related. In addition, the practical accuracy limit in representing scan data with CAD entities was established. In the case of the Hymarc Hyscan 45C laser scanner, this limit was determined to be 8\( \mu \text{m} \).

The strengths and weaknesses involved in using CMM and laser scanning data in the reverse engineering process were identified, through several case studies, as shown in Table 3.7. In most cases, these strengths and weaknesses were diametrically opposed, justifying the development of a reverse engineering system that combines both types of data collection. Aside from addressing a wider range of applications, such a system would provide much greater flexibility in specifying data accuracy, density, and process time.

From the case studies several other important, but less obvious, issues were encountered. These include the:
- reduced machine work volume when using the laser scanner;
- data collection strategies / planning;
- visualization during CAD model construction; and
- part symmetry.

When using the laser scanner, the CMM working volume is reduced from approximately 0.18 m\(^3\) to as little as 0.06 m\(^3\), allowing for full freedom in scanner rotation. This is due to the large stand-off distance of the scanner. Additionally, the
scanner must have room to navigate between the part and any datum artifacts, decreasing the usable volume further. This reduction in working volume is an important consideration in selecting the CMM/laser scanner pair. The DEA Mistral CMM, for example, is just barely large enough to accommodate the scanner and alignment sphere. The use of multiple datum artifacts, however, is not feasible unless they are attached to the part itself.

Since CMM probing generates sparse data sets, and requires surface normal estimation for tip compensation, significantly more effort must be spent on planning the data acquisition. Typically, this strategy will reflect the methods anticipated for CAD entity construction, as in the cross-sections for lofting in the hip prosthesis study. In contrast, laser scanning only involves selecting the proper viewing angles for full part coverage.

Once the data is captured, a CAD model must be constructed. Here, the dense laser scan data is superior since it conveys considerable shape information, increasing modeling visualization. This makes the surface construction process much faster and easier, particularly where blending between complex surfaces occurs. Another method to reduce process time is the use of part symmetry. In the case of symmetrical parts, such as the hip prosthesis and the automotive piston, partial data sets and associated CAD entities can be reflected to complete the model. This technique enhances design intent where balance and symmetry are important part attributes, and is highly compatible with a combined approach where CMM data can accurately represent the geometric primitives from which symmetry planes may be defined.

The work of this chapter has also provided a more specific definition of the reverse engineering CAD model construction process, as diagrammed in Figure 3.21. Further, the role and requirements of CAD software packages in providing efficient support of the reverse engineering process have been clarified. Remaining Chapters aim at quantifying, characterizing, and reducing the effects of major process errors encountered in generating combined CMM and laser scan data sets.
CHAPTER 4 - CMM AND LASER SCANNING DATA SET ERROR ESTIMATION

4.0: OBJECTIVES

The focus of this section is on quantifying the process errors involved in digitizing a primarily prismatic part, and a free form surface using various CMM and laser scanning techniques. In both studies highly accurate data were constructed, using the DEA Surfer™ System, to facilitate the comparison. All results were analyzed using functions available in the Imageware Surfer™ software.

4.1: STUDY #1 – AUTOMOTIVE BODY-IN-WHITE BRACKET

The automotive bracket, shown in Figure 4.1 (a), was chosen for initial study. It is composed of primarily prismatic design features, however, it exhibited a high degree of form error, which is characteristic of stamping processes. Initially, the bracket surface was prepared with paint primer, allowing it to be laser scanned and probed easily. This surface was deemed neutral, and a representative network of boundaries was marked on it. The result of this process is shown in Figure 4.1 (b).

![Figure 4.1: a) Automotive bracket. b) Primed bracket with patch boundary network.](image)

The Surfer™ system was used to generate a reverse engineered surface model of the part. This surface model consisted of 77 individual surface patches, and required 38 hours to complete. Stringent accuracy criteria were imposed, since the model was to be used as a datum for comparison. These criteria consisted of an average patch accuracy of 3μm, as verified by inspection, and better than 95% of CMM inspection
points inside of a ±10μm deviation band. The resultant surface model is shown in Figure 4.2, and a summary of the error characteristics by region appears in Table 4.1.

Figure 4.2: Datum surface model of automotive bracket generated using DEA Surfer™.

Table 4.1: Patch Error Characteristics of Surfer™ Datum Model

| Region             | Number of Patches | Average Deviation* (μm) | Maximum Absolute Deviation (μm) | % of Inspection Deviations > |10μm| |
|--------------------|-------------------|-------------------------|---------------------------------|-----------------------------|-----|
| Plane 1            | 9                 | 0                       | 15                              | 3.2                         |
| Plane 2            | 19                | 0                       | 13                              | 0.9                         |
| Plane 3            | 6                 | 0                       | 10                              | 0                           |
| Plane 4            | 3                 | 0                       | 13                              | 1.0                         |
| Plane 5            | 3                 | 2                       | 12                              | 1.7                         |
| Plane 6            | 3                 | 0                       | 11                              | 1.5                         |
| Plane 7            | 2                 | 0                       | 16                              | 3.5                         |
| Fillet 1           | 4                 | 2                       | 15                              | 4.7                         |
| Fillet 2           | 6                 | 1                       | 11                              | 0.5                         |
| Fillet 3           | 1                 | 0                       | 15                              | 0.5                         |
| Fillet 4           | 2                 | -1                      | 12                              | 0.5                         |
| Fillet 5           | 2                 | -1                      | 12                              | 1.0                         |
| Fillet 6           | 5                 | -1                      | 19                              | 1.5                         |
| Complex Fillet     | 5                 | 0                       | 13                              | 2.6                         |
| Curved Region      | 7                 | 0                       | 15                              | 1.7                         |
| **Overall**        | **77**            | **0**                   | **19**                          | **1.6**                     |

* Deviations based on a 100 point isoparametric grid of inspection points for each patch.

** Overall represents the culmination of 77 x 100 = 7700 inspection points.
4.1.1: Digitization Using CMM Techniques

Probe tip compensation was performed using a single surface normal estimate for each planar region. This estimate was obtained from a plane fit to a number of sample locations in the region. The fillets were probed using a proposed technique whereby the compensation vector is defined by a weighted average of the bounding plane unit normals [98]. Figure 4.3 and Equation 4.1 describe this technique. The data collected using this approach was then compared to data gathered using compensation in the direction of the closest major CMM axis to the fillet surface normal for each point (approach direction).

![Diagram of fillet surface normal estimation](image)

**Figure 4.3:** Estimation of fillet surface normal from weighted average of bounding plane unit normals.

\[
F_N = \frac{(1 - A)N_1 + AN_2}{| (1 - A)N_1 + AN_2 |} \tag{4.1}
\]

where: \(F_N\) is the fillet surface normal at the measurement point of interest.
\(P_i\) are the bounding planes of the fillet.
\(N_i\) are the unit normals of the bounding planes \(P_i\).
\(A\) is the relative distance along the arc of the fillet, between the planes.

4.1.2: Digitization Using Laser Scanning Techniques

The laser scanner was used to digitize the automotive bracket from five different views. The views were selected so that the scanner axis was normal to the majority of the part surfaces being scanned from that particular view. This is a typical operating procedure for minimizing "off normal" scanning error. Inevitably, however, some misaligned data collection will always result. Such data may be removed by manual segmentation using an appropriate software package.
4.1.3: Results from Comparison to the Stamped Bracket Datum Model

The distances between the CMM point data and the datum surfaces were determined. A deviation vector plot is given in Figure 4.4 (a). The data on the planar regions show relatively small deviations. These deviations arise primarily due to the uncertainty with which the global normal estimates the true surface normal, in light of the form error, and due to random mechanisms. The proposed fillet probing technique generated an average error of 10μm in digitizing the part fillets. Comparatively, compensation using the direction of the major CMM axis closest to the fillet normal, yielded an average error of 170μm.

Figure 4.4: a) Deviation vector plot for CMM data versus datum. b) Deviation texture plot for laser scanning data versus datum.
The laser scanned point cloud was not perfectly aligned with the comparative datum model, due to errors in the mechanism which transforms acquired laser scan data from the u-v space into the three dimensional CMM space. Therefore, the direct registration function in the Imageware Surfacer software was used to transform the point cloud, based on a least squares fit to the datum surfaces, into alignment with the Surfer™ model. Several iterations of the direct registration process were performed, from different starting locations of the point cloud, to ensure that the transformation was not based on a single local minimum solution. The deviation plot of Figure 4.4 (b) represents an estimate of the laser scanning process performance.

The error characteristics of the CMM and laser scanning point clouds show that an order of magnitude difference in process accuracy is observable. The major components of the systematic error in the laser scanning process are the:

- registration error; and
- primary digitization error.

The digitization error component is expected to be relatively low, given the near planar features in this part, although a higher contribution is expected from the filleted areas.

4.2: STUDY #2 – COMPUTER MOUSE FREE-FORM SURFACE

In this study, the accuracy in digitizing the free form surface of a computer mouse, shown in Figure 4.5, was estimated for several CMM and laser scanning techniques. The data was collected on the large top surface of the mouse. In the CMM case, a 4 by 6 uniform grid of points was targeted.

Figure 4.5: Computer mouse used in surface digitization error study.
Four existing approaches, and a proposed fifth (#5), were examined:

1. compensation in the direction of a major CMM axis (-Z axis);
2. local plane approximation at each CMM digitization location;
3. inspection of a surface generated from uncompensated CMM data;
4. single view laser digitization and registration; and
5. CMM inspection of a surface generated from laser scan data.

All data sets were compared to a Surfer™ constructed datum, and deviation results were obtained using the Imageware Surfacer software. Where the inspection of a normal approximating surface was employed (techniques 3 and 5), the Origin Checkmate software was used to generate the probe paths.

4.2.1: Results from Comparison to the Free Form Mouse Datum Surface

The deviation vector plots for all approaches are shown in Figures 4.6 to 4.8, and a comparison is made in Table 4.2.

**Figure 4.6:** Distance deviation plots for CMM-based free-form digitization techniques.
**Figure 4.7:** Distance deviation plot of single view registered laser scanned data.

**Figure 4.8:** Distance deviation plot for laser scanned surface inspection.

**Table 4.2:** Average Deviation of Points from Surfer™ Datum

<table>
<thead>
<tr>
<th>Digitization Technique</th>
<th>Number of Points</th>
<th>Average Deviation ($\mu$m)</th>
<th>Standard Deviation ($\mu$m)</th>
<th>Maximum Deviation ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>60.6</td>
<td>67.8</td>
<td>194.2</td>
</tr>
<tr>
<td>2</td>
<td>96</td>
<td>3.4</td>
<td>2.3</td>
<td>9.2</td>
</tr>
<tr>
<td>3</td>
<td>72</td>
<td>3.9</td>
<td>2.6</td>
<td>10.9</td>
</tr>
<tr>
<td>4</td>
<td>31352</td>
<td>12.2</td>
<td>10.1</td>
<td>62.1</td>
</tr>
<tr>
<td>5</td>
<td>31376</td>
<td>4.7</td>
<td>2.9</td>
<td>9.6</td>
</tr>
<tr>
<td>Datum</td>
<td>---</td>
<td>0</td>
<td>2.7</td>
<td>7.1*</td>
</tr>
</tbody>
</table>

* The maximum deviation of a 100 point inspection of the datum surface.

It is evident from the results, that the local plane approximation and the uncompensated surface inspection approaches yield highly accurate results, with errors considered indiscernible from the datum. The error plot for the fourth approach shows
that the deviations associated with the single view laser scanning digitization are higher than those found in the CMM based techniques, but not by the magnitudes expressed in Study #1. In fact, the 12µm average deviation figure obtained from this free form surface is expected to be similar to, if not less accurate than that obtained on the planar regions of the automotive bracket. This implies that the registration error is a large component of the overall laser scanning process error. A further investigation of the registration error is presented in Chapter 7.

The proposed approach of generating an approximate surface from laser scan data, and optimizing its accuracy through inspection yielded results comparable to purely CMM based techniques, and is much faster in overall process time. This introduces the possibility of optimizing the accuracy and process time in the generation of reverse engineered data sets by combining digitization methods, a topic that is covered more thoroughly in Chapter 8.

4.3: DISCUSSION

Results from this chapter indicate that the overall digitization process errors are an order of magnitude greater for the Hymarc Hyscan 45C than for the DEA Mistral CMM with PH9 probe, 69µm versus 7µm respectively. In the computer mouse study, however, the single view digitization error of the laser scanner was found to be 12µm, much less than the earlier 69µm result. Since the object surfaces and scanning methods were similar in each case, this infers that systematic registration error is a major contributor in the overall data set error.

The computer mouse study also showed that the digitization accuracy in guiding the CMM probe, using a normal approximating surface generated from laser scanned data, was approximately the same as for the purely CMM-based techniques, 4.7µm versus 3-4µm respectively. This clearly demonstrates the merit in combining techniques to optimize accuracy. The main challenge in doing so is accurately transforming both forms of data into a common coordinate system. This can be facilitated using precisely manufactured geometric primitives as view datums. Chapters 5, 6, and 7 discuss the uncertainty levels associated with this approach, and provide techniques for reducing their contribution to the overall data set error.
CHAPTER 5 – SUBSTITUTE GEOMETRY GENERATION FROM CMM DATA

5.0: OBJECTIVES

The interaction of various factors on the uncertainty in generating geometric primitives from CMM measurement data, discussed in Section 1.4, is of high concern for inspection. It is also significant for reverse engineering applications since primitives:

- often represent functional design features, requiring high reconstruction accuracy;
- are typically used in systematic multiple view registration; and
- represent the main basis for transforming data sets, obtained using different digitization technologies, into a common coordinate system.

Research to date has not provided significant methodology for the generation of substitute geometry from prismatic part features in which the specifics of the form errors are not known. Most work has focused on the effect of sampling strategies and fitting algorithms on primitives with known, or simulated form error, as discussed in Section 1.4. The goal of this chapter is to show the feasibility of a proposed methodology for the automatic reconstruction of such primitives, leading to a reasonable, although not necessarily fully optimized, accuracy / process time tradeoff. Manufactured planes were used in developing the methodology, however, direct extension may be made to other primitives.

5.1: FITTING COMPARISON – HYMARC AND IMAGEWARE ALGORITHMS

Since results obtained from the fitting of least squares primitives to both CMM and laser scanned data sets will be employed in characterizing various phenomena in the next few chapters, a fitting performance comparison was made between the Hymarc and Imageware algorithms. This comparison characterizes consistency between the algorithms, and acts as an assessment of implementation correctness through mutual conformance. Since both algorithms were coded several years after the 1988 GIDEP alert [49], comparable results were expected at the level of precision required for the remainder of this work.

Several data sets were prepared from both CMM and laser scanning sources. The selection covered point clouds typically encountered in working with these devices. There were also several atypical point clouds evaluated, along with one data set for each
primitive originating through the US National Institute of Science and Technology (NIST), with accompanying correct fit parameters. Several of these data sets are depicted in Appendix A.

Tables B1 and B2 of Appendix B compare the results of the least squares fit parameters for each data set, based on the different algorithms. ANSI C programs were written to convert data from the CMM inspection file format to columnar text, and from columnar text to the Hymarc format. Source code is included in Appendix C.

The plane fit parameter comparison is provided in Table B1. It is observed that no differences occur for the A through D parameters associated with all data sets, except for NIST2. Comparison of the fit parameters to the published results of the NIST data show a difference of 1E-6 in the A parameter for both algorithms, with no change in any other parameters for the Imageware implementation. The Hymarc results are observed to deviate by 3E-6 in the B and C parameters, and by 5E-6 in the D parameter. The deviation is not considered significant to experimental results, as accuracy to this number of significant figures is not required. Further, perfect conformance is observed for the types of data sets normally encountered.

The sphere fit parameter comparison is provided in Table B2. There are no observable differences in the generated fit parameters for the CMM and NIST based point clouds. However, for the laser scanned data sets, discrepancies are noticeable in the Z components of the sphere center and the radius value for all. The magnitudes of the deviations vary between 0.5 and 2.8 microns for the Z component of the sphere center, and 0 to 2 microns for the radius. These types of data sets are regularly encountered, and thus this represents a small, but not significant, source of error.

5.2: CMM PROGRAMMING METHODOLOGY

For CMM data collection relevant to this, and further work, three parametric programs to sample primitives were written, one for each of planes, cylinders, and spheres. The final version of these programs is included in Appendix D, as coded in the DEA Part Programming Language (DEAPPL). The programs employ a uniform sampling strategy that is equidistant, equiangular, or a combination of the two, depending on the primitive to be sampled. The plane-sampling program is written in a local Cartesian
coordinate system, while the cylinder and sphere sampling programs are written in cylindrical and spherical coordinate systems respectively. The general flow of the CMM programs is illustrated in Figure 5.1.

5.3: SUBSTITUTE GEOMETRY GENERATION FROM MANUFACTURED PLANES

The literature survey on the sampling of primitives revealed very little in the way of experimental data. It has been established, primarily through simulation studies, that the uncertainty in estimating the least squares fit parameters corresponding to an infinite sample size on primitive geometry reduces as the actual sample size increases. However, the selection of the smallest uniform sample size that provides a given level of uncertainty in the estimation has a high dependence on the nature of the part form error, other factors being equal.

In this study, five manufactured planes were CMM sampled using a uniform grid strategy. These included a:
- lapped aluminum plane;
- fly cut renshape plane;
- stamped plane from the BIW bracket;
- milled aluminum plane; and
- plane with surface wear/defects.

The planes were iteratively sampled, incrementing the number of points per side by 1 in each dimension, to a maximum sampling grid between 22 by 22 points and 30 by 30 points. Additional long run samples at 32, 48, and 64 point grid dimensions were also taken in many cases.

The variations in the successive least squares plane locations and orientations were determined using the maximum sample size plane as a datum. These, and other similar, calculations were performed within Imageware Surfacer. A copy of the script is provided in Appendix E. The selected evaluation criteria were the X, Y, and Z components of the angle between the fit plane normal and the datum, as well as the maximum, minimum, and average distances. The angular and minimum distance criteria were chosen with the functionality of CMM software packages in mind. The data is plotted in Figures 5.2 to 5.7.
Figure 5.1: Flow diagram illustrating the progression of a general CMM program.
In general, the plots show trends whereby the criteria converge on or near the long run estimate, and the variability in the respective criteria from one plane fit to the next decreases as sample size increases. However, the rates of convergence vary.

In two cases, namely the lapped aluminum and faced stainless steel planes, increasing the number of sampling points had virtually no effect on the variability of the angular components. However, mild trends in the distance criteria were still observed for the faced and fly cut planes. The accompanying low average flatness, 4μm to 7μm in all cases, for these planes indicates that the nature (frequency and magnitude) of the form error did not give rise to a significant relationship with sample size.

Figure 5.2: Location and Orientation Variations for Lapped Aluminum Plane Fitting

<table>
<thead>
<tr>
<th>Angular Dev. from Max. Sample Size (mili-Deg.)</th>
<th>Distance Dev. from Max. Sample Size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-Angle Dev.</td>
<td></td>
</tr>
<tr>
<td>Y-Angle Dev.</td>
<td></td>
</tr>
<tr>
<td>Z-Angle Dev.</td>
<td></td>
</tr>
<tr>
<td>Max. Dist.</td>
<td></td>
</tr>
<tr>
<td>Ave. Dist.</td>
<td></td>
</tr>
<tr>
<td>Min. Dist.</td>
<td></td>
</tr>
</tbody>
</table>

Ave. Flatness: 3.9μm
Figure 5.3: Location and Orientation Variations for Fly Cut Renshape Plane

Figure 5.4: Location and Orientation Variations for Stamped Bracket Plane from BIW Bracket
Figure 5.5: Location and Orientation Variations for Milled Aluminum Plane

Figure 5.6: Location and Orientation Variations for Plane with Surface/Wear Defects
5.4: PLANE SAMPLING IDEOLOGY

5.4.1: Parameter Variation Threshold Method

The plots of Section 5.3 indicate that, as the number of sample points increase, the location and orientation of a fitted least squares plane approach that associated with a very large sample size. One technique for predicting when a large enough sample size is reached, such that the bulk of the uncertainty in the location and orientation of the plane has been removed, might be to monitor the plane to plane distance and angular variations for successive plane fits. Once these variations drop below threshold values, the sample size would be deemed large enough. Figures 5.8 and 5.9 provide generic CMM programming flowcharts for this approach. Note that in the plane sampling procedure, no location is sampled more than once due to the storage and linear search of the array of target locations (Calc_Pnt[]). This ensures that no appreciable increase in measurement time results for a given sample size.

While this method may have merit, particularly for planes with higher form error magnitudes, several concerns and considerations arise. Initially, it is somewhat inflexible and unintuitive in setting and changing the desired accuracy of the result. Secondly, for planes with less sizable, but still significant form errors, the magnitudes of the parameter variation thresholds would be relatively close to the levels of location and orientation variability inherent in generating the planes. Lastly, the variation threshold values would likely have some dependence on the physical probe configuration and measurement settings. It would be necessary to explore and define this relationship.

5.4.2: Design of Experiments Method

An alternative approach that largely eliminates the sensitivities associated with the use of parameter variation thresholds is proposed, drawing on design of experiments techniques. In this approach, the location and orientation of a least squares plane, fitted from uniformly sampled CMM data, is predicted given the measurement settings, and manufacturing process. Figure 5.9 provides a CMM programming flowchart for this “Intelligent Plane Sampling Approach.” Details on the development of the NP prediction procedure are provided in Section 5.6.
Figure 5.7: Flowchart of the Parameter Variation Threshold Method of plane sampling.
Figure 5.8: Generic plane sampling procedure flow diagram.

A large number of factors may affect the location and orientation uncertainty of substitute geometry, some of which are listed in Table 5.1. Several of these factors have been identified and studied by other researchers, as discussed in Section 1.4.

Table 5.1: Factors That Affect the Location and Orientation of Substitute Primitives

<table>
<thead>
<tr>
<th>Group</th>
<th>Factors Affecting CMM Measurement Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement Environment</td>
<td>• Temperature</td>
</tr>
<tr>
<td></td>
<td>• Humidity</td>
</tr>
<tr>
<td></td>
<td>• Vibration</td>
</tr>
<tr>
<td>CMM Hardware</td>
<td>• Positioning Errors</td>
</tr>
<tr>
<td></td>
<td>• Distortion due to Loading</td>
</tr>
<tr>
<td></td>
<td>• Probe Errors (Positioning, Lobing, etc.).</td>
</tr>
<tr>
<td></td>
<td>• Operating Pressure</td>
</tr>
<tr>
<td>Fitting Algorithm</td>
<td>• Selection</td>
</tr>
<tr>
<td></td>
<td>• Implementation</td>
</tr>
<tr>
<td></td>
<td>• Convergence Criteria</td>
</tr>
<tr>
<td>Measurement Settings</td>
<td>• Tip Radius</td>
</tr>
<tr>
<td></td>
<td>• Probe Velocity</td>
</tr>
<tr>
<td></td>
<td>• Sampling Pattern</td>
</tr>
<tr>
<td></td>
<td>• Contact Force</td>
</tr>
<tr>
<td></td>
<td>• Stylus Length</td>
</tr>
<tr>
<td></td>
<td>• Probe Acceleration</td>
</tr>
<tr>
<td></td>
<td>• Sample Size</td>
</tr>
<tr>
<td></td>
<td>• Approach Distance</td>
</tr>
<tr>
<td></td>
<td>• Approach: Direction</td>
</tr>
<tr>
<td></td>
<td>• Coverage Area</td>
</tr>
<tr>
<td>Part Characteristics</td>
<td>• Form Error</td>
</tr>
<tr>
<td></td>
<td>• Feature Accessibility</td>
</tr>
<tr>
<td></td>
<td>• Surface Finish</td>
</tr>
<tr>
<td></td>
<td>• Material</td>
</tr>
<tr>
<td></td>
<td>• Alignment on CMM</td>
</tr>
</tbody>
</table>
From an applications standpoint, many of these factors cannot easily be varied during data collection, or are typically tightly controlled. CMM hardware factors, for example, are fixed by the particular machine/probe combination, while factors relating to the measured part are largely determined by its design and manufacture. In the case of the measurement surroundings, it is common for CMMs to be installed in
environmentally controlled rooms, minimizing the variation due to factors such as temperature, humidity, and vibration.

In Section 5.5, the feasibility of the Intelligent Plane Sampling Approach is assessed by running screening experiments that identify and verify the ability to resolve significant plane location and orientation effects, attributable to measurement settings and part characteristics, using CMM data collection. The measured responses for all work are primarily the change in the Z-component of the plane centroid, indicating location, and the change in total angle between planes, indicating orientation. In some cases, the data set flatness is also measured as a response. In the studies, the least squares fitting method is used, due to its widespread implementation abroad.

5.5: DESIGNED EXPERIMENTATION

5.5.1: Factors Affecting the Mean Location and Orientation of Planes Generated by Least Squares Fitting to Uniformly Distributed CMM Data

5.5.1.1: Coverage Area and Sample Size

Sampling strategy and coverage area, as discussed in Section 1.4, typically have the largest impact on the location and orientation of fitted primitives. In this section, an L₈ orthogonal array experimental design is used to gauge the relative magnitude of the number of sample points (NP) and coverage area ratio (AR), in comparison to those of approach distance (AD in mm) and probe velocity (PV in % of machine maximum), on the location, orientation, and flatness associated with least squares fitting to CMM data collected from manufactured planes. Further, the significance of the area ratio and sample size effects is investigated in relation to the topology of the manufacturing form error for each plane. The fifteen manufactured planes studied are referred to as:

- lapped aluminum;
- fly cut renshape;
- fly cut aluminum #1;
- fly cut aluminum #2;
- milled aluminum #1;
- milled aluminum #2;
- aluminum cylinder face;
- stainless steel cylinder face;
- stepped aluminum cylinder face;
- stamped shcct stecl #1;
- stamped sheet steel #2;
- cast aluminum #1;
- cast aluminum #2;
- worn/serviced; and
- injection molded.
A three-repetition experiment, based on the L₉ orthogonal array shown in Figure 5.10, was run for each of the planes. The factors are distributed in the array such that column 3 holds the sum of the area ratio / sample size interaction and the approach distance / probe velocity interaction. Since the approach distance and probe velocity effects were typically small, this column is considered a good approximation of the area ratio / sample size interaction without confounding.

<table>
<thead>
<tr>
<th>Run #</th>
<th>AR</th>
<th>NF</th>
<th>ARxNP</th>
<th>AD (mm)</th>
<th>c5</th>
<th>c6</th>
<th>FV %</th>
<th>Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1</td>
<td>9</td>
<td>+</td>
<td>6</td>
<td>100</td>
<td>40</td>
<td>---</td>
<td>Flatness</td>
</tr>
<tr>
<td>2</td>
<td>0.8</td>
<td>9</td>
<td>-</td>
<td>6</td>
<td>100</td>
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<td>3</td>
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<tr>
<td>6</td>
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<td>---</td>
</tr>
<tr>
<td>7</td>
<td>0.1</td>
<td>121</td>
<td>+</td>
<td>20</td>
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-ave_Flat --- --- --- --- --- --- --- ---
+ave_Flat --- --- --- --- --- --- --- ---
ME_Flat --- --- --- --- --- --- --- ---
-ave_Cent --- --- --- --- --- --- --- ---
+ave_Cent --- --- --- --- --- --- --- ---
ME_Cent --- --- --- --- --- --- --- ---
-ave_Ang --- --- --- --- --- --- --- ---
+ave_Ang --- --- --- --- --- --- --- ---
ME_Ang --- --- --- --- --- --- --- ---

**Figure 5.10:** L₉ orthogonal array used in studying the effects of area ratio and sample size on the mean location and orientation of planes fitted from CMM data.

The main effects associated with each of the responses are listed in Table 5.2 for all planes. The significance of each main effect was determined using normal plots for each measured response. Figures 5.11 (a) to (c) show normal plots for the fly cut aluminum #2 plane, after removal of the area ratio factor, which enhances the resolution of weaker effects. Table 5.3 lists all factors deemed significant for each of the 15 manufactured planes, in order of increasing average flatness.
### Table 5.2: Factor Main Effects on Plane Location and Orientation from L6 Experiment

<table>
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<th>Factors</th>
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<td>Angle</td>
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<td>Angle</td>
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<td></td>
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<td>Flatness</td>
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<tr>
<td></td>
<td>Position</td>
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<td></td>
<td>Angle</td>
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<tr>
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<td>Flatness</td>
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<td>Position</td>
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<td>Angle</td>
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Figure 5.11: Le experiment half-normal factor plots.
Table 5.3: Summary of Significant Factor Main Effects on Plane Location and Orientation from L₄ Experiment

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<tr>
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<th>FLATNESS</th>
<th>CENTROID</th>
<th>ANGLE</th>
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<td>AD c5 c6</td>
<td>PV AD c5 c6</td>
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<td>2.3</td>
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<td></td>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fly Cut Renshape</td>
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<td>2.1 2.7</td>
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<td>4.6 3.6</td>
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<td>3.6 4.0</td>
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<td>41 4.1 6.6</td>
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<tr>
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<td></td>
<td>2.9 2.8</td>
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<tr>
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<td>69 2.2 2.4</td>
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<td>30 4.5</td>
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<td>5.0 7.2 5.1</td>
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<td>447 26 30</td>
<td>76 38 16</td>
<td>16 172 28</td>
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</table>
Table 5.3 clearly shows that the area ratio had a strong affect on all three responses for all planes with average flatness values greater than 19μm, and for the Fly Cut Renshape plane. The sample size, and its interaction with area ratio, was also significant for most of the planes having flatness values exceeding 19μm. On the other hand, the group of planes with average flatness values less than 4.6μm were largely immune to all factor effects. Further, the Milled Aluminum #1, Milled Aluminum #2, and Fly Cut Aluminum #2 planes were not affected by area ratio at all.

While the fitted plane flatness indicates the magnitude of the form error, it does not provide information about its topology or frequency. This was investigated using high density CMM scans. For each manufactured plane, a least squares plane was fitted from its high-density data set. Distance deviation plots were then generated for the data, with respect to the fitted planes, as shown in Figures 5.12 (a) through (n).

![a) Lapped aluminum.](image1)

![b) Stainless steel cylinder face.](image2)

![c) Fly cut aluminum.](image3)

![d) Fly cut renshape.](image4)
e) Milled aluminum #1.

f) Fly cut aluminum #2.

g) Milled aluminum #2.

h) Worn/serviced plane.

i) Stamped sheet steel #1.

j) Stamped sheet steel #2.
Figure 5.12: Distance deviation plots for high-density CMM scans of manufactured planes used in feasibility study of Intelligent Plane Sampling Approach.

The interesting thing to note from the plots, is that the same three planes having flatness values greater than 5μm, and whose responses were unaffected by the area ratio factor, are the only three planes having form error topologies with high frequencies relative to the size of the sampled area. This is highlighted on Table 5.3 by the word "High" in the form error frequency column for the three planes. For all other planes, the resulting form errors are irregular, and of low frequency with respect to the sampled area. This suggests that the flatness, location, and orientation of the fitted least squares plane is not appreciably affected by the size of the sampled area, where the form error is regular and has a high frequency relative to the size of the sampled area.
5.5.2: Remaining Factors

All remaining measurement settings from Table 5.1, with the exception of probe orientation, were investigated. Specifically, these are the number of sample points (NP), approach distance (AD in mm), probe tip diameter (TD in mm), probe stylus length (SL in mm), probe velocity (PV in % of machine maximum), contact force (CF in # of rotations), and probe acceleration (PA in % of machine maximum). Due to the large number of possible probe orientations, 720 in all, the choice of 2 or 3 settings was not considered to be a reliable indicator of the effect of this factor. On the other hand, selecting a larger number of settings would have resulted in a significant increase in the required number of experimental runs in combination with all of the other factors. Thus, it was deemed more appropriate to investigate and rule out other non-contributing measurement settings first, and then either incorporate probe orientation in a new array with those settings found to be significant, or to examine its individual affect on location and orientation uncertainty, and assume no significant interactions with other factors.

In examining the group of measurement settings, the L₃₂ orthogonal array experimental design of Figure 5.13 was chosen. With this design, nearly all measurement settings and their interactions were explored free from confounding. Since changing the probe tip diameter, stylus length, and contact force required re-qualifying the probe, five repetitions of the experiment were run in order to average the effects of the measurement errors introduced by this process. The experiment was conducted on the following four planes:

- lapped aluminum;
- milled aluminum #2;
- stamped sheet steel #1; and
- cast aluminum #2.

The effect values for each of the columns was calculated, and normal plots used to identify factors in which the change in level setting lead to a statistically significant shift in either the plane location or orientation response mean. Table 5.4 provides a summary of the significant factor effects, omitting columns in which no effects were deemed significant over all 4 planes.
| Run # | NP | AD | NPxAD | TD | ADxTD | CPA | SL | NPxSL | ADxSL | TDAxP | TDAxSL | ADxPA | NPxPA | PV | CF | NPxCF | ADxCF | TDAxCF | TDAxPA | ADxPA | NPxPA | SLxCF | PVxPA |
|------|----|----|-------|----|-------|-----|----|-------|-------|-------|-------|-------|-------|------|-----|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1    | 9  | 8  | +     | 1   | +     | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     | +     |
| 2    | 49 | 8   | - | 1 | +     | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 3    | 9   | 24  | - | 1 | +     | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 4    | 49 | 24 + | 1 | +   | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 5    | 9  | 8   | + | 3   | -   | -   | -    | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 6    | 49 | 8   | - | 3 | +     | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 7    | 9  | 24  | - | 3 | +     | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 8    | 49 | 24  | + | 3 | +     | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 9  | 9  | 8   | + | 1 | +     | +   | -   | 30    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 10 | 49 | 8   | - | 1 | +     | +   | -   | 30    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 11 | 9   | 24  | - | 1 | +     | +   | -   | 30    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 12 | 49 | 24  | + | 1 | -     | -   | +   | 30    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 13 | 9   | 8   | + | 3 | -     | -   | +   | 30    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 14 | 49 | 8   | - | 3 | +     | +   | -   | 30    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 15 | 9   | 24  | - | 3 | +     | +   | -   | 30    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 16 | 49 | 24  | + | 3 | +     | +   | -   | 30    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 17 | 9   | 8   | + | 1 | +     | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 18 | 49 | 8   | - | 1 | +     | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 19 | 9   | 24  | - | 1 | +     | +   | -   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 20 | 49 | 24  | + | 1 | -     | -   | +   | 10    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 21 | 9   | 8   | + | 3 | -     | -   | +   | 10    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 22 | 49 | 8   | - | 3 | +     | +   | -   | 10    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 23 | 9   | 24  | - | 3 | +     | +   | -   | 10    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 24 | 49 | 24  | + | 3 | +     | +   | -   | 10    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 25 | 9   | 8   | + | 1 | +     | +   | -   | 30    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 26 | 49 | 8   | - | 1 | +     | +   | -   | 30    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 27 | 9   | 24  | - | 1 | +     | +   | -   | 30    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 28 | 49 | 24  | + | 1 | -     | -   | +   | 30    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 29 | 9   | 8   | + | 3 | -     | -   | +   | 30    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 30 | 49 | 8   | - | 3 | +     | +   | -   | 30    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 31 | 9   | 24  | - | 3 | +     | +   | -   | 30    | -     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |
| 32 | 49 | 24  | + | 3 | +     | +   | -   | 30    | +     | +     | +     | +     | -     | -    | -    | 100  | 2    | +     | +     | +     | +     | +     | +     | +     |

**Figure 5.13:** L₉² orthogonal array used in studying location and orientation effects of CMM measurement settings.
Table 5.4: Summary of Significant Factor Main Effects on Plane Location and Orientation from L_{27} Experiment

<table>
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<tr>
<th>PLANE</th>
<th>Measured Response</th>
<th>NP (mm)</th>
<th>AD (mm)</th>
<th>TD (mm)</th>
<th>SL (mm)</th>
<th>NP×FV</th>
<th>PV (% max)</th>
<th>CF (% max)</th>
<th>AD×CF</th>
<th>NP×PA</th>
<th>SL×CF</th>
<th>CF×FV</th>
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</table>

- **Strong Effects**
- **Weak Effects**
All of the factors studied, demonstrated some significance and resolvability with respect to the resulting least squares plane location and orientation, except for probe acceleration. Contact force had the strongest and most consistent impact across the four planes. Probe tip diameter and stylus length consistently yielded strong location affects with only marginal influence on orientation. The number of sample points also had a strong affect on both location and orientation for all planes except for the lapped aluminum plane, which is consistent with the results of Table 5.3. Approach distance and probe velocity generated the weakest and least frequent effects among the six factors. The probe velocity effect was really only significant for the stamped plane, which can be explained by the fact that the plane exhibited bending during data collection, also the reason that contact force was such a dominate factor for this plane. Of the large number of possible interactions, only 6 produced regular effects, which were weak. In all cases, the interaction effects were associated with either contact force or sample size, among the strongest of the factor effects.

5.5.3: Factors Affecting the Location and Orientation Variability of Planes Generated by Least Squares Fitting to Uniformly Distributed CMM Data

An important consideration governing the reproducibility of a prediction equation developed from the factor effects discussed in Section 5.5.1, is the robustness of the chosen measurement setting configuration. In general, by conducting an orthogonal array experiment in the presence of minimum and maximum noise conditions, the standard deviation of the overall response data can be used to identify factor level settings that are more robust to the noise. From the point of view of CMM data collection, the differing characteristics of manufactured planes may be viewed as noise factors that induce variability in the measured location and orientation responses. By using two planes, one of low and one of high form error, minimum and maximum measurement noise levels can be defined, and a robustness study undertaken.

In collecting the L_{32} experimental data of Section 5.5.1.2, the planes involved were chosen with the secondary aim of defining 3 variability studies, in addition to evaluating main factor effects. In each study, the lapped aluminum plane would represent the low noise condition, while the other planes would correspond to three forms of high noise conditions. Figure 5.14 shows the corresponding lapped aluminum / cast aluminum #2 noise study array, which is indicative of all three cases.
<table>
<thead>
<tr>
<th>Run #</th>
<th>NP</th>
<th>AD</th>
<th>TD</th>
<th>SL</th>
<th>PV</th>
<th>CF</th>
<th>PA</th>
<th>N1 Ave</th>
<th>N2 Ave</th>
<th>Response Ave.</th>
<th>Response σ</th>
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<td>3.8</td>
<td>0.1</td>
<td>8.9</td>
<td>67.2</td>
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</table>

**Figure 5.14:** L\(_{32}\) orthogonal array for the lapped aluminum (N1) / cast aluminum #2 (N2) noise study.
A necessary pre-condition for a valid variability study, however, is a clear separation of the response means of the planes individually, induced by the differing noise conditions. The individual response means and standard deviations associated with the \(L_{32}\) experimental data for the planes are provided in Table 5.5. From the table, the location and orientation response means do not show sufficient separation since the high standard deviation values result in an overlap of the normal sampling distributions of any two planes within the first standard deviation.

**Table 5.5: Location and Orientation Response Data from \(L_{32}\) Experiment of Sect. 5.5.1.2**

<table>
<thead>
<tr>
<th>Plane</th>
<th>Change in Location ((\mu m))</th>
<th>Change in Orientation ((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>Lapped Aluminum</td>
<td>5.9</td>
<td>4.4</td>
</tr>
<tr>
<td>Milled Aluminum #2</td>
<td>7.6</td>
<td>5.1</td>
</tr>
<tr>
<td>Stamped Sheet Steel #1</td>
<td>8.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Cast Aluminum #2</td>
<td>8.7</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Examining the data of Figure 5.14 reveals why the variance is so large. One reason for location variability is that a new probe qualification was required for each group of four runs, which are separated by alternating shaded and non-shaded regions in the figure. This results in an alignment error when combining the data from the various groups. Clearly, the mean location for each group of four runs shows a significant trend from group to group. Since tip qualification depends on generating a least squares sphere from CMM sampled data, many of the factors that dictate this misalignment are the same as those for planes. In future work, this issue may be handled in several ways. First, hold the contact force constant, since it is rarely varied during part measurement, and has a large effect on location. Second, monitor the fit center of the gauge for each qualification, and compensate for any resulting location uncertainty. Finally, use simulation, which alleviates the problem entirely. In this case, the challenge is to devise an analytical model of the prove system which accurately reflects its behavior with respect to the factors under study. In retrospect, this method significantly reduces experimentation time, and provides greater flexibility in defining part form error.
5.6: PREDICTION EQUATION IDEOLOGY

The results of the main effect screening studies of Section 5.5.1 indicate that the following factors are significant, in varied degrees and with dependence on form error topology, in affecting the location and orientation uncertainty of least squares planes generated from uniformly distributed CMM data:

- area of coverage;
- sample size;
- approach distance;
- tip diameter;
- stylus length;
- probe velocity; and
- contact force;

Further, the effects can be resolved using design of experiments techniques.

It might be possible to develop a complex model that predicts the appropriate sample size corresponding to a given level of location and orientation uncertainty from the combination of measurement settings, manufacturing process parameters, part/material characteristics, and so on. This would be a daunting task, whose magnitude prohibits venture. Moreover, in reverse engineering applications, information on part feature manufacture is generally limited to visual evidence. This is typically sufficient only to identify the process, which precludes the use of such a model for lack of information.

A more pragmatic approach is to assume similar topologies for the resultant form errors of individual manufacturing processes, under the range of process parameters, and develop separate prediction equations that average the contributions of the measurement control factors, sample size, and area ratio, on the level of location and orientation uncertainty. In doing so, the measured plane flatness would also be a factor, used to indicate the magnitude of the form error. With this in mind, a relationship similar to that of Equation 5.1 is envisioned. Note that the contact force has been excluded from contention since it is very rare for this setting to change.

\[
\zeta = A_{FL}(L_{FL}) + A_{AR}(L_{AR}) + A_{NP}(L_{NP}) + A_{AD}(L_{AD}) + A_{TD}(L_{TD}) + A_{SL}(L_{SL}) + A_{PV}(L_{PV}) + A_{PO}(L_{PO}) \tag{5.1}
\]

where: \(\zeta\) are the uncertainties in the plane location or orientation;
\(L_i\) are the polynomial vectors of the various factors levels; and
\(A_i\) are coefficient vectors.
Given such a relationship for a number of manufacturing processes, the process of interest, a pre-defined accuracy level, and the plane flatness value, determined dynamically during measurement, the corresponding sample size can be calculated. Using this information the framework for the NP Prediction Procedure, part of the Intelligent Plane Sampling Approach of Figure 5.9, is described in Figure 5.15.

![Diagram](image)

**Figure 5.15:** Generic NP Prediction Procedure flow diagram.

### 5.7: DISCUSSION

A methodology for reducing the location and orientation uncertainty of least squares planes, generated from uniformly distributed CMM sampling patterns, is proposed in this chapter for reverse engineering applications. Based on the ability to resolve significant measurement control factor effects using design of experiments techniques, the development of an equation that predicts the required sample size for a given manufacturing process and specified uncertainty level, seems feasible.

To further develop the methodology, a strategy must be devised to rigorously explore the factor effects on controlled groups of planes from a number of manufacturing processes. To be effective, each group of planes must encompass the typical range of production parameters encountered for the respective process. This
phase will require considerable planning and designed experimentation to assess the significance of the change in form error, due to varying the process parameters, on the location and orientation responses.

Once the control groups of planes have been specified, a designed experiment relating the measurement control factors and group of planes to location and orientation uncertainty must be devised. Since the purpose is to develop a prediction relationship, for use in the NP prediction procedure of Figure 5.16, the number of levels for many of the factors will need to be increased. From experimental results in this chapter, some forecasts for the number of levels for each factor are provided in Table 5.6. The ultimate deliverable must be the overall process definition, specific orthogonal arrays, and groups of manufactured primitives required to develop the relationships on any CMM with kinematic touch trigger probe.

**Table 5.6:** Forecasted Number of Levels Required for Factors in Development of a Relationship for use in the NP Prediction Procedure

<table>
<thead>
<tr>
<th>Factor</th>
<th>Forecasted Number of Levels</th>
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</thead>
<tbody>
<tr>
<td>FL</td>
<td>1 for each plane in specified control group.</td>
</tr>
<tr>
<td>AR</td>
<td>To be determined during control group specification.</td>
</tr>
<tr>
<td>NP</td>
<td>10 (cover range of 2x2 through 11x11)</td>
</tr>
<tr>
<td>AD</td>
<td>3 (8 mm, 16 mm, 24 mm)</td>
</tr>
<tr>
<td>TD</td>
<td>3 (1 mm, 3 mm, 5 mm)</td>
</tr>
<tr>
<td>SL</td>
<td>3 (10 mm, 30 mm, 50 mm)</td>
</tr>
<tr>
<td>PV</td>
<td>3 (40%, 70%, 100% of machine maximum)</td>
</tr>
<tr>
<td>PO</td>
<td>To be determined through independent factor study.</td>
</tr>
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</table>
CHAPTER 6 – UNCERTAINTIES IN LASER SCANNING DATA COLLECTION

6.0: OBJECTIVES

While a relatively significant amount of research work has focused on characterizing CMM measurement uncertainty (see Section 1.4), very little has considered uncertainty propagation as related to laser scanned data. Reasons for this may include the large number of unique implementations of the technology, the relative newness of the technology, or the limited use of laser scanning in precision work. Regardless, a description and understanding of the major process uncertainties for a particular technology can be instrumental in developing methods to enhance its performance and widen its scope of application. This chapter is dedicated to the exploration of such uncertainties for the Hymarc Hyscan 45C laser scanner, and lays the foundation for the registration error compensation methodology of Chapter 7.

6.1: LASER SCANNING DIGITIZATION UNCERTAINTIES

This section identifies and quantifies a number of major uncertainties encountered during single view digitization using the Hymarc Hyscan 45C laser scanner. It does not consider uncertainties associated with the CMM, which have been dealt with in detail by many authors, as discussed in Section 1.4.

6.1.1: Uncertainty as a Function of Ranging Distance

The change in location of laser scan data was assessed as the distance between the camera and the target object, the ranging distance, was increased. Beginning at the top of the scanner Field of View (FOV), the alignment plate was repeatedly scanned, increasing the ranging distance in 2mm steps between successive scans, until the bottom was reached. A total of 56mm was traversed. A least squares plane was generated from the data of each scan. The change in location of the Z-component of each fitted plane, relative to that of the initial ranging position, was determined, and is plotted in Figure 6.1. The results show that significant uncertainty in the scan data location exists with variation in the ranging distance.

6.1.2: Uncertainty as a Function of Time

The digitization uncertainty in the laser scan data capture may increase with time, due primarily to charge buildup on the laser scanner CCD detector array, and
thermal effects. An assessment of this effect was made by digitizing the alignment plate, at a constant ranging distance, over a 2.5 hour time period. The root mean square (RMS) error, and change in location, of the resulting least squares planes generated from the data acquired at each time interval was determined. These are plotted in Figure 6.2. The magnitudes of the resulting trends are too small to represent significant sources of uncertainty.

**Figure 6.1:** Plane Location as Function of FOV Position

**Figure 6.2:** Fit Plane RMS and Location vs. Time
6.1.3: Uncertainty as a Function of the Angle Between the Scanning Axis and Object Surface Normal

It is well known that digitization uncertainties show a dependence on the angle between the scanning axis (z-axis of Figure 2.4) and the object surface normal [112] for many laser scanning technologies. However, due to large uncertainties in both view registration, and in generating substitute geometry from scan data, as discussed in Section 6.2, estimating the digitization uncertainty of the Hymarc Hyscan 45C as a function of this angle is not straightforward. In this study, the uncertainty trends associated with substitute geometry generation, discussed in Section 6.2, were used to estimate the digitization uncertainty associated with this angular misalignment.

From the results of Section 6.2, the location uncertainty vector associated with a least squares sphere fitted to the data of a symmetrically laser scanned physical sphere, is known to be approximately parallel with the scanning axis. With this in mind, a ceramic sphere, having an average radius of 19.056mm, based on the inspection data of Table 6.6, was symmetrically scanned twice. For each scanned data set, a least squares sphere was generated with a fixed radius of 19.056mm. Each fitted sphere was then translated, along the scanning axis, until its circumference was coincident with the scan data, in the region where the scanning axis and surface normal were closely aligned. In each case, a cross section was taken, through the sphere center, both parallel and perpendicular to the scanner FOV.

The distance deviations between the relocated sphere and scan data were recorded, within each section plane, as a function of absolute angle, measured with respect to the scanner axis. Since the ranging distance on the sphere surface changed in tandem with the angle between the surface normal and scanner axis, the distance deviation values were corrected using the trend established in Figure 6.1. The adjusted distance deviations are plotted in Figures 6.3 and 6.4, as a function of angle. The results are considered to be accurate to within 10μm.

Figure 6.3 shows a clear and significant increase in the digitization error, particularly when the angular misalignment within the scanner FOV exceeds 20°. As such, scan data collected on a curved surface has less curvature than does the object
surface. Meanwhile, no significant trend was revealed for the direction normal to the FOV, as is evident in Figure 6.4.

**Figure 6.3:** Digitization Error as a Function of Angle in Plane of Scanner FOV

![Graph showing digitization error as a function of angle in the plane of the scanner FOV.]

**Figure 6.4:** Digitization Error as a Function of Angle in Plane Normal to Scanner FOV

![Graph showing digitization error as a function of angle in the plane normal to the scanner FOV.]

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6.2: UNCERTAINTIES IN SUBSTITUTE GEOMETRY GENERATION FROM LASER SCAN DATA

In Chapter 4, it was established that the process errors in digitizing a part, associated with the Hymarc Hyscan 45C laser scanner, were approximately an order of magnitude greater than for the CMM. It was further hypothesized that a large contribution to the overall uncertainty results from the registration component, which depends primarily on the results of least squares fitting to data acquired on an alignment sphere. For this reason, as well as those described in Section 5.0, the uncertainty involved in generating geometric primitives is investigated here. Specifically, the variability in defining the location and orientation of least squares cylinders and spheres is compared using several laser scanning sampling strategies.

6.2.1: Uncertainty in Substitute Geometry Size, Location, and Orientation, as a Function of Scan Data Distribution

Scan data analyzed during this study was acquired from a 50mm diameter machined Renshape cylinder, and a 38.1mm diameter ceramic sphere. Four sampling strategies, as shown in Figures 6.5 (a) through (d), were used to vary the scan data distribution. These strategies are:

1. three registered views;
2. asymmetrical single view scanning;
3. symmetrical single view scanning;
4. single view axial scanning (FOV parallel with cylinder axis).

In the registered views strategy, three angular orientations (−90°, 0°, and 90°) of the laser scanner were employed in digitizing the artifacts, and three complete registered data sets were obtained. Each time the camera orientation was changed, the new view was aligned according to the procedures discussed in Section 2.0.2. For strategies 2 and 3, the plane of scanning symmetry coincided with the XZ plane of the CMM.

The cylinder was fixtured on the CMM with its axis parallel to the machine X-axis. For all data collection, the scanner was transported along the X-axis and incremented along the Y-axis. Scans were taken in steps between the positive and negative boundary positions (±Yb of Figure 6.6) of the center of the artifact.
Figure 6.5: Laser scan data sampling distributions used in studying the uncertainties in least squares cylinder size, location, and orientation.

Figure 6.6: Scanning configuration for symmetrical and asymmetrical strategies.
The vertical camera orientation was used for all data collection in strategies 2 and 3. The asymmetrical data is comprised of the given artifact scans at the various positions (steps) along the Y-axis. The symmetrical data sets were derived from these, by coupling the two scans at the same incremental position on either side of the plane of symmetry.

In making comparisons of size, the cylinder and sphere were sampled using the parametric CMM programs, discussed in Section 5.2. In the case of the cylinder, five 1488 point data sets were obtained. For the sphere, five 960 point data sets were obtained. In each case, the various fit radii were averaged, which was deemed representative of the actual cylinder. The individual values are recorded in Tables 6.2 and 6.6.

It should be noted that a common, exact, coordinate system does not exist between the CMM and the laser scanner. This makes a direct comparison of location and orientation, obtained using both digitizers, impossible. Thus, the laser scanning work is expressed in terms of relative size, location, and orientation from a common datum.

6.2.1.1: Experimental Results Obtained from Renshape Cylinder

Initially, the size, location, and orientation of least squares cylinders, generated from the data of three individual views (0° and ±90°), were compared with a similar cylinder, constructed from a composite of all three data sets. Table 6.1 provides the variation in size, location, and orientation of the cylinders. In all cases, the radius is expressed relative to the average CMM inspection value of Table 6.2.

Variation in fitted cylinder location is indicated by the displacement of the cylinder axes midpoints, while the change in orientation is indicated by the angle between respective axes. The former is expressed using the Y and Z-components of the Euclidean distance between midpoints, since the length of the fitted cylinders varied unavoidably with the scan data (marked by the change in the X coordinates of the midpoints). Given the relatively small change in angle between the various cylinder axes, the error in this approach reaches a maximum of approximately 1μm to 2μm.
Table 6.1: Variation in Location, Orientation, and Size of Cylinder Fit from Registered Views.

<table>
<thead>
<tr>
<th>View (Deg.)</th>
<th>Radius* (um)</th>
<th>Angle w X-Axis (Deg.)</th>
<th>Angle w Y-Axis (Deg.)</th>
<th>Angle w Z-Axis (Deg.)</th>
<th>X Coord. (um)</th>
<th>Y Coord. (um)</th>
<th>Z Coord. (um)</th>
<th>YZ Dist. (um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-90</td>
<td>534</td>
<td>-0.0049</td>
<td>0.0020</td>
<td>0.0050</td>
<td>1072</td>
<td>405</td>
<td>152</td>
<td>433</td>
</tr>
<tr>
<td>0</td>
<td>492</td>
<td>0.0006</td>
<td>-0.0077</td>
<td>0.0077</td>
<td>992</td>
<td>146</td>
<td>-356</td>
<td>385</td>
</tr>
<tr>
<td>90</td>
<td>544</td>
<td>-0.0083</td>
<td>0.0012</td>
<td>0.0110</td>
<td>-1012</td>
<td>-456</td>
<td>-49</td>
<td>459</td>
</tr>
<tr>
<td>All Reg.</td>
<td>140</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* Radius value relative to that of average CMM inspection value (25.008mm).

Table 6.2: CMM Inspection of Renshape Cylinder (1488 Points per Sample).

<table>
<thead>
<tr>
<th>Trial</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Ave. (um)</th>
</tr>
</thead>
</table>

The results obtained using the asymmetrical and symmetrical scanning strategies are provided in Tables 6.3 and 6.4, and are plotted in Figures 6.7 and 6.8. For these studies, the bounding data sets at the ±15mm step positions, ±Yb of Figure 6.6, were chosen as size and location datums. Where the single view scanning distribution is concerned, one data set was acquired. The radius of the cylinder fitted to
this data was 25.023mm, which shows much better correlation with the averaged CMM inspection value than any of the cylinders generated from the other three methods.

Table 6.3: Variation in Size, Location, and Orientation of Cylinder Fit from Asymmetrical Laser Scan Data

<table>
<thead>
<tr>
<th>Position (mm)</th>
<th>Radius* (µm)</th>
<th>Angle w X-Axis (Deg.)</th>
<th>Angle w Y-Axis (Deg.)</th>
<th>Angle w Z-Axis (Deg.)</th>
<th>X Coord. (µm)</th>
<th>Y Coord. (µm)</th>
<th>Z Coord. (µm)</th>
<th>YZ Dist. (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>-16</td>
<td>-0.0001</td>
<td>-0.0039</td>
<td>0.0027</td>
<td>-158</td>
<td>-47</td>
<td>13</td>
<td>49</td>
</tr>
<tr>
<td>9</td>
<td>-18</td>
<td>0.0143</td>
<td>-0.0259</td>
<td>0.0010</td>
<td>-880</td>
<td>-76</td>
<td>3</td>
<td>76</td>
</tr>
<tr>
<td>6</td>
<td>-13</td>
<td>0.0069</td>
<td>-0.0162</td>
<td>0.0028</td>
<td>-1421</td>
<td>-112</td>
<td>5</td>
<td>112</td>
</tr>
<tr>
<td>3</td>
<td>-1</td>
<td>-0.0003</td>
<td>-0.0061</td>
<td>0.0044</td>
<td>-749</td>
<td>-149</td>
<td>-5</td>
<td>149</td>
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<td>0</td>
<td>21</td>
<td>0.0016</td>
<td>-0.0052</td>
<td>0.0022</td>
<td>-233</td>
<td>-193</td>
<td>-26</td>
<td>194</td>
</tr>
<tr>
<td>-3</td>
<td>2</td>
<td>-0.0137</td>
<td>0.0216</td>
<td>0.0032</td>
<td>-725</td>
<td>-229</td>
<td>-6</td>
<td>229</td>
</tr>
<tr>
<td>-6</td>
<td>12</td>
<td>-0.0050</td>
<td>-0.0016</td>
<td>0.0070</td>
<td>-1465</td>
<td>-262</td>
<td>-18</td>
<td>262</td>
</tr>
<tr>
<td>-9</td>
<td>1</td>
<td>0.0198</td>
<td>-0.0316</td>
<td>-0.0015</td>
<td>-901</td>
<td>-297</td>
<td>-1</td>
<td>297</td>
</tr>
<tr>
<td>-12</td>
<td>1</td>
<td>0.0150</td>
<td>-0.0025</td>
<td>-0.0003</td>
<td>-63</td>
<td>-329</td>
<td>6</td>
<td>329</td>
</tr>
<tr>
<td>-15</td>
<td>13</td>
<td>0.0071</td>
<td>-0.0117</td>
<td>-0.0007</td>
<td>-745</td>
<td>-377</td>
<td>-22</td>
<td>378</td>
</tr>
</tbody>
</table>

* Radius value relative to that of cylinder fitted from data at ±15mm position (25.476mm).

Table 6.4: Variation in Size, Location, and Orientation of Cylinder Fit from Symmetrical Laser Scan Data.

<table>
<thead>
<tr>
<th>Position (mm)</th>
<th>Radius* (µm)</th>
<th>Angle w X-Axis (Deg.)</th>
<th>Angle w Y-Axis (Deg.)</th>
<th>Angle w Z-Axis (Deg.)</th>
<th>X Coord. (µm)</th>
<th>Y Coord. (µm)</th>
<th>Z Coord. (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>51</td>
<td>0.0037</td>
<td>-0.0083</td>
<td>0.0013</td>
<td>265</td>
<td>-5</td>
<td>-39</td>
</tr>
<tr>
<td>9</td>
<td>99</td>
<td>0.0158</td>
<td>-0.0235</td>
<td>-0.0023</td>
<td>-480</td>
<td>-6</td>
<td>-83</td>
</tr>
<tr>
<td>6</td>
<td>184</td>
<td>0.0035</td>
<td>-0.0068</td>
<td>0.0005</td>
<td>-1020</td>
<td>-8</td>
<td>-167</td>
</tr>
<tr>
<td>3</td>
<td>267</td>
<td>-0.0055</td>
<td>0.0102</td>
<td>0</td>
<td>-326</td>
<td>-12</td>
<td>-250</td>
</tr>
<tr>
<td>0</td>
<td>358</td>
<td>0.0012</td>
<td>-0.0015</td>
<td>-0.0004</td>
<td>190</td>
<td>-17</td>
<td>-345</td>
</tr>
</tbody>
</table>

* Radius value relative to that of cylinder fitted from data at ±15mm position (25.139mm).

6.2.1.2: Discussion of Results Obtained in the Cylinder Sampling Study

All cylinder sampling strategies, with the exception of the axial scanning strategy, show moderate to large deviations in fit radii when compared to the averaged CMM value of 25.008mm. The deviation ranges are (from Tables 6.1 to 6.4):

- three registered views: 97 to 140µm;
- single view asymmetrical scanning: 450 to 501µm;
- single view symmetrical scanning: 131 to 489µm;
- single view axial scanning: 15µm.
Figure 6.7: Cylinder Fit Parameter Variations for Asymmetrical Scanning

Figure 6.8: Cylinder Fit Parameter Variations for Symmetrical Scanning

The registered and single view scanning strategies generated relatively constant deviations in the fit radii, except in the case of symmetrical scanning. Here, the fit radius at the greatest separation (±15mm) was found to be 25.139mm, with the level of uncertainty in the radius estimate growing progressively as the position at 0mm was
approached (25.497mm). In addition, despite registration error, the three view
registered data set led to considerably less uncertainty in cylinder size than the single
view scanning approaches. This indicates that the reduction in curvature of the scan
data, as discussed in Section 6.1.3, plays a more significant role in driving size
uncertainty than does the total registration error.

Figures 6.7 and 6.8 demonstrate that the location of the resulting least squares
cylinder is highly dependent on scan symmetry, or lack thereof. In the case of
asymmetrical scanning, the large change in location of the axis midpoint, indicated by
the YZ coordinate distance in Figure 6.7, is accommodated primarily by the change in
the Y-component of the coordinate. Variation in the Z-component and radius value is
also observed, but to a lesser degree. However, for symmetrical scanning, the converse
is true. Both the Z-component and the radius value change in tandem, with very little
variation being displayed in the Y-component.

In comparison to all other strategies, single view axial scanning is clearly the
best where possible to implement. The significantly improved radius estimate reflects
the reduced impact on the digitization uncertainty that arises as the angle between the
object surface normal and scanning axis, in the plane perpendicular to the FOV,
increases (see Section 6.1.3). Moreover, this strategy is far less dependent on the
physical diameter of the cylinder than the other three.

The change in orientation of the fitted cylinders, while not plotted, is recorded in
Tables 6.1, 6.3, and 6.4 by Cartesian angular components. Deviations as high as 0.05°
are observed. However, they are of little significance when compared to size and
location deviations of several hundred micrometers.

6.2.1.3: Experimental Results Obtained from Ceramic Sphere

In a manner similar to that for the Renshape cylinder, scan data was collected
from the 38.1mm diameter ceramic sphere. The registered views, single view
asymmetrical, and single view symmetrical sampling strategies were studied. Table 6.5
describes the variation in size and location of the least squares spheres constructed
from the data of three individual views (0° and ±90°), in comparison to that generated
from the combined data of the three views. The radius values are expressed in relation
to the average CMM inspection value of Table 6.6, while the Euclidean distances between the center points of the respective fitted spheres indicate the location variation.

Table 6.5: Variation in Location and Size of Sphere Fit from Registered Views.

<table>
<thead>
<tr>
<th>View (Deg.)</th>
<th>Radius* (μm)</th>
<th>X Coord. (μm)</th>
<th>Y Coord. (μm)</th>
<th>Z Coord. (μm)</th>
<th>Dist. Bet. Centers (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-90</td>
<td>147</td>
<td>12</td>
<td>-86</td>
<td>-63</td>
<td>107</td>
</tr>
<tr>
<td>0</td>
<td>138</td>
<td>-1</td>
<td>28</td>
<td>-86</td>
<td>91</td>
</tr>
<tr>
<td>90</td>
<td>150</td>
<td>-11</td>
<td>78</td>
<td>110</td>
<td>135</td>
</tr>
<tr>
<td>All Reg.</td>
<td>80</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* Radius value relative to that of average CMM inspection value (19.056mm).

Table 6.2

<table>
<thead>
<tr>
<th>View (Deg.)</th>
<th>Radius* (μm)</th>
<th>X Coord. (μm)</th>
<th>Y Coord. (μm)</th>
<th>Z Coord. (μm)</th>
<th>Dist. Bet. Centers (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-90</td>
<td>88</td>
<td>-34</td>
<td>-14</td>
<td>163</td>
<td>167</td>
</tr>
<tr>
<td>0</td>
<td>149</td>
<td>8</td>
<td>53</td>
<td>-88</td>
<td>103</td>
</tr>
<tr>
<td>90</td>
<td>149</td>
<td>15</td>
<td>-101</td>
<td>-91</td>
<td>137</td>
</tr>
<tr>
<td>All Reg.</td>
<td>75</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>vs. 1</td>
<td>-4</td>
<td>7</td>
<td>12</td>
<td>-14</td>
<td>20</td>
</tr>
</tbody>
</table>

* Radius value relative to that of average CMM inspection value (19.056mm).

Table 6.3

<table>
<thead>
<tr>
<th>View (Deg.)</th>
<th>Radius* (μm)</th>
<th>X Coord. (μm)</th>
<th>Y Coord. (μm)</th>
<th>Z Coord. (μm)</th>
<th>Dist. Bet. Centers (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-90</td>
<td>168</td>
<td>-8</td>
<td>104</td>
<td>95</td>
<td>153</td>
</tr>
<tr>
<td>0</td>
<td>120</td>
<td>1</td>
<td>42</td>
<td>-91</td>
<td>86</td>
</tr>
<tr>
<td>90</td>
<td>113</td>
<td>5</td>
<td>-57</td>
<td>-68</td>
<td>76</td>
</tr>
<tr>
<td>All Reg.</td>
<td>72</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>vs. 1</td>
<td>-7</td>
<td>-6</td>
<td>-23</td>
<td>27</td>
<td>36</td>
</tr>
<tr>
<td>vs. 2</td>
<td>-3</td>
<td>-13</td>
<td>-34</td>
<td>41</td>
<td>55</td>
</tr>
</tbody>
</table>

* Radius value relative to that of average CMM inspection value (19.056mm).

Table 6.6: CMM Inspection of Ceramic Sphere (960 Points per Sample).

<table>
<thead>
<tr>
<th>Trial</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Ave. (μm)</th>
</tr>
</thead>
</table>

The results obtained from asymmetrical and symmetrical scanning are provided in Tables 6.7 and 6.8, and are plotted in Figures 6.9 and 6.10. For these studies, the
bounding data sets at the ±8mm step positions, ±Y₀ of Figure 6.6, were chosen as datums for both location and size.

**Table 6.7:** Variation in Size and Location of Cylinder Fit from Asymmetrical Laser Scan Data

<table>
<thead>
<tr>
<th>Position (mm)</th>
<th>Radius* (μm)</th>
<th>X Coord. (μm)</th>
<th>Y Coord. (μm)</th>
<th>Z Coord. (μm)</th>
<th>YZ Dist. (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>14</td>
<td>0</td>
<td>5</td>
<td>-16</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>-1</td>
<td>12</td>
<td>-33</td>
<td>35</td>
</tr>
<tr>
<td>2</td>
<td>45</td>
<td>-1</td>
<td>23</td>
<td>-52</td>
<td>56</td>
</tr>
<tr>
<td>0</td>
<td>50</td>
<td>-2</td>
<td>43</td>
<td>-56</td>
<td>71</td>
</tr>
<tr>
<td>-2</td>
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<td>-58</td>
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<td>-4</td>
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<tr>
<td>-10</td>
<td>1</td>
<td>-3</td>
<td>101</td>
<td>-1</td>
<td>101</td>
</tr>
</tbody>
</table>

*Radius value relative to that of sphere fitted from data at ±8mm position (19.125mm).

**Table 6.8:** Variation in Size and Location of Cylinder Fit from Symmetrical Laser Scan Data

<table>
<thead>
<tr>
<th>Position (mm)</th>
<th>Radius* (μm)</th>
<th>X Coord. (μm)</th>
<th>Y Coord. (μm)</th>
<th>Z Coord. (μm)</th>
<th>Dist. Bet. Centers (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>25</td>
<td>0</td>
<td>-2</td>
<td>-27</td>
<td>27</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>-1</td>
<td>-6</td>
<td>-54</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>64</td>
<td>-1</td>
<td>-12</td>
<td>-72</td>
<td>73</td>
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<tr>
<td>0</td>
<td>66</td>
<td>0</td>
<td>-14</td>
<td>-75</td>
<td>76</td>
</tr>
</tbody>
</table>

*Radius value relative to that of sphere fitted from data at ±8mm position (19.109mm).
**Figure 6.9:** Sphere Fit Parameter Variations for Asymmetrical Scanning

**Figure 6.10:** Cylinder Fit Parameter Variations for Symmetrical Scanning
6.2.1.4: Discussion of Results Obtained in the Sphere Sampling Study

All sphere sampling strategies also show moderate to large deviations in fit radii when compared to the averaged CMM value (19.056mm). However, the magnitudes are considerably less than those for the cylinder. The fitted sphere radius value deviation ranges are:

- three registered views: 72 to 80μm;
- single view asymmetrical scanning: 69 to 119μm;
- single view symmetrical scanning: 53 to 119μm.

As with the cylinder, the fully registered point cloud provides a better estimate of the true radius than the asymmetrical single view strategies. Further, the symmetrical sampling shows an increasing level of uncertainty on progression from the boundary data sets to the central data sets (19.109mm to 19.175mm).

Figures 6.9 and 6.10 demonstrate that the sphere location has a high dependence on scan symmetry. Both the Z-component and radius show significant variation in the asymmetrical case. In fact, the location deviation from the reference (8mm in Figure 6.9) is dominated by the Z-component until a scanner position at approximately 0mm is reached, at which point the Y-component supercedes. Additionally, the radius value mirrors the Z-component behavior closely, but with the opposite sign.

For the symmetrical scanning case, although the plots have a slightly different shape, similar behavior with the cylinder is evident. Of greatest importance is the manner in which the increase in fitted sphere radius matches the magnitude of the change in the Z-component, which dictates the change in sphere location in general. This indicates that the direction vector, defining the sphere location uncertainty for a perfectly symmetrical scan from the 0° orientation, is parallel with the scanner axis (Z-axis), and is predictable.
6.3: DISCUSSION

The experimental work detailed in Section 6.1 has provided a first order quantification of major digitization errors associated with the Hymarc Hyscan 45C laser scanner. Based on these results, the errors as a function of ranging distance and of angle between the scanner axis and part surface normal, were deemed significant. The trends describing their respective behaviors are shown in Figures 6.1 and 6.3.

In Section 6.2, the affect of varying sample point distribution, and hence the interaction between the digitization error function and part geometry, was shown to significantly impact the size and location of least squares primitives fitted from laser scan data. The associated trends are provided by Figures 6.7 through 6.10.

The results of this chapter present several methods for reducing overall data set error. Firstly, maintain a constant ranging distance when scanning a part, which minimizes the relative digitization error. Secondly, choose appropriate viewing angles in order to maintain the camera perpendicular to part surfaces. In practice, this will not always be possible. Here, data trimming and segmentation can be used to augment the approach. Finally, use the symmetrical behavior of the size and location trends in generating fitted spheres, to better predict the true location of a scanned sphere. This latter approach, aimed at reducing the registration error in combining CMM and laser scanned data, is examined in Chapter 7.
CHAPTER 7 – REGISTRATION ERROR QUANTIFICATION AND COMPENSATION

7.0: OBJECTIVES

The results of the sphere location uncertainty study, most notably Figures 6.9 and 6.10, indicate that it is possible to predict the true location of a least squares sphere, generated from laser scanned data, with greater certainty than is provided by fitting to scan data alone. Since the view registration procedure of the Hymarc Hyscan 45C laser scanning system uses a well calibrated sphere to establish a common datum, and since spheres can be scanned equivalently from all camera orientations, the ability to more accurately predict the true sphere location directly impacts the systematic registration accuracy. The primary focus of this chapter is to quantify the overall registration error for the Hyscan 45C, develop a compensation methodology based on the sphere sampling results of Section 6.2, and illustrate the impact of this methodology in reducing the systematic error in registering multiple views.

7.1: SYSTEMATIC REGISTRATION ERROR CHARACTERIZATION

7.1.1: Measurement of Laser Scanner Calibration Plate Width from Scan Data

In an initial study of the laser scanner registration performance, the thickness of the alignment plate, a well calibrated artifact upon which digitization error is minimized, was measured three times using both laser scan and CMM data. Systematic registration procedures were employed for the two required views, at 180° to one another. In determining the plate thickness the average distance between least squares planes, generated from data taken on each side, was used. The difference in plate thickness values obtained is provided in Table 7.1.

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Laser Scanner Width – CMM Width (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+156</td>
</tr>
<tr>
<td>2</td>
<td>+138</td>
</tr>
<tr>
<td>3</td>
<td>+153</td>
</tr>
<tr>
<td>Average</td>
<td>+149</td>
</tr>
</tbody>
</table>

Table 7.1: Comparision of Measured Alignment Plate Thickness using CMM and Laser Scan Data
Typically, a least squares plane generated from scan data taken on either side of the alignment plate will yield RMS distance deviations of approximately 8μm. Thus, the bulk of the error in measuring the alignment plate width is attributed to registration error.

7.1.2: Registration Error Estimation using an Evaluation Artifact

In studying the stamped automotive bracket of Chapter 4, it was hypothesized that, due to the primarily planar part surfaces, registration error was a major contributor to the total error of the resultant point cloud in representing the part. In seeking a more refined estimate, the artifact of Figure 7.1 was used to characterize the registration performance of the Hymarc Hyscan 45C. This registration evaluation artifact was manufactured from Renshape, with five machine ground surfaces separated by 45° at adjoining edges.

![Figure 7.1: Registration evaluation artifact.](image)

The registration artifact was positioned on the CMM table, in direct proximity to the laser scanner alignment sphere. A reverse engineered CAD surface model, representing the artifact, was created from a dense set of CMM data obtained from the artifact surfaces. Three complete laser scan data sets were also collected from the artifact. Each of these was comprised of data taken from five viewing angles (±90°, ±45°, and 0°), normal to the respective part surfaces. A constant ranging distance was maintained, and the alignment sphere symmetrically scanned while collecting the data, both provisions being a consequence of the digitization uncertainty results of Chapter 6.
The views were then registered using systematic procedures, forming one complete scan cloud of the artifact. Further, the data obtained from each of the camera orientations was trimmed to the width of the respective surface, eliminating off-normal digitization error. Another consequence of the Chapter 6 results.

Once registered, the complete point clouds were least squares fitted to the surface model of the registration evaluation artifact. Specifically, the Imageware Surfacer 8.0 direct registration algorithm was employed. Figure 7.2 provides a typical distance deviation whisker plot, as obtained for one of the three point clouds after fitting. Table 7.2 compares the resulting distance deviation information for all three data sets.

![Image](image_url)

**Figure 7.2:** Distance deviation plot comparing uncompensated data set to CAD model of the registration evaluation artifact.

**Table 7.2:** Average Distance Deviation Results for Uncompensated Data Sets

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Average Linear Distance (µm)</th>
<th>RMS Distance (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.8</td>
<td>50.5</td>
</tr>
<tr>
<td>2</td>
<td>43.2</td>
<td>54.8</td>
</tr>
<tr>
<td>3</td>
<td>46.4</td>
<td>59.2</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>43.8</strong></td>
<td><strong>54.8</strong></td>
</tr>
</tbody>
</table>
7.2: ARTIFACT-BASED REGISTRATION ERROR COMPENSATION

7.2.1: Registration Error Compensation Methodology

An understanding of the uncertainty behavior in generating substitute geometry from laser scan data of the Hymarc Hyscan 45C was integral in developing a registration error compensation methodology. The compensation scheme is based on two main principles:

1. Minimizing the uncertainty in the relative location of scan data obtained from each individual view.
2. Providing a better estimate of the relative location of view datum artifacts, namely spheres, than is provided by least squares fitting alone.

In the former case, major considerations involve:

1. Maintaining a constant ranging distance for all target objects.
2. Keeping the angle between the scanner axis and surface normal to a minimum.
3. Scanning view datum artifacts using similar coverage areas.

The main idea in improving the estimate of the datum sphere location is derived from the symmetrical deviation trends of Figures 6.9 and 6.10. From the plots, it may be inferred that, for a perfectly symmetrical single view scan of a precisely manufactured sphere, the sphere center uncertainty vector lies along the scanner axis. Additionally, Section 6.1.3 has shown that, in scanning a sphere, the rise in digitization error with the angle between the scanner axis and object surface normal, generates a scan data set displaying less curvature than does the physical sphere. Fitting then produces a least squares sphere of larger size, the magnitude of which depends on the radius of the physical sphere, which causes a large uncertainty in sphere location. As an illustration of the radial dependence, Table 7.3 compares the difference in least squares and physical sphere radii for both the ceramic sphere, studied in Chapter 6, and the laser scanner alignment sphere, which is the systematic registration artifact.

In the region on the sphere surface where the angle between the scanning axis and surface normal is small, the digitization uncertainty is at a minimum. If the circumference of the least squares sphere was coincident with the scan data in this region, the uncertainty in sphere location would be approximated by the difference between the fitted and true sphere radii. However, as is evident from Figure 7.3, the
minimization of the RMS distance between a fitted sphere and scan data causes the surface to lie above the data from this region of low digitization uncertainty.

**Table 7.3:** Comparison of Fit Sphere Radii for Symmetrical Laser Scan and CMM Data

<table>
<thead>
<tr>
<th>Trial</th>
<th>Diameter from Laser Scan Data (mm)</th>
<th>Diameter from CMM Data (mm)</th>
<th>Difference (Laser – CMM) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alignment Sphere</td>
<td>Ceramic Sphere</td>
<td>Alignment Sphere</td>
</tr>
<tr>
<td>1</td>
<td>38.221</td>
<td>19.176</td>
<td>38.128</td>
</tr>
<tr>
<td>2</td>
<td>38.225</td>
<td>19.178</td>
<td>38.125</td>
</tr>
<tr>
<td>3</td>
<td>38.223</td>
<td>19.172</td>
<td>38.125</td>
</tr>
</tbody>
</table>

**Figure 7.3:** Distance deviations of laser scan data to fitted sphere.

The location uncertainty resulting from a least squares fit to the data of a symmetrically laser scanned sphere, can be estimated as an offset along the scanning axis. The magnitude of this offset is approximately equal to the sphere fit radius minus both the physical radius, and the degree of circumferential non-coincidence in the region of low digitization uncertainty, as shown in Figure 7.4. This mechanism, as illustrated in Figure 7.4, is a significant contributor to the systematic registration error of the Hymarc Hyscan 45C laser scanner, and is compounded by asymmetrical scanning of the registration sphere. However, for the symmetrical case, its effects are predictable, and a calibration for a given registration artifact can be made in compensating for its effects.
Figure 7.4: Uncertainty in sphere location arising from least squares fit to symmetrical laser scan data.

The predicted offset value was compared to measured results, to judge the validity of this uncertainty model, and to estimate the required offset value in the case of the laser scanner alignment sphere. In the case of the measured offset value, the distance between the laser alignment sphere and the calibration plate, positioned directly beneath it, was determined using both CMM and laser scanning data. The difference in distances was taken as the measured offset value, assuming minimal digitization uncertainty with respect to the calibration plate. In arriving at the predicted value, the circumferential separation was determined by considering only the scan data in the immediate vicinity (point P of Figure 7.4). Three trials were used, with the results being provided in Table 7.4.

The methodology was applied to the data sets collected from the registration evaluation artifact since good correlation between the measured and predicted offset values was found.
Table 7.4: Registration Compensation Offset Value Estimation and Comparison

<table>
<thead>
<tr>
<th>Trial</th>
<th>Measured Offset Value (µm)</th>
<th>Sphere Fit Diameter (mm)</th>
<th>Separation at Circumference (µm)</th>
<th>Predicted Offset Value (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>79</td>
<td>38.221</td>
<td>21</td>
<td>75</td>
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<tr>
<td>2</td>
<td>80</td>
<td>38.223</td>
<td>24</td>
<td>74</td>
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<tr>
<td>3</td>
<td>75</td>
<td>38.225</td>
<td>22</td>
<td>78</td>
</tr>
<tr>
<td>Ave.</td>
<td><strong>78</strong></td>
<td><strong>-----</strong></td>
<td><strong>-----</strong></td>
<td><strong>75</strong></td>
</tr>
</tbody>
</table>

7.2.2: Registration Error Compensation Results

The views comprising the three complete data sets studied in Section 7.2.2 were offset along the scanning axis, corresponding to their particular orientation, by the average predicted offset value from Table 7.4. The resulting compensated data sets were then compared to the CAD model of the registration evaluation artifact in the same manner as the uncompensated data sets discussed in Section 7.2.2. Figure 7.5 provides a deviation whisker plot for one of the compensated data sets, equivalent to that of Figure 7.3, which was based on systematic registration procedures. Table 7.5 compares the resulting distance deviation information for all three compensated data sets, as well as the uncompensated data sets.

![Figure 7.5: Distance deviation plot comparing compensated data set to CAD model of the registration evaluation artifact.](image)
The results show that the average decrease in the linear distance deviations of the scan data, with respect to the registration artifact surface model, was 74%, specifically a drop from 43.8\(\mu m\) to 11.3\(\mu m\). Since the same view data was used in both the compensated and uncompensated cases, and the digitization error was held to a minimum, the difference is attributed entirely to an improvement in registration performance.

\textbf{Table 7.5: Average Distance Deviation Results for Compensated and Uncompensated Data Sets}

<table>
<thead>
<tr>
<th>Trial #</th>
<th>Average Linear Distance ((\mu m))</th>
<th>RMS Distance ((\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41.8</td>
<td>11.6</td>
</tr>
<tr>
<td>2</td>
<td>43.2</td>
<td>9.8</td>
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<tr>
<td>3</td>
<td>46.4</td>
<td>12.5</td>
</tr>
<tr>
<td>Average</td>
<td>43.8</td>
<td>11.3</td>
</tr>
<tr>
<td>Improvement</td>
<td>-----</td>
<td>74%</td>
</tr>
</tbody>
</table>

7.3: DISCUSSION

The trends established in the study on generating substitute geometry from laser scan data, specifically Section 6.2, were employed in developing the registration error compensation methodology, for the Hymarc Hyscan 45C laser scanner, discussed in this chapter. For the registration evaluation artifact, this methodology led to a 74% decrease, on average, in the linear distance deviations of the scan data with respect to the surface model of the artifact. In addition to this compensation technique, minimizing the total data set error requires maintaining a constant ranging distance, and selecting viewing angles in which the camera is perpendicular to the part surfaces as much as possible. These provisions stem from the ranging distance and angular error trends of Figures 6.1 and 6.3, respectively.

The error compensation methodology does not explicitly consider angularity errors between the various camera views. This is primarily because the small amount of machine working volume used in the study did not lead to appreciably magnified effects. For machines of larger working volume, the compensation technique may be applied to a set of three or more datum spheres, which constrain all degrees of freedom between the views. These spheres may also be attached to the part surfaces to allow
movement of the part in cases where it is larger than the working volume, or must be
turned over for data capture on the bottom. The automotive fender of Chapter 3 is an
example of when this might be necessary. In any case, care must be exhibited in
locating the spheres so that the scanner can navigate between them, and scan all
relevant part and datum sphere surfaces.
CHAPTER 8 – DISCUSSION, CONCLUSIONS, AND FUTURE WORK

8.0: SUMMARY OF RESULTS

The literature survey discussed a number of research areas relevant to CMM and laser scanning data collection. Among these are:

- methods of high-speed digitization;
- applications for high-speed digitization technologies;
- factors involved with CMM measurement uncertainty;
- uncertainties involved with CMM sampling and the generation of fitted primitives;
- techniques for CMM data collection on free-form surfaces; and
- approaches to the registration of data sets acquired from multiple scanning views.

The work of Chapters 3 through 7 aimed at bridging gaps in the body of CMM and laser scanning research knowledge, with emphasis on factors critical to developing a reverse engineering system that combines both data types.

In Chapter 3, the strengths and weaknesses of using CMM and laser scanning in the reverse engineering process were shown to be the opposite of one another. This justifies combining both types of data in addressing a wider range of applications, and allowing greater flexibility in engineering data set characteristics. In addition, a number of crucial issues affecting the reverse engineering decision-making process arose during the case studies. These include the:

- reduction in machine working volume due to the laser scanner stand-off distance;
- importance of data collection strategy relative to the chosen digitization method;
- significance of data density to visualization during CAD model construction; and
- opportunities presented by part symmetry in reducing process time and preserving design intent / function.

A comparison of the digitization error magnitudes for the CMM and laser scanner was made in Chapter 4, complementing the qualitative results of Chapter 3. From the automotive BIW bracket study, the average CMM overall data set error was found to be 7µm, compared with 69µm for the laser scanner. In work with the computer mouse, the digitization error for a number of CMM reverse engineering techniques was found to be less than 4µm, while the single view laser scanning digitization error was estimated at 12µm on average. This latter finding was much lower
than the previous 69μm value, indicating that registration error is a major component of the overall laser scanned data set errors for the BIW bracket. Finally, the combined approach taken in generating a normal approximating surface from laser scanned data, followed by CMM inspection of the surface, yielded an average error of 4.7μm. This result is only marginally less accurate than purely CMM-based techniques, and strengthens the justification for generating unified data sets.

For combined data sets, the total registration error is dictated by the uncertainties in determining the location and orientation of prismatic artifacts relative to the part, from the CMM and laser scanned data. Chapter 5 presents a new approach to controlling these uncertainties in CMM data collection. The basic idea involves using design of experiments techniques to develop relationships which, given the manufacturing process, maximum sample size, and desired level of accuracy, predict the required sample size for digitizing the artifact. Fractional factorial experiments were conducted to assess the approach. Based on the ability to resolve significant measurement control factor effects, the development of such relationships was deemed feasible. However, considerable future work is needed. The ultimate deliverable must be the overall process definition, specific orthogonal arrays, and groups of manufactured primitives required to develop the relationships on any CMM with kinematic touch trigger probe.

The uncertainties in laser scanning data collection, and in the size, location, and orientation of least squares primitives, were gauged in Chapter 6. Ranging distance variation and the increase in the angle between the scanner axis and surface normal, in the scanner field of view, yielded significant data collection errors. Trends describing their respective behaviors are provided in Figures 6.1 and 6.3. Moreover, the interaction of these errors with part geometry in the sampling of geometric primitives induced significant uncertainty in determining their size and location. This is clearly shown in Figures 6.7 to 6.10. These results explain the high levels of registration error, inferred from the studies of Chapter 4, and provide opportunities for reducing overall data set error by minimizing or compensating for their effects.

Finally, in Chapter 7, the multiple view registration performance of the Hymarc Hyscan 45C laser scanner was assessed, using an artifact comprised of planar surfaces.
An offsetting error compensation scheme was then developed, based on the uncertainty trends established in Chapter 6, which more accurately predicts the true location of view datum spheres. For the artifact under study, a 74% decrease in overall data set error resulted, in comparison to the uncompensated result, as noted in Table 7.5. This is a key element in reducing the error in combining CMM and laser scanned data.

8.1: INTEGRATED REVERSE ENGINEERING SYSTEM FRAMEWORK

A properly engineered system is significantly more than the sum of its individual parts. While the methods and techniques of Chapters 3 through 7 have individual merit, the real value is in their cumulative contribution towards the development of a reverse engineering system, capable of the precise generation of unified CMM and laser scanned data sets. Such a system will exploit the contrasting strengths and weaknesses inherent to both data collection methods, provide flexibility in dictating resultant point cloud characteristics, and expand the range of applications beyond that of the individual technologies. Having bridged some gaps in the body of research knowledge to date, the work herein strengthens the framework for an integrated system that combines both CMM and laser scanning data collection. Conceptually, such a system is shown in Figure 8.1, based on the resources available at the Intelligent Manufacturing Systems Centre.

At the core of the system is an interface that ties together the various software, and related hardware, components reviewed in Chapter 2. The software layers are represented as three concentric rings, among which specific system functions have been distributed. These functions have been grouped by the general data collection requirements they satisfy, except for those outlined by dashed ovals, which can be relevant for multiple groups and stages.

The specific system functions depend on methods and techniques developed in literature, and herein, for their working definitions. The functions in grey shaded ovals refer to literature entirely, while those in nor-shaded ovals have been treated, at least in part, in this work. In addition, the functions contained in ovals with thick solid borders are discussed for future work, in Section 8.3.
Figure 8.1: Framework for a reverse engineering system that combines CMM and laser scanning data collection.
In Figure 8.1, the relative positions of the functions, amongst the software layers within each group, reflects the level at which they would most logically be coded. For some functions, this may include more than one software level. In such cases, the functions are shown between the relevant rings with connecting dots and lines.

8.2: CONCLUSIONS

CMM and laser scanning digitization each have a number of contrasting advantages and disadvantages limiting their scope in reverse engineering applications. Systems with the ability to precisely couple both data collection methods offer significant flexibility in dictating digitization accuracy, density, and process times. This flexibility increases the range of reverse engineering applications for such a system beyond that which can be defined by the sum of the individual methods. In this work, compensation techniques were developed which significantly reduce errors inherent to combining CMM and laser scan data. Using these techniques as a basis, a viable reverse engineering system framework was presented which ties together methods from literature, experimental facilities, and the work herein.

8.3: FUTURE WORK

The very broad nature of this work makes it relatively easy to identify a number of avenues for future work. This section describes five such avenues.

8.3.1: Computer Coding of the Integrated Reverse Engineering System

In the development of several of the techniques from Chapters 3 through 7, small segments of computer code were written. Examples of these are included in the appendices. These, however, are merely a starting point. A significant amount of work in the future development of the system must be in defining the software interface, establishing seamless communication between the various existing software components and coding environments, as shown in Figure 8.1, and developing and expanding on algorithms that accomplish the functions described.

8.3.2: Laser Scanning Guided CMM Digitization

In Section 4.2, the digitization errors associated with the CMM inspection of a normal approximating surface, generated from laser scan data, were found to be
comparable to those of purely CMM-based techniques. However, the process has a significantly higher potential efficiency. Given a system capable of combined CMM and laser scanning data collection, this technique may be efficiently implemented by automatically generating polygonal surfaces from laser scan data, and using these to guide CMM inspection. Moreover, this exciting application can be coupled with work on optimizing CMM sampling strategies for free-form surfaces, currently being conducted in the Intelligent Manufacturing Systems Centre at the University of Windsor [39].

8.3.3: Combined Scanner/Probe Path Planning, Optimization, and Automation

A number of publications involving CMM probe path planning, optimization, and collision avoidance can be found in literature [129, 130, 131]. In some cases, laser scanner manufacturers offer limited functionality in these areas with their systems [56]. None, however, offer such functionality for combined data collection. This represents a significant research opportunity.

Expanding of this theme, an even more viable opportunity exists. By using a CCD camera(s) to acquire 2D images of a part prior to scanning, and algorithms to analyze and identify its features from a minimal number of images, it is feasible to fully automate and optimize combined laser scanning and CMM probe path generation. This would represent the ultimate in system efficiency, flexibility, and capability.

8.3.4: Completion and Refinement of the Intelligent Primitive Sampling Approach

A new approach to managing the uncertainty levels in generating substitute primitives from CMM data was described in Chapter 5. While the feasibility of using design of experiments techniques to resolve the effects of various factors on the size, location, and orientation of least squares primitives was confirmed, considerable work remains. Foremost is the development of predictive relationships that link measurement control factor effects to sample size and substitute geometry uncertainties, based on the sampling of control groups of artifacts from several manufacturing processes. Using such relationships, the sampling approach of Figure 5.9 can be implemented.
8.3.5: Trend-Based Laser Scanning Digitization Error Compensation

In Section 6.1.3, trends describing the laser scanning digitization error, as a function of the angle between the scanning axis and the part surface normal, were developed. The trend in the plane of the scanner field of view was found to be significant, and can be described by a continuous function, as shown in Figure 6.3. Potentially, the raw scan data could be used to approximate the surface normal at data point, and develop an error compensation algorithm. For spheres, and hence as a registration compensation algorithm, this approach has been validated by the work in Chapters 6 and 7. For free-form geometry, this would require investigating the digitization error for both concave and convex topologies of the scan line.
APPENDIX A – SAMPLE OF DATA CLOUDS USED IN HYMARC / IMAGWARE FITTING COMPARISON

Ren7b

Lsr17

nist2

stamp2

plane1
Table B1: Comparison of Least Squares Plane Fit Results – Imageware and Hymarc

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Algorithm</th>
<th># Data Points</th>
<th>Plane Equation</th>
<th>Errors</th>
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</thead>
<tbody>
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<td></td>
<td></td>
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<td>Ax</td>
<td>By</td>
<td>Cz</td>
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<td>CMM Data Sets</td>
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<td></td>
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### Table B2: Comparison of Least Squares Sphere Fit Results – Imageware and Hymarc

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<tr>
<th>Data Set</th>
<th># Data Points</th>
<th>RMS (μm)</th>
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<th>Imageware Sphere Center</th>
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APPENDIX C - ANSI C SOURCE CODE FOR FILE CONVERSION PROGRAMS

電位計ぎC FILE CONVERSION PROGRAM
Written by Chris Rolls   February 10, 1999

This program extracts XYZ measured coordinates reported in a
DEA Tutor for Windows 2.0 inspection file (*.mea). The points are
written in an ASCII file (*.asc) in three columns (X Y Z), separated by
a space only.

******************************************************************************
#include <stdio.h>
#include <stdlib.h>
#include <string.h>

main()
{
    FILE *meaPtr;
    FILE *ascPtr;
    char line[100] = "";
    char temporary[40];
    char mea[20];
    char asc[20];
    int response, dummy;
    float component;

    do {
        printf("\nEnter the tutor file name (*.mea): ");
        gets(temporary);
        sscanf(temporary, "%s", mea);
        printf("Enter output file name (*.asc): ");
        gets(temporary);
        sscanf(temporary, "%s", asc);

        if ((meaPtr = fopen(mea, "r")) == NULL)
            printf("\nCannot open %s", mea);
        if ((ascPtr = fopen(asc, "w")) == NULL)
            printf("\nCannot open %s", asc);
        while (!feof(meaPtr)) {
            sscanf(meaPtr, "%s %f", line, &component);
            if (line[0] == 'X')
                fprintf(ascPtr, "%8.4f", component);
            if (line[0] == 'Y')
                fprintf(ascPtr, "%8.4f", component);
            if (line[0] == 'Z')
                fprintf(ascPtr, "%8.4f\n", component);
        }
        fclose(meaPtr);
        fclose(ascPtr);
    }
printf("\n\nConvert another file (y/n)? ");
response = getchar();
dummy = getchar();
}
while (response != 'n' && response != 'N');
return 0;

/* END OF PROGRAM */

SAMPLE OUTPUT FILE CONVERSION – DEA2ASC

DEA (*.mea) File

** SP00101 (Z direction) **
Inspection
# 2 SHOULD Ref. Sys 0
X  0.0106  0.0000  0.0106  0.0000  -0.0000  0.0106
Y  20.0049  20.0000  0.0049  0.0000  -0.0000  0.0049
Z -0.0097  0.0000  -0.0097  0.5000  -0.5000

** SP00102 (Z direction) **
Inspection
# 4 SHOULD Ref. Sys 0
X  76.0167  76.0000  0.0167  0.0000  -0.0000  0.0167
Y  19.9959  20.0000  -0.0041  0.0000  -0.0000  0.0041
Z -0.0004  0.0000  -0.0004  0.5000  -0.5000

** SP00103 (Z direction) **
Inspection
# 6 SHOULD Ref. Sys 0
X  -0.0185  0.0000  -0.0185  0.0000  -0.0000  0.0185
Y  96.0030  96.0000  0.0030  0.0000  -0.0000  0.0030
Z  -0.0049  0.0000  -0.0049  0.5000  -0.5000

ASCII (*.asc) Output File

0.0106  20.0049  -0.0097
76.0167  19.9959  -0.0004
-0.0185  96.0030  -0.0049
TESTALG.C FILE CONVERSION PROGRAM
Written by: Chris Rolls    March 16, 1999

The program reads an ASCII file of data points composed of 3 columns separated by a single space, as output by DEA2ASC.C. It generates a file in the HYSCAN file format for point data. This file can then be used with the HYSCAN plane and sphere fitting routines (planefit* and xyzfit*) in the /usr/bin directory of the SGI machine upon which the scanner software interface is installed.

*******************************************************************************/

#include <stdio.h>
#include <stdlib.h>
#include <string.h>

void header(char *, int);
void footer(char *);

main()
{
    FILE *ascPtr, *hymPtr;
    char asc[20], hym = ".hym";
    char temp[40];
    char *hymarc;
    float x[2500], y[2500], z[2500];
    int cnt = 0, length, i;

    printf("Enter ASC file for conversion (*.asc): ");
    gets(temp);
    sscanf(temp, "%s", asc);
    hymarc = strtok(temp, ".");
    strcat(hymarc, hym);

    if ((ascPtr = fopen(asc, "r")) == NULL)
        printf("Cannot open file %.s for reading.", asc);
    if ((hymPtr = fopen(hymarc, "w")) == NULL)
        printf("Cannot open file %.s for writing.
", hymarc);

    do {
        fscanf(ascPtr,"%f%f%f", &x[cnt], &y[cnt], &z[cnt]);
        cnt++;
    } while(fgetc(ascPtr) != '*');

    header(hymPtr, cnt - 1);
    for (i = 0; i < cnt - 1; i++)
        fprintf(hymPtr, "%.5f %.5f %.5f
", x[i], y[i], z[i]);

    footer(hymPtr);
    fclose(ascPtr);
fclose(hymPtr);
return 0;
}

void header(char * hPtr, int count)
{
    fprintf(hPtr,"1\n4594802\n----------XYZ\n98.05.29-00:07:42\n");
    fprintf(hPtr,"0.000\n\n98.05.29-00:07:49\n4900\n-0.500 0.000 ");
    fprintf(hPtr,"0.000 0.000 0.000 -125705.000\n0.000 0.500 0.000 ");
    fprintf(hPtr,"-1.000 .000 -448558.000\n0.000 0.000 0.500 0.002 ");
    fprintf(hPtr,"1.000 117268.000\n0.000 \n0.000 \n0.000 ");
    fprintf(hPtr,"0.000\n\nBOTH1024X1STRM\n-------------------\n");
    fprintf(hPtr,"%d\n", count);
}

void footer(char * hPtr)
{
    fprintf(hPtr, "BOTH1024X1STRM\n-------------------\n0");
} /* END OF PROGRAM */
APPENDIX D - PARAMETRIC DEAPPL PROGRAMS FOR THE CMM SAMPLING OF PRIMITIVES

program plane[WM1,WM2]
element_array memory[100]
******************************************************************************
!* PLANE.TSC UNIFORM PLANE SAMPLING PROGRAM
!* Written by Chris Rolls March 10, 1999
!* 
!* This program samples a plane of specified length and width, using a
!* grid pattern with a specified number of points in each direction.
!* The program REQUIRES that:
!* a) The probe position (0,0) be the first qualified probe.
!* b) The CMM OPERATOR ENSURES unobstructed access of the probe
!* to the plane along the plane normal (probe in the -z direction).
!* c) A part reference system be created such that the length and
!* width of the plane lie along the +X- and +Y-axes, with the Z-axis pointing upwards with respect to the CMM bed.
!* 
!* The program outputs a file "plane##.mea" according to Tutor for Windows
!* normal operating procedures. The file is located in c:\wtutor\meas\.
!* 
******************************************************************************

!* VARIABLE DECLARATIONS
integer xpts, ypts
real xsize, ysize, offset, xstep, ystep
coord mpoint

!* MACHINE OPERATION PARAMETERS
metric_mode
deg_angle
mspeed 90
pspeed 100
acc 70
synchrodev
dist_approach 10.0

!* INPUT SECTION - Reads plane size, probe tip diameter, and number of points
!* to probe in each direction.
read prompt "Enter plane dimension in x direction: " (xsize)
read prompt "Enter plane dimension in y direction: " (ysize)

!* Input offset from origin in which to start probing. Enter 0 if no offset.
read prompt "Enter edge offset: " (offset)
read prompt "Enter number of points to probe in x direction: " (xpts)
read prompt "Enter number of points to probe in y direction: " (ypts)
!* PROGRAM MAIN BODY - Calculates approach distance, and theoretical plane
!* points for probing. Measures data according to specified planar grid.
ncmove
open("plane")

!* Initial clearance move, probe selection, and approach direction.
movex(Y=0, Z=120)
probe(1,1)
movex(X=offset, Y=offset, Z=40)
approach(0,0,-1)

!* Set measurement spacings.
xstep = xsize / (xpts-1)
ystep = ysize / (ypts-1)

!* Loop to measure grid of points.
for x = 1 to xpts
  for y = 1 to ypts
    mpoint = {offset + xstep * (x-1), offset + ystep * (y-1), 0}
    msh[memory[y], 1]
    movet(mpoint)
    !* Write measurement to file and to screen (dy).
    output file 1 memory[y]
    output dy memory[y]
  end_for
end_for

movex(Z=40)
movex(X=offset, Y=offset)
close

endstat
end_program
program CYLIND[WM1,WM2]
element_array memory[300]

*******************************************************************************

!* CYLIND.TSC UNIFORM CYLINDER SAMPLING PROGRAM
!* Written by Chris Rolls    March 12, 1999
!* *
!* This program samples a cylinder from a part reference system created
!* with the cylinder axis as the Z axis, pointing upward from the CMM
!* bed. The reference system must be located on the top face of the cylinder.
!* The sampling pattern is equiangular about the radius, and equally spaced
!* spaced along the axis. The spacing may be selected as either equal to the arc
!* length of the increment about the radius, or user specified.
!* The program REQUIRES that:
!* a) Probe positions be QUALIFIED IN THE ORDER 1.(0.0), 2.(90.0.- 180.0)
!* .... incrementing by 7.5 in B, up to (90.0, 172.5), for a total 49 positions.
!* b) The CMM OPERATOR ENSURES that the cylinder is situated such that
!* the (90,B) orientations of the PH9 have unobstructed access to
!* the cylinder for 360 degrees about the Z axis.
!* c) A part reference system be created at the top of the cylinder,
!* with axis roughly parallel to the machine Z axis, and the origin
!* at the intersection of the cylinder axis and top face.
!* *
!* This program outputs a file “cylXXX.meas” according to Tutor for Windows
!* normal operating procedures. The file is located in c:\wtutor\meas.
!********************************************************************************

!* VARIABLE DECLARATIONS
integer FLAG,NSTEPS,A,POS
real CHECK,THETA,ZSTEP,DELTA,XCOMP,YCOMP,ZCOMP,DIA,UPPER,LOWER
coord MIN,MAX,MPOINT
string ANSWER[1]
FLAG=1

!* MACHINE OPERATION PARAMETERS
metric_mode
deg_angle
mspeed 90
pspeed 100
acc 70
synchrodev
dist_approach 10.0

!* INPUT SECTION - Reads cylinder sampling pattern info and dimensions
loop
   read prompt "Enter sample increment about radius (Multiple of 7.5 Deg): "
      (THETA)
      CHECK=THETA/7.5-round (THETA/7.5)
exif ((CHECK eq 0) and (THETA le 120))
end_loop
loop
read prompt "Input cylinder diameter (mm - max of 200): " (DIA)
exitf ((DIA gt 0) and (DIA le 200))
end_loop
loop
read prompt "Axial step equal to sampling arc length (Y/N)? " (ANSWER)
if (ANSWER eq "y") or (ANSWER eq "Y") then
  ZSTEP=(DIA/2)*((3.14159*THETA)/180)
elif (ANSWER eq "n") or (ANSWER eq "N") then
  read prompt "Enter Z increment (mm): " (ZSTEP)
else
  FLAG=0
end_if
exitf (FLAG eq 1)
end_loop
!
* User prompted to manually measure a point on the sphere to set the
* UPPER Z axis bound for probing.
probe (2,1)
dy ("Measure point on cylinder representing upper probing bound.")
approach (-1,0,0)
ndy
msh (WM1,1)
MAX=WM1
UPPER=MAX|z
!
* User prompted to manually measure a point on the sphere to set the
* LOWER Z axis bound for probing.
dy ("Measure point on cylinder representing lower probing bound.")
approach (-1,0,0)
ndy
msh (WM1,1)
MIN=WM1
LOWER=MIN|z
dy ("Move probe to above cylinder before NCMOVE begins!")
!
* PROGRAM MAIN BODY - Calculates sampling positions given input and
* measurement bounds from user. Probes at given angular position from
* UPPER to LOWER along Z axis and then reorients.
NSTEPS=trunc (abs (UPPER-LOWER)/ZSTEP)
DELTA=(abs (UPPER-LOWER)-(NSTEPS*ZSTEP))/2
A=round(360/THETA)
cmp
open("cyl")
!
* Initial clearance move.
move (X=0,Y=0,Z=125)
for I=1 to A by 1

! Choose probe orientation based on angular spacing.
POS=round(THETA/7.5)*[I-1]+2
probe (POS, 1)

!* Calculate positioning point.
XCOMP=cos((I-1)*THETA)
YCOMP=sin((I-1)*THETA)
mov (X=XCOMP*(DIA/2+30), Y=YCOMP*(DIA/2+30))
mov (Z=UPPER-DELTA)

!* Measurement along cylinder axis at radial sampling position.
for J=1 to NSTEPS by 1
  ZCOMP=(UPPER-DELTA)-(J-1)*ZSTEP
  MPOINT=[(DIA/2)*XCOMP,(DIA/2)*YCOMP,ZCOMP];
  approach(-XCOMP, -YCOMP, 0)
msh (memory[J], 1, 1)
movtf (MPOINT)
output file 1 memory[J]
output dy memory[J]
end_for

!* Move probe away for reorientation.
mov (Z=140)
end_for

!* Retract probe for reorientation.
mov(Z=180)
probe(1, 1)
mov(X=0, Y=0)
close
endstat
end_program
program sphere(WM1,WM2)
element_array memory[100]

******************************************************************************
!* SPHERE.TSC UNIFORM SPHERE SAMPLING PROGRAM
!* Written by Chris Rolls   March 20, 1999
!* 
!* This program samples a sphere using a reference system at the sphere
!* origin. The sampling pattern is equiangular in a spherical coordinate
!* system whereby \( X = R \cdot \cos(\alpha) \cdot \sin(\theta) \), \( Y = R \cdot \sin(\alpha) \cdot \cos(\theta) \),
!* and \( Z = R \cdot \cos(\alpha) \), and \( R \) is the radius of the sphere.
!* The program REQUIRES that:
!* a) Probe positions be QUALIFIED IN THE ORDER 1.(0,0), 2.(90.0,-180.0)
!*     .... incrementing by 7.5 in B, up to (90.0,172.5), for a total of 49 positions.
!* b) The CMM OPERATOR ENSURES that the sphere allows the PH9, (90,B)
!*     orientations, unobstructed access to the sphere for 360 degrees
!*     about the Z axis (rfsys), and for theta degrees from the
!*     same Z axis.
!* c) A part reference system be created and made current at the sphere
!*     center, with axes parallel to the machine axes.
!* 
!* The program outputs a file "spbr00x.meu" according to Tutor for Windows
!* normal operating procedures. The file is located in c:\wtutor\meas\.
!* 
!*******************************************************************************

!* VARIABLE DECLARATIONS
!* 
!* \( \alpha \) is the angle of the XY plane projected position vector of a point
!* on the sphere, with respect to the X axis (rfsys).
!* \( \theta \) is the angle of the point position vector with respect to the
!* \( Z \) axis (rfsys).
!* DI is the sphere diameter (min = 4mm, max = 100 mm).
!* pos is the probe head number.
!* mpoint is a calculated target coordinate on the sphere to be measured.
!* depart is a coordinate used to maneuver the probe out of proximity with
!* the sphere for subsequent repositioning.
!* integer a, t, pos, flag
!* real check, ALPHA, THETA, DI, xcomp, ycomp, zcomp
!* coord mpoint, depart

!* MACHINE OPERATION PARAMETERS
metric_mode
deg_ange
mspeed 90
pspeed 100
acc 70
synchrodev

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!* INPUT SECTION - Reads sphere size and validates equiangular parameters.
loop
  read prompt "Enter Theta Range (Deg - Multiple of 7.5): " (THETA)
  check = THETA/7.5 - round(THETA/7.5)
  exif((check eq 0) and (THETA le 180))
end_loop
loop
  read prompt "Enter Alpha Increment (Deg): " (ALPHA)
  check = THETA/ALPHA - round(THETA/ALPHA)
  exif((check eq 0) and (ALPHA le 120))
end_loop
loop
  read prompt "Enter Sphere Diameter (mm): " (DIA)
  exif((DIA ge 4) and (DIA le 100))
end_loop

!* PROGRAM MAIN BODY - Calculates theoretical points on sphere, probes, *
!* and outputs measured results to file.
ncmove
dist_approach 10.0
a = round(360/ALPHA)
t = round(THETA/ALPHA)
pos = 2
flag = 1
open("sphr")

!* Initial clearance move.
move(X=0,Y=0,Z=DIA+100)
probe(1,1)
approach(0,0,-1)

!* Measure single point on top of sphere from (0,0) orientation.
mem(key[1],1)
movet(X=0,Y=0,Z=DIA/2)
output file 1 memory[1]
output dy memory[1]

for i = 0 to a-1 by 1
  for j = 1 to t by 1

    !*** Calculate theoretical point on sphere for measurement.
    xcomp = cos(ALPHA*i)*sin(ALPHA*j)
ycomp = sin(ALPHA*i)*sin(ALPHA*j)
zcomp = cos(ALPHA*j)
    mpoint = {xcomp,ycomp,zcomp} * DIA/2
    approach(-xcomp,-ycomp,-zcomp)

    !*** Choose probe orientation.
    if (round(ALPHA*j) le 30) then
      probe (1,1)
elsif (flag eq 1) then
    probe(pos,1)
    move(X=xcomp*2*DIA, Y=ycomp*2*DIA)
    move(Z=0)
    flag = 0
end_if

!* Measure compensated surface point and output to file.
    msh(memory[j],1)
    movetf(mpoint)
    output file 1 memory[j]
    output dy memory[j]
end_for

!* retract for probe change.
    depart = -DIA * 1.5 *{-xcomp,-ycomp,-zcomp/2}
    move(depart)
    move(Z=DIA+75)
    flag = 1
    pos = pos + round(ALPHA/7.5)
end_for

probe(1,1)

!* retract probe.
move(X=0,Y=0,Z=DIA+25)
close

endstat
end_program
APPENDIX E - IMAGEWARE SURFACER SCRIPT FILES USED IN
ANALYZING LOCATION AND ORIENTATION
UNCERTAINTY TRENDS

# rolls_plane_samp.cmd
# Written by Chris Rolls July 12, 2000
#
# This program takes all data clouds imported into Imageware Surfacer, fits a least
# squares plane to each one, and calculates the centroid of the plane, and the distance
# and orientation of the plane with respect to a datum plane. The datum plane must
# be created in the software before running the script file. The information is outputted
# to a text file (*.txt).
#

function rolls_plane_samp() {

    fileh=open("planesam.txt","w");

    show_all_clouds();
    show_all_surfaces();
    cloud_name=clouds();
    surf_name=surfaces();
    printf(surf_name);
    len=length(cloud_name);
    fit_name=vector(len);
    angle=vector(len);
    centroid=vector(len);
    dist=vector(len);
    flatness=vector(len);

    # Calculate Flatness of All Clouds
    for (i=0; i LT len; i++) {
        flatness[i]=cloud_flatness(cloud_name[i]);
    }

    # Fit Planes to All Clouds
    for (i=0; i LT len; i++) {
        fit_name[i]=fit_plane(cloud_name[i],0,vector(3,0,0,0),vector(3,0,0,0));
    }

    # Calculate Centroid of Datum Plane.
    fit_param=surface_parameter_limits(surf_name[0]);
    mid_param=vector(3,fit_param[0][0],(fit_param[1][1]-fit_param[0][1])/2,
                   (fit_param[1][2]-fit_param[0][2])/2);
    centroid[0]=surface_point(mid_param);
    dist[0]=0;
}

    # Calculate Centroid of Each Fitted Plane, and Distance to Datum Centroid.
    for (i=1; i LT len; i++) {
```
fit_param=surface_parameter_limits(fit_name[i]);
mid_param=vector(3,fit_param[0][0],(fit_param[1][1]-fit_param[0][1])/2,
(fit_param[1][2]-fit_param[0][2])/2);
centroid[i]=surface_point(mid_param);
dist[i]=centroid[i][0][2]-centroid[0][0][2];
}

# Calculate Angle of Each Fitted Plane to Datum
for i=0; i LT len; i++ {
    angle[i]=surf_surf_angle(vector(3,fit_name[i],0.5,0.5),
    vector(3,surf_name[0],0.5,0.5));
}

# Output Cloud Name, Distance to Datum, and Angle to Datum.
write(fileh,'Cloud,Flatness,Centroid,Distance,Angle\n');
for i=0; i LT len; i++ {
    write(fileh,cloud_name[i],",",flatness[i]*1000,"",centroid[i][0][2]*1000,"",
    dist[i]*1000,"",angle[i]*1000,"\n");
}

close(fileh);
```
# rolls_sphere_fit.cmd
# Written by Chris Rolls July 17, 2000
#
# This program takes all data clouds imported into Imageware Surfacer, fits a least
# squares sphere to each one, and calculates the center, radii, and fit errors in each
# case. This information is then outputted to a text (.txt) file.
#
function rolls_sphere_fit() {

fileh=open("spherefit.txt", "w");

# Ungroup, Set All Clouds Visible, and Determine Number of Clouds.
if[group_name=groups()] {
    do_ungroup(group_name);
}
show_all_clouds();
cld_name=clouds();

len=length(cld_name);
fit_name=vector(len);
sphr_info=vector(len,vector(4));
fit_error=vector(len,vector(15));

# Fit Spheres to All Clouds, and Determine Center Points, Radii, and Fit Errors.
for (i=0; i LT len; i++) {
    fit_name[i]=fit_sphere(cld_name[i], $false, 1);
sphr_info[i]=surface_sphere_info(fit_name[i]);
    fit_vec=vector(1,fit_name[i]);
cld_vec=vector(1,cld_name[i]);
    fit_error[i]=compute_surf_cloud_error_adv(fit_vec,cld_vec,1,1,1,$false,0);
}

# Output Cloud Name, Fit Centers and Radii, and Fit Error.
write(fileh,"Cloud ,Center ,Radius ,Pos Error , ,Neg Error , ,Abs Error, , ,\n");
write(fileh,"Name,X,Y,Z,R mm,Max,Ave,Std Dev,Max,Ave,Std Dev,\n");
for(i=0; i LT len; i++) {
    write(fileh,cld_name[i],",",sphr_info[i][0][0]*1000,"",sphr_info[i][0][1]*1000,
   ",",sphr_info[i][0][2]*1000,"",sphr_info[i][0][3]*1000,
   ",",fit_error[i][1]*1000,"",fit_error[i][2]*1000,"",fit_error[i][3]*1000,
   ",",fit_error[i][4]*1000,"",fit_error[i][5]*1000,"",fit_error[i][6]*1000,
   ",",fit_error[i][7]*1000,"",fit_error[i][8]*1000,"\n");
}
close(fileh);
}
function rolls_cylinder_fit() {

    fileh=open("cylfit.txt", "w");

    # Ungroup, Set All Clouds Visible, and Determine Number of Clouds.
    if(group_name=groups()) {
        do_ungroup(group_name);
    }
    show_all_clouds();
    cld_name=clouds();

    len=length(cld_name);
    xmin=vector(len);
    xmax=vector(len);
    fit_name=vector(len);
    cyl_info=vector(len);
    fit_error=vector(len);
    centroid=vector(len);

    # Generate New Scan Clouds by Trimming All Clouds to the Length of the Smallest
    # One.
    cld_pt=get_point(cld_name[0],1);
    xmin[0]=cld_pt[0];
    xmax[0]=xmin[0];
    for(i=1; i LT len; i++) {
        xmin[i]=xmin[0];
        xmax[i]=xmin[0];
    }
    ylin=pr[1];
    ymin=ylin;
    zmin=pr[2];
    zmax=zmin;

    for (h=0; h LT len; h++) {
        num_pts=cloud_num_data(cld_name[h]);
        for(i=2; i LT num_pts+1; i++) {
            cld_pt=get_point(cld_name[h],i);
            if(cld_pt[0] LT xmin[h]) {
                } elseif(cld_pt[0] GT xmax[h]) {
                    xmax[h]=pr[0];
            }
        }
    }
}
if(cld_pt[1] LT ymin) {
    ymin=cld_pt[1];
} elseif(cld_pt[1] GT ymax) {
    ymax=cld_pt[1];
}
if(cld_pt[2] LT zmin) {
    zmin=cld_pt[2];
} elseif(cld_pt[2] GT zmax) {
    zmax=cld_pt[2];
}

xtrimmin=xmin[0];
xtrimmax=xmax[0];
for(i=1; i LT len; i++) {
    if(xmin[i] GT xtrimmin) {
        xtrimmin=xmin[i];
    } elseif(xmax[i] LT xtrimmax) {
        xtrimmax=xmax[i];
    }
}

trim_box=vector(2,vector(3,xtrimmin,ymin,zmin),
vector(3,xtrimmax,ymax,zmax));
trim_cld=extract_cloud_bbox(cld_name, trim_box);

# Fit Cylinders to All Trimmed Clouds, and Determine Plane Coefficients and Fit Errors.
for(i=0; i LT len; i++) {
    fit_name[i]=fit_cylinder(cld_name[i],false,1);
    cyl_info[i]=surface_cylinder_info(fit_name[i]);
    fit_error=compute_surf_cloud_error_adv(fit_name,trim_cld,0,1,1,false,0);
}

write(fileh,"Cloud, ,Center, ,Radius, ,Axis Orient, ,Height, ,Pos Error, , ,",
     "Neg Error, , ,Abs Error, ,\n");
write(fileh,"Name,X,Y,Z,R,DX,DY,DZ,H,Max,Ave,Std Dev,Max,Ave,",
     "Std Dev\n");

for (i=0; i LT len; i++) {
    write(fileh, fit_name[i],",",cyl_info[i][0][0],",",cyl_info[i][0][1],
     "",cyl_info[i][0][2],",",cyl_info[i][1],",",cyl_info[i][2][0],
     "",cyl_info[i][2][1],"",cyl_info[i][2][2],",",cyl_info[i][3],"\n");
}
close(fileh);
}
REFERENCES


[59] Imageware, a Division of SDRC (Structural Dynamics Research Corporation), www.sdrc.com/nav/software-services/imageware/.


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