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Computer-Aided Planning for Laser Scanning

by

Xiaoyong (Ted) Yang

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

Windsor, Ontario, Canada
2001

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ABSTRACT

In recent years, laser scanning has been applied in the manufacturing industry as a tool for inspection and 3-D digitization as well as in reverse engineering. It has many advantages compared with the traditional contact measurement techniques, such as coordinate measuring machines (CMM). However, nowadays most of the scanning task is performed manually with the trial-and-error approach. In order to perform laser scanning more efficiently, automated laser scanning planning needs to be developed based on the CAD model of a given part.

This research presents a computer-aided planning method for laser scanner based on CAD model of the part. The method integrates three planning criteria, namely visibility, efficiency, and accuracy into the planning system. A feature differentiation method, based on the ray tracing algorithm, is proposed and applied to detect steep walls of certain deep concavity features, such as slots, holes, and pockets, which are very hard to reach by laser scanning but are suitable for CMM probing. The method automatically generates a consistent and efficient scanning plan by avoiding the unnecessary trials in manual operations and reducing inaccuracy and inconsistency introduced by variation among different operators.

The proposed methods and algorithms have been implemented and integrated into a Computer-Aided Laser-scanning Planner (CALP) for inspection applications. The system can automatically generate the scanning plan including the number of patches,
scanning directions, scanner placements, scanner moving lines, and scanner moving paths.

An artifact block with five planar surfaces is used to test the scanning plan which is generated from the proposed methods. The experiment has demonstrated that the scanning plan can be integrated to CMM offline program and to automate the scanning process of the Hymarc 45C laser scanner mounted on DEA Mistral CMM. Computer simulations have been performed on some complex surfaces with deep concavity and cavity features to test the feature differentiation algorithm and scanning planning performance. A computer-aided planning system for laser scanning, which can automatically generate the scanning plan, has been developed in this thesis in order to improve the laser scanning process for complex surfaces.
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Chapter 1 INTRODUCTION

1.1 BACKGROUND

1.1.1 Overview of Dimensional Inspection

Dimensional inspection plays an important role in modern manufacturing since the dimensional and geometric specifications have to be met for high-quality products. The development and application of CAD/CAM technology has significantly improved the efficiency and accuracy of production. Also, the integration of CAD and inspection devices to improve the inspection efficiency has been an active area of research since the concept of CAD-directed inspection was introduced in the early 1980s (Hopp, 1984).

CAD-based inspection involves the inspection planning based on the CAD model information, which can automate or optimize the inspection process for specific inspection device. It also involves the verification of conformity of the geometric model of the ideal object with the geometric model of the actual object. The former model, referred to as the reference object model (CAD model), encodes the nominal geometry of the ideal object as well as the allowable tolerances. The later model usually is created from the data acquired by the process of measurement. Then the manufactured part will be decided whether to be accepted or rejected accordingly. The Figure 1.1 describes the inspection planning and verification process (Limaiem, 1996).
In the inspection task, the inspection planning is an important and complex process. It deals with how to acquire adequate data efficiently from the actual part. The extent of difficulty of inspection planning depends on the complexity of the part, the data acquisition methods and devices. There are many different methods for acquiring dimensional data, as shown in Figure 1.2 (Varady, et al, 1997). Essentially, each method uses some mechanism or phenomenon for interacting with the surface or volume of the object of interest. There are non-contact methods, where light, sound, or magnetic fields are used, while in other tactile methods the surface is touched by using mechanical probes at the end of an arm, e.g. robot or coordinate measuring machine.
The coordinate measuring machine (CMM) probably is the most popular and precise data acquisition device when compared with manual and non-contact measurement devices. It employs a touch probe mounted on the vertical arm of a three-axis gantry style translation system. The essential system components of a CMM include (Bosch, 1995):

(1) The mechanical set-up with the three axes and the displacement transducers,
(2) Probe head with a touch trigger or analog probe to probe the workpieces in all spatial directions,
(3) Control unit and a computer with peripheral equipment, and
(4) Software to calculate and represent the results.
The touch probe records the precise 3-D location of the points on the surface. It produces measurement accuracy ranging from 0.001" to 0.0001" (ElMaraghy, H. A. and ElMaraghy, W. M., 1994). A typical inspection procedure using CMM is composed of the following steps:

1. Choose the features or surfaces of the part to be inspected.
2. Align the reference frame of the part with the reference frame of the CMM and the operator generally takes some points on the workpiece. (Figure 1.3)
3. Choose the probe.
4. Choose the probe orientation with which the maximum number of measurements may be performed.
5. The operator drives the probe to touch the points on the workpiece to acquire the dimensional information which is then used by the software to check if the specified dimensions and tolerances are met.

![Figure 1.3: The Coordinate Systems for Parts and CMM](image-url)
Usually the CMM can be operated in four modes: manual mode, teaching mode, off-line interactive programming mode and automated planning and program generation mode (Limaïem, 1996). CMMs are widely used to digitize objects which contain quadratic features such as planes, spheres, cylinders and cones, since very few data points are required to construct an approximate model. However, if measurement points in a set are obtained by means of the contact probe, the generated model may differ from the real part model because of the probe radius compensation errors (see Figure 1.4). This compensation is a difficult task when applied to the free-form surfaces and may become a critical factor when precise measurement of point data is required.

![Figure 1.4: Radius Compensation Errors of the Probe](image)

In order to minimize the compensation errors, the probing direction of the CMM should coincide with the normal vectors of the surface at the probed points (Menq and Chen, 1996). Another disadvantage of CMMs is the slow rate of data collection, which
reduces the effectiveness of CMMs when large data is required for accurate free-form surface definition. The advent of programmable CMMs and more accurate and flexible machines (i.e. motorized probe heads) give the opportunity to automate the inspection planning using CMMs. The methods and achievements in the area of the automated inspection planning for CMM are reported in Chapter Two.

1.1.2 Overview of Laser Scanning Technology

Many branches of the industry, particularly the automotive and the aerospace sectors, manufacture components comprising free-form surfaces, such as automotive body panels, aircraft fuselage and wing parts, compressor, and turbine blades. Previous inspection methods for these parts, manual measurements and coordinate measuring machines (CMMs), captured only critical dimensions. They could not determine whether the entire part had been manufactured correctly because there were not enough data points to represent the entire shape. The emergence of fast, accurate optical sensors overcomes these obstacles and offers tremendous potential in manufacturing applications. A laser scanner captures millions of data points very quickly. Using special surfacing software, scanned data is superimposed on a CAD surface model of the part, showing instantly where the physical object deviates from the original model.

The 3-D laser scanner is based upon triangulation (Figure 1.5) and utilizes a solid-state scanning and detection system in conjunction with signal processing electronics to collect accurate high-speed height data.
Figure 1.5: Principle of Triangulation

In the past several years, laser-scanning technique has been applied in the manufacturing industry as a tool for inspection and 3-D digitization in reverse engineering process as well since it has a lot of advantages compared with the traditional contact measurement, coordinate measuring machine (CMM), such as:

(1) High data collection rate, 10KHz for Hysan 45C (Hymarc);
(2) High-resolution digitization of 3-D free form surfaces;
(3) No surface deformation or damage results for parts made of soft materials, such as foil, plastics, wood, wax and clay materials;
(4) No calculation of probe tip compensation is needed;
(5) More accurate and more efficient especially when inspecting complicated and free-form surfaces;
(6) Possible to perform full surface scanning coverage.

Table 1 shows difference between tactile probe and laser scanner on CMM.
Table 1.1: Comparison of Tactile Probe and Laser Scanner on CMM

<table>
<thead>
<tr>
<th></th>
<th>Tactile Probing</th>
<th>Laser Scanning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data Collection Rate</td>
<td>Low</td>
<td>Very High</td>
</tr>
<tr>
<td>Motion Mode</td>
<td>Discrete Point-to-Point</td>
<td>Fly During Scanning</td>
</tr>
<tr>
<td>Damage on the Surface</td>
<td>Possible</td>
<td>No</td>
</tr>
<tr>
<td>Better on (the surface)</td>
<td>Primitive and Conic Surfaces</td>
<td>Free Form Surfaces</td>
</tr>
<tr>
<td>Surface Requirement</td>
<td>Hard Surface and Need Support</td>
<td>Reflectivity</td>
</tr>
<tr>
<td>Probe Calibration/Scanner Alignment</td>
<td>Programmable/Faster</td>
<td>Manual/Slow</td>
</tr>
<tr>
<td>Available Orientations</td>
<td>More (720)</td>
<td>Limited (on configuration)</td>
</tr>
<tr>
<td>Measurement Accuracy</td>
<td>High (2.5~25 micron)</td>
<td>Low (25~50 Micron)</td>
</tr>
<tr>
<td>Factors Affecting the Accuracy</td>
<td>Less</td>
<td>More</td>
</tr>
<tr>
<td>Possibility of Collision</td>
<td>Very High</td>
<td>Low</td>
</tr>
<tr>
<td>Effective Working Volume</td>
<td>Larger</td>
<td>Smaller</td>
</tr>
</tbody>
</table>

There exist three major types of laser-scanning devices for the current practice (Lee and Park, 2000). The first type has a configuration with the laser-scanning probe mounted on a three-axis transport mechanism in which the axes are orthogonal to each other. The second type uses a cylindrical configuration where either the part or the laser-scanning probe is rotated to acquire point data for each height level of the part. The third type uses a robotic arm equipped with a laser probe at the end of arm tooling. In most researches, the laser scanner is mounted on a CMM, which serves as an accurate translation system. A laser scanning system which consists of a Hymarc Hyscan 45C laser-based digitizer and CMM is shown in Figure 1.6.

The laser scanning system is driven by CMM to move in the x, y, and z direction. The Hyscan 45C laser scanner system computes the coordinates of the points on the object surfaces based on the principle of active triangulation, using a synchronized
scanning scheme. Figure 1.7 shows the synchronized scanning structure that makes use of a two-side-coated scanning mirror.

One side of the mirror participates in the projection of a laser beam on the object, whereas the other side redirects the light reflected by the object into a CCD detector system through focusing lens. The laser beam sweeps along the surface of the object as the scanning mirror is rotated about its center. The position of the image on the detector and the known angular position of the scanning mirror allow the calculation of the coordinates of the spot on the object. The main advantage of this approach is to simultaneously obtain high resolution and large field of view contrary to standard triangulation geometry where a compromise is made between resolution and field of view (Prieto, Redarce, Noulanger and Lepage, 1999)

Figure 1.6: Hymarc Hyscan 45C Scanner and CMM (Hymarc Ltd., 1998)
However, only the surface which is falling in the defined scanning window, called field of view, can generate the scan data. The depth of the view is 60 mm and the width is 60 mm. There is also a standoff between the scanner and the field of view, which should be kept during scanning. The following gives the specifications for Hyscan 45C scanning system: (See Figure 1.6)

(1) Point sample rate 10 KHz;
(2) Range accuracy $\pm 0.025$ mm (.001") 3-Sigma;
(3) Lateral resolution (nominal) 0.1 mm;
(4) Depth of field (DOF, nominal) 60 mm (2.4");
(5) Scan width (nominal) 60 mm (2.4");
(6) Stand off (nominal) 100 mm (4.0");
(7) Digitizing volume determined by motion system.
The validity of the scanner accuracy specifications is verified by collecting scan lines on a high-precision sphere surface. Since in most cases a single scanning pass may not be able to cover the whole part, the laser scanner will need to be planned and operated from different viewpoints to cover the whole object. Raw data collected by the scanner which are generated by different scanning records are called "cloud data" due to their unformatted or unstructured spatial arrangement.

1.2 MOTIVATION AND OBJECTIVES

Since laser scanning offers a high-resolution digitization, it is particularly applicable to CAD-based inspections for parts with 3D complex free form surfaces. However, even in currently employed laser scanning systems, most of the scanning task is performed manually to drive the laser scanner along the different axes and orientations. The operator has to determine many appropriate sensor parameters, such as scanner position and orientation, scanning path, etc. The manual inspection operation takes an extensive amount of time and often causes inconsistent results due to trial-and-error based approaches, for example, excessive (over) scanning or missing some regions (under scanning) (Xi and Shu, 1999).

Lamb, Baird, and Greenspan (1999) indicated that the emergence of fast, accurate optical sensors offers tremendous potential to improve the throughput of digitizing applications, but it appears that this potential has not yet been fully realized. Hymarc Ltd. has conducted an informal survey of practical applications using it Hyscan 45C laser
digitizer to assess typical system throughput. Results indicate that the sensor bandwidth is frequently under-utilized. This is attributed to the fact that much of the scanning task is performed by moving the scanning probe manually. In order to perform laser-scanning inspection more efficiently, an automated inspection planning method needs to be developed based on the CAD model of a given part.

Lee and Park (2000) also noted that there exist no systematic methodologies for measuring parts using laser scanners, and inspection operation has been done by the intuition of skilled workers. They found that few algorithms exist related to generating scanning plans for laser scanners. Therefore, there is a need for research in methodologies and algorithms for automated laser scanning planning.

The survey of laser scanning planning and accessibility analysis reveals that when the part has some deep concavity features, such as slots, pockets, or deep holes, it is very hard or even impossible to plan the scanner to reach some regions of these features because of the limitations of laser scanning techniques.

In order to solve the problem mentioned above and improve the efficiency of scanning planning, several objectives have been defined for the research work. They are:

(1) To identify and characterize the major factors which affect the laser scanning process and results, such as visibility, accuracy, and efficiency. The major factors are to be modeled and integrated into the planning methodology.
(2) To develop a method that can segregate the concavity features before scanning planning for laser scanner.

(3) To develop a method to automatically generate the scanning plan based on the CAD model and user-defined parameters. This is to be accomplished through the implementation of the various algorithms for laser scanning planning.

(4) To validate the scanning planning method by both experiments and computer simulations.

1.3 THESIS OVERVIEW

This thesis is organized into 6 chapters and 4 appendixes:

Chapter 1 provides the introduction of CAD-based inspection planning and verification process. CMM tactile probing and laser scanning techniques are introduced and compared. The motivation and objectives of this research are also presented.

In Chapter 2, thorough literature review of important research work related CMM and laser scanner planning is provided. The comparison of inspection planning for two different techniques is presented as well.

Chapter 3 analyses the factors that affect the scanning planning. Sampling methods for extracting surface information are discussed. A feature differentiation method based on the ray tracing algorithm is presented.
Chapter 4 presents a computer-aided scanning planning method for line laser scanners to automatically generate the scanning plan. The method includes three modules, clustering, scanner placement, and patch-based path planning. Some examples are provided to demonstrate the algorithms.

In Chapter 5, both computer simulations and experiments are used to test the method and algorithms. The simulation process demonstrates that the scanning plan for laser scanner can be generated automatically. The experiment shows that the generated scanning plan can be integrated to CMM offline program and automate the laser scanning process.

The thesis is concluded with a discussion of conclusion, contributions, and suggestions for further research work in Chapter 6.
Chapter 2 LITERATURE REVIEW

In recent years, inspection planning has received wide attention. There have been a lot of research efforts using CAD model to generate the inspection plan for CMM and scanning plan for laser scanner. This chapter reviews some of the important research work in CMM and laser scanner technology. The comparison of inspection planning for CMM and laser scanner is also discussed in Section 4.

2.1 OVERVIEW OF INSPECTION PLANNING FOR CMM

The automated CAD-directed inspection planning systems for CMMs have been proposed by many researchers in past years. Figure 2.1 describes the general planning structure for CMM probe inspection.

![General Planning Structure for CMM Probing Inspection](image)

Figure 2.1: General Planning Structure for CMM Probing Inspection

Since CMM touch probing performance is based on the point by point approach, it is necessary to find the optimum number of inspection points as well as their optimum locations for the part inspection, especially for free form surfaces, in order to minimize the inspection time and the deviation of the substitute geometry from the nominal CAD data. Three sampling schema are most commonly used in the literature, i.e., uniform or equidistant sampling, completely randomized sampling, and stratified sampling (Dowling

15
et al., 1997 and Hocken et al., 1993). The summary of techniques for measurement point sampling is as follow:

- A neural networks technique to achieve the optimal sample size for the inspection of internal holes. (Zhang, et al. 1996)

- Mathematical techniques, such as the Hammersley sequence, used for sampling of planar surfaces. (Woo and Liang, 1993)

- Mean curvature analysis for Bezier surface patches. (Cho and Kim, 1995)

- Adaptive sampling, local adjustment sampling, and the finite element centroid sampling were applied to optimize the locations of sample points. (Menq, et al. 1990)

- Equi-parametric sampling, patch size based sampling, mean curvature based sampling, optimal sampling using genetic algorithms and hybrid sampling approaches for free form surface inspection. (ElKott, et al., 1999, 2000)

- The stratified sampling technique for spherical features. (Fang et al., 2001)

Because the CMM uses contact sensing approach, the CMM probe gets close to the inspected part very often and actually works in the proximity of the part. The part itself, therefore, could become the obstacle to the inspection path. Only desired touch between the probe and the part is acceptable while undesired or unexpected contacts, namely interference (or collisions), should be avoided (Menq, et al., 1992, Yao, et al., 1995). That is why accessibility analysis is a very important aspect of automated CMM inspection planning (Limaiem and ElMaraghy, 1999). In the past decade, most of research work on CMM inspection planning focused on the accessibility analysis to evaluate the accessibility of measuring points in order to avoid the interference or collisions and
minimize unnecessary changes in probe orientation during inspection planning. A summary of techniques for accessibility analysis is as follow:

- Local/global accessibility cones (Spyridi and Requicha, 1990);
- Ray tracing technique (Limaiem and ElMaraghy, 1999; Lin and Murugappan, 1999);
- Accessibility cone (Yao and Menq, 1995);
- Visibility Map (VMAP) (Jackman and Park, 1998; Kweon, and Medeiros, 1998; Woo, 1994);
- Swept-volume method (Fan and Leu, 1998);
- Hierarchical planning system using heuristics (Menq, Yao and Wong, 1992);
- Boundary intersection method (Gu and Chan, 1996);
- Intersection of Concentric Spherical Shells (ICSS) (Limaiem and ElMaraghy, 1999).
- Combined Local, Feature, Probe and Global Accessibility Analysis (Vafaeesefat and ElMaraghy, 2000).

The summary of literature survey on CMM inspection planning is shown in Table 2.1.
<table>
<thead>
<tr>
<th>Researchers and Affiliation</th>
<th>Research Project And Year</th>
<th>Features</th>
<th>Test and Implementation Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hong-Tzong Yau and Chia-Hsiang Meng, Ohio State University, USA.</td>
<td>Automated CMM Path Planning For Dimensional Inspection of Dies and Molds Having Complex Surfaces (1995)</td>
<td>CAD-directed; Automated collision detection; Automated path modification and probe angle selection; Complex surfaces</td>
<td>CATIA ROBOTICS and CATGEO Module FORTRAN program</td>
</tr>
<tr>
<td>P. Gu and K. Chan, University of Saskatchewan, Canada.</td>
<td>Generative Inspection Process and Probe Path Planning for CMM (1996)</td>
<td>STEP-based; Object-oriented; Graphical simulation of inspection; Collision-free;</td>
<td>OOIP*; GPM*/*AutoCAD Interface Environment and AutoLisp.</td>
</tr>
<tr>
<td>Kuang-Chao Fan and Ming C. Leu, National Taiwan University, Taiwan.</td>
<td>Intelligent Planning of CAD-Directed Inspection for CMMs (1998)</td>
<td>CAD-directed; Feature-based; Collision detection (using swept-volume analysis); probe rotation;</td>
<td>AutoCAD</td>
</tr>
</tbody>
</table>
| Yueh-Jaw Lin and Prabakar Murugappan, The University of Akron, USA. | A New Algorithm for Determining a Collision-Free Path for a CMM Probe (1999)              | CAD-directed; Collision-free (using ray tracing technique);                                                                 where
2.2 OVERVIEW OF SCANNING PLANNING FOR LASER SCANNER

The goal of laser sensor planning is to automatically generate appropriate sensor orientations, positions and moving paths for scanning surfaces of the object. The laser scanner systems are then able to operate more flexibly, autonomously and efficiently. The laser scanner planning has recently become a very active area of research with a number of researchers addressing various aspects of the problem.

Non-contact three-dimensional digitization has been studied by Saito, et al. (1991). Goh et al (1986) first studied the methods applicable for the dimensional inspection of engineering components by using a compact solid-state laser triangulation sensor on a computer-assisted coordinate measuring machine (CMM).

In past years, many attempts to achieve the goal of automating the laser scanning process have been reported in the literature. The scanning planning for laser scanner could be presented as an optimization problem where the optimal laser scanner viewpoint and scanning path must satisfy certain constraints. Zussman, Schuler and Seliger (1994) and Lamb, Baird and Greenspan (1999) described the constraints considered in the planning.
- View angle: Constraint on the angle between the incident laser beam and the surface normal.
- Field of view (FOV): The surface being scanned should be within the length of a laser stripe.
- Depth of view (DOV): The scanned surface should be within a specified range of distance from the laser source.
- The incident beam as well as the reflected beam should not interfere with the part or the probe itself, no shadows and occlusions occur.
- Sensor orientation must be constant during data acquisition.
- Free-collision between the CMM, sensor and object.
- Number of changes in sensor orientation is to be minimized.
- Reflectivity of an object under inspection should be considered.

Many researchers have proposed different methods and algorithms to improve the efficiency and accuracy of laser scanning application in inspection. Their research mainly involved:

- CAD-based constraint recognition, analysis and modeling in laser scanner planning.
- Feature accessibility/detectability analysis for laser scanner.
- Automating scanning plans.
- Tests and implementations.
2.2.1 Literature Review of Scanning Planning for Laser Scanner

The work of Cheng and Menq

Cheng and Menq (1995) presented an integrated laser/CMM system for the dimensional inspection of objects made of soft materials. An inexpensive laser sensor (LB-12/LB-72) is combined with their existing automated inspection environment. They have done the following in their research:

- Geometric transformation algorithm, which defines the geometrical relationship between the laser inspection point and the probe tip center.
- Calibration algorithm, which defines the conversion vector for the laser probe.
- Vector matching algorithms, which is used to align the laser beam and the surface normal at the point being inspected.
- Verification that the alignment of the laser beam with the surface normal of the inspection point is vital for performing the laser inspection.

There are also some limitations in their system. Only 40-mm standoff distance of the laser head gave the system a limited inspection range. It might cause collision of the laser head with the object surface while executing the inspection plan, but they didn’t consider the collision detection and avoidance. They neither consider the influences on inspection accuracy, which is brought by changing positions and orientations of laser head. Furthermore, the method based on the devices they used may not be applicable to other environments.

The work of Zussman and his team
Zussman, et al. (1994) presented an automated planning system using laser scanner sensors to determine the optimal location of sensor viewpoints. For the first time, they systematically analyzed the particular optical constraints dependent on the sensors and the geometrical constraints of the objects. They used the optimisation approach to determine the optimal location of sensor viewpoints. However, their algorithm was only applicable to 2D profile of a surface and could not be used to scan an entire surface of an object. The laser scanner in the experiment was mounted on six degrees of freedom robot and did not need any further setups of the part.

Elber and Zussman (1998) developed an algorithm that can calculate the number of scans and corresponding optimal scanning orientations for a part with free-form surface using a surface decomposition method. The method used the Gauss map of surface to decompose the surface into different regions, but they only considered the limit on the angle between the surface normal and the incident beam in determining the visibility of a point on a surface, and did not consider the possible shadow and occlusion generated by the part or the laser probe itself. In addition, they only calculated the visibility as the local visibility, not global visibility; therefore, the number of scans was not optimized.

Funtowicz, et al (1998, 1999) developed an algorithm that can scan a part completely by combining the approaches mentioned in the previous two papers. However, they assumed that there was no limitation for orientations of laser scanner. The rules and methods to determine location and density of points to be scanned were not given. Lastly, they did not consider the occlusion and collision, either.
The work of Bernard and his team

Bernard and Veron (1999) presented a new method to automatically scan a known part through automation of off-line data generation, simulation and validation of the laser sensor scanning process. The scanning environment and digitalization steps were simulated in commercial software, CimStation Paint Module, in order to test and verify the efficiency of digitisation. However, their "simulation – validation - generation" method of the 3D laser scanning process is mostly realized through the software simulation, the software capability of integrating all constraints should be considered.

Bernard, et al. (1999) continued the previous research and presented a paper related to "simulation – validation – CAPP for generation of 3D – laser scanning process". They proposed to use some elements of a computer-aided process planning system for automatic scanning process generation. One is to determine the different orientations between the sensor and the part, and the second is the definition of the trajectories, for each orientation, which allow digitizing the maximum part surface.

Bernard and Veron (2000) proposed a solution that uses the visibility theory to automatically determine the scanning strategies for the digitization of 3D complex parts, using a plane laser sensor. They proposed an original solution based on the visibility concept, with three levels, local, global, and real visibility. This approach used the spherical geometry and integrated the use of the Gaussian sphere. In order to obtain the real visibility, the following additional constraints should be taken into account:

- Sensor physical volume, which may lead to collision.
- Possibilities of shadow and occlusion.
- The angle between the laser and the normal vector of surface of the part.
- The limitation of sensor's translation and orientation.

The algorithm has been implemented and tested, but the generation of scanning path from different positions needs to be considered.

**The work of Xi and his team**

Xi and Shu (1999) addressed the problem of path planning for the 3-D line laser scanning from the point of view of inspection. They considered the constraints of field of view (FOV) and depth of view (DOV) and tried to find the optimal FOV settings in order to maximize the coverage for each line scanning. Then the path planning for the laser scanner may be found for driving this line to follow the surface. They presented the part slicing method to divide the CAD model of the part to be scanned into a number of sections, due to the limit of scanning width a single scanning pass may not always be able to cover the whole surface. For each section, the surface profile is obtained by projecting the surface onto the slicing plane and the upper and lower boundary of each section surface is determined. The scanning path for each section is generated by setting the top of FOV along the upper surface boundary. The coverage region is established by adding the depth of view. All the paths are connected in a conventional zig-zag fashion to form a complete scanning path. Their methodology is also tested by using a Hymarc 3-D line laser scanner mounted on a CMM.
However, the proposed path planning is appropriate for simple flat surface scanning since it doesn't consider the view angle limitation and surface accessibility, and the rules to slice the part are not given.

The work of Lamb and his team

Lamb, Baird and Greenspan (1999) presented an architecture and prototype implementation of an automated 3D digitisation system, which determines the sensor placement, viewpoints and collision-free trajectories. The digitisation process can be done by selecting one or more digitizing strategy, which are in three levels of low-level strategy, semi-autonomous and fully autonomous strategy. The following figure depicts the Hymarc/NRC system architecture.

![Diagram of automated Hymarc/NRC 3-D digitizing system architecture](image_url)

**Figure 2.2: Automated Hymarc/NRC 3-D Digitizing System Architecture (Lamb, et al, 1999)**

25
They have done the following work in the research:

- Semi-autonomous digitizing strategies: edge-scan, raster-scan, box-scan, profile-scan, and servo-in-depth.
- Path planning and collision detection by using voxel map.
- A prototype implementation of the automated 3D digitization system, RapidScan.

Although it is a prototype system, RapidScan demonstrated a new direction that is to provide a fast, reliable and easy-to-use method for creating digitized models of physical objects. This system has different scanning strategies in accordance with different features of objects. However, more scanning strategy modules still need to be developed, especially for some complex features, such as free-form surfaces and concavities.

**The work of Milroy and his team**

Milroy, Bradley and Vickers (1996) developed an automated scanning system based on orthogonal cross sections (OCS) for part digitisation in reverse engineering application. The part is unknown before scanning. The orthogonal cross section (OCS) model is built from a triangulated facet model of the scanned data and its creation involves three distinct steps:

1. A dense scan is taken and is converted to a triangulated surface.

2. Cross sections are created by intersecting the surface with equi-spaced x, y, and z cutting planes. These are referred to as local sections to distinguish them from the combined global sections.
(3) The new local sections are merged with the global model (the sections from previous scans) by discarding portions of sections that overlap, adding the new sections, and making appropriate connections to form continuous segments.

In their approach, an OCS model is produced from an initial top scan. After generating cross sections from the scan, the range of possible orientations of the unmapped surface at the outer edge of the sectioned region is estimated. The estimation is used to select viewpoints for subsequent scans. As the outer surfaces are mapped, optimal viewpoints that avoid occlusions can then be determined for the inner surfaces, and scanning continues until the OCS model is completed. Their algorithm was tested experimentally using the Hyscan (Hymarc) laser scanner, Mitutoyo CMM and SGI Indigo workstation.

Milroy, et al. were the first to present the automated scanning approach to perform a complete, autonomous scanning of an unknown object of arbitrary shape. However, the merging approach used in the model to make appropriate connections to form continuous segments may produce some errors. Since the positions and orientations of a laser scanner are limited, it will be more difficult when the method is applied to some objects with many invisible areas, such as deep holes and irregular cavities.

The work of Lee and Park

Lee and Park (2000) proposed algorithms that lead to an automated inspection planning for parts that contain complicated shapes and free-form surfaces. The proposed methods consist of three steps:
(1) Accessibility analysis for each sampled point considering constraints. The constraints include the view angle, the depth of view, occlusions, and collisions.

(2) The number of scans and the most desired direction for each scan are calculated.

(3) The scan path that gives the minimum scanning time is generated.

Lee and Park calculated locally accessible directions (LAD) and globally accessible directions (GAD) for each mesh point to determine the parameters of each scan.

![Flowchart of the Proposed Algorithms by Lee and Park (2000)](image)

**Figure 2.3:** Flowchart of the Proposed Algorithms by Lee and Park (2000)

Application examples proved that the algorithms are effective for free-form surfaces. In order to eliminate the re-orientation limitation of laser sensor, they used rotary table for part setup and registration. The calculation of transformation matrix for the rotary table is also given. By automating the generation of the scan plan, the cost and time of inspection was significantly reduced compared to manual operations. However, the accuracy and efficiency of their algorithms may need to be further improved by taking into account some complicated features of the part. Additionally, the sampling method
that can reduce the number of points while maintaining the accuracy of the surface needs to be further developed.

The work of Tarbox and his team

Tarbox, et al. (1995) presented a series of three planning algorithms for finding a set of sensing operations for completely measuring the exposed surface of an object to be inspected. The characteristics of their method are:

- Considering the constraints of view angle, depth of view, and occlusion as well.
- Evaluating viewability and measurability.

Then three planning algorithms were developed to automatically plan for the geometric acquisition of workpieces. Three case studies, (1) a sphere; (2) a NASA tetrahedron construction node; (3) a coffee cup, each with a different degree of difficulty in terms of the effort required in making surface point measurements, were presented. However, they assumed there is no limitation for the orientation of sensors. They also found that the coffee cup was extremely difficult to inspect due to the deep concavity inside. In this case, a study of the feature suitability for inspection using laser sensor may need to be conducted in order to reduce the unnecessary effort for some impossible-to-view, or even hard-to-view regions.

The work of Prieto and his team

Prieto, Redarce, Noulanger and Lepage (1999) developed a method for automatic inspection of parts with complex surfaces. Because the use of laser range sensor allows
significant improvement in acquisition speed but does not equal the accuracy obtained with a coordinate measuring machine, they suggested improving the accuracy of the depth measurements by optimum 3D data acquisition. They found that the accuracy of 3D measured points is a function of the distance and of the incident angle relative to the surface. Their strategy guaranties that the found viewpoints meet the best accuracy conditions in the scanning process.

The 3D data acquisition strategy algorithm is described in Figure 2.4. This planning strategy allows us to digitize the whole part or some surfaces of interest with a specified accuracy. This is important for inspection tasks, where most of the time we are just interested in verifying the specification of some few surfaces.

![Figure 2.4: 3D Data Acquisition Strategy Algorithm by Prieto, et al.](image-url)
### 2.2.2 Summary of Scanning Planning for Laser Scanner

#### Table 2.3: Summary of Literature Survey on Laser Scanner Planning

<table>
<thead>
<tr>
<th>Researchers</th>
<th>Objectives</th>
<th>Constraints</th>
<th>Methods/Algorithms</th>
<th>Test/Device Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen and Menq (1995)</td>
<td>Integrated laser/CMM system</td>
<td>Geometric transformation between the laser probe and CMM reading; Calibration of the laser/CMM system; Angle of incidence;</td>
<td>CAD-based; Transformation and calibration algorithms; Vector matching algorithm; CAD-based localization algorithm</td>
<td>LB-12/LB-72 laser system; CORDAX (CMM); CATIA-CATGEO and MSP (FORTRAN);</td>
</tr>
<tr>
<td>Funtowicz and Zussman (1994,1998, 1999)</td>
<td>Coverage of entire surface and minimal length scanning path</td>
<td>Surface Geometrical Constr: - Accessibility of the inspected feature; - Desired accuracy; Constraints of Scanner: - Field of View; - Depth of View; - View Angle</td>
<td>2D-based 2D profile of a surface; Free-form surfaces; Surface Decomposition method;</td>
<td>Matlab simulation; Catia and Fortran 77; Six DOF Robot (ABB 3000); Laser Scanner.</td>
</tr>
<tr>
<td>Bernard, et al. (1999,2000)</td>
<td>To automatically generate the measuring process of the part.</td>
<td>Shadow and occlusion; Angle between laser beam and the normal of surface; Visibility;</td>
<td>Knowledge-based; Visibility theory; Simulation-validation-generation loop;</td>
<td>GAMMA 1203, KLS 52 plane laser sensor; CimStation Inspection, Robotics and Paint.</td>
</tr>
<tr>
<td>Xi and Shu (1999)</td>
<td>Automated path planning for 3-D line laser scanner-Maximum coverage</td>
<td>Field of View (FOV);</td>
<td>CAD-based; Slicing approach;</td>
<td>Hymarc 3-D line laser scanner; Brown and Sharpe CMM;</td>
</tr>
<tr>
<td>Lamb, Baird and Greenspan (1999)</td>
<td>An automated 3D digitization system</td>
<td>Depth of Field; View Angle; Constant Sensor Orientation; Constant velocity; Min. No. of swaths; Min. No. of orientation changes; Collision Free;</td>
<td>Sensor-based and model-based; Digitizing strategies;</td>
<td>Hycscan 45C and Brown&amp;Sharpe DE A,</td>
</tr>
<tr>
<td>Milroy, et al. (1995,1996, 1997)</td>
<td>Automated laser scanning in reverse engineering</td>
<td>Occlusion; Edge and steep surface;</td>
<td>Orthogonal cross sections (OCS) model; BESTGAZE algorithm;</td>
<td>Hycscan 45C and Mitutoyo BHN 710 CMM;</td>
</tr>
<tr>
<td>Lee and Park (2000)</td>
<td>Scan Direction; Number of Scan; Scan path;</td>
<td>View Angle; Field of View (FOV); Depth of View (DOV); Occlusion; Collision;</td>
<td>CAD-based Free-form surfaces; LAD and GAD Techniques;</td>
<td>SURVEYOR 1200 CMM &amp; Rotary Table; CATIA-CATGEO Library;</td>
</tr>
</tbody>
</table>
2.3 COMPARISON OF PLANNING FOR CMM AND LASER SCANNER

The CMM and laser scanner as two different acquisition techniques have their own advantages and disadvantages. But they have a similar acquisition principle, that is, in order to get the coordinate data, they have to be able to reach the target and get the feedback. Also they have similar planning problem, which is how to cover the objects completely and efficiently with the optimal collision-free path. Therefore, it is important to recognize the differences and similarities between two methods in order to efficiently develop the inspection planning method for laser scanner.

2.3.1 Differences

(1) More constraints on scanning sensor probes compared with CMM tactile probe, such as: sensor-dependent constraints, shadows and occlusions;

(2) Fewer available positions and orientations for scanner than CMM tactile probe;

(3) Limited real working volume for laser scanner;

(4) Changing laser scanner orientation requires re-calibration;

(5) More factors affecting the accuracy when using laser sensor, such as the incident angle of laser beam, the changes of orientations, and the motion direction and speed during scanning;

2.3.2 Similarities

(1) Sampling methods are needed for both techniques.

(2) Accessibility/Visibility analysis techniques are applicable to both methods.
(3) Collision detection methods apply to both CMM probes and scanners/mounts.

(4) Path planning techniques for CMM inspection may be applicable to laser scanner.

2.4 DISCUSSION

This chapter began with the literature overview of inspection planning for CMM. A detailed literature review on scanning planning for laser scanner was presented. The comparison of planning for CMM and laser scanner was also provided at the end of this chapter. A number of problems related to laser scanning planning have been covered in the literature, such as identifying and modeling the constraints, visibility analysis, and laser scanner path planning. However, for some complex surfaces with deep concavity features, laser scanner may encounter difficulties to scan and these features need to be detected for other suitable inspection methods. The next chapter discusses the factors that affect the scanning planning, and a feature differentiation method based on ray tracing algorithm is presented.
Chapter 3 LASER SCANNING FACTORS ANALYSIS

In order to improve the scanning process, the automated scanning planning for laser scanner has to deal with some difficulties, such as how to extract the surface information, to solve visibility problem, to meet accuracy requirement, to increase the efficiency and, furthermore, how to consider these factors in the scanning planning. In this chapter, the main factors that affect the scanning planning have been analyzed and integrated into the planning task.

3.1 SAMPLING METHOD

Since the laser scanner is able to quickly obtain a large amount of point data from part surface, it is possible to perform a complete scanning of the parts instead of sampled point to point tactile probing using CMM. Therefore the full coverage of scanning of the surface is desirable in most cases. For CAD-based scanning planning, the CAD model usually is available to assist the planning task and help determine the sensor scanning parameters.

In order to simplify the surface information, a sampling method for target surfaces is applied to extract the necessary information from CAD model. The sampled points and their normal vectors on the surface are generated from the CAD model and they provide the simple but necessary information which can help to cluster the sampled points into different groups and to divide the whole surface into different patches. Then the laser scanning parameters and moving paths are determined for each of these patches. The
sampling process can be done in software, such as SDRC I-DEAS Freeform (former Imageware Surfacer) or by computer-aided sampling methods (ElKott, 2001).

Some research work has been done in sampling techniques, which can also be applied in laser scanner planning. For primitive surfaces, the equi-parametric (isoparametric) sampling method may be used. For free form surfaces, ElKott, et al. (1999, 2000, 2001) developed computer-aided free form surfaces sampling methods for CMM inspection planning. Four sampling techniques, equi-parametric sampling, patch size based sampling, mean curvature based sampling and hybrid sampling approach, have been presented. Optimum sampling plans, based on the Genetic Algorithms (GAs), were also developed.

Because the proposed laser scanner planning is mainly based on the sampled points and normal vectors, the density and distribution of sampled points affect the result of scanning planning. More sampled points will represent the surface and its features more precisely, but the computation will be increased accordingly. When applying the sampling methods, the density and distribution should make sampled points cover the surfaces uniformly to reflect all features to be scanned.

3.2 VISIBILITY

Because the laser scanner works on the principle of triangulation, in order to have a successful scan, the incident beam has to reach the surface and the reflected beam by the surface has to be detected by the camera. In other word, the surface has to be "visible or
accessible" to the laser and sensor. That’s why visibility is a very important issue in the scanning planning.

The visibility analysis method for CMM tactile probe inspection (see Section 2.2 in Chapter 2) may be appropriate for analyzing the visibility of laser scanner. But there are still differences in applications. The algorithm for tactile probe is based on each single point. The accessibility of one point has nothing to do with another point, because the CMM and probe configurations are able to access each point discretely and accurately.

For the laser scanner, the potential of the laser triangulation probe is better realized if the measurements are performed “on the fly”. In the case of laser scanner mounted on the CMM, the configuration of the CMM constrains the measurements to be performed in straight-line scans, with constant probe orientation. The scanning path is therefore made up of a sequence of linear machine moves that alternately perform scanning and probe reorientation. However, each reorientation of the probe requires an alignment process and stopping the machine to change the orientation, so it is vital to minimize the number of reorientations in order to measure a given component as efficiently as possible.

For the visibility issue, the related work done by other researchers is reviewed first. Then the constraints and limitations that affect the visibility for laser scanning will be analyzed thoroughly. A feature differentiation method, which would detect certain deep concavity features, will be presented.
3.2.1 Related Work

So far, much research on the visibility analysis is based on the sampled points. Funtowicz and Zussman (1998, 1999) employed the Gauss map, which takes each point and its unit normal vector, to decompose the surface into different clusters. And all points in one cluster are locally visible, which means meeting the constraints of view angle. However, their algorithm didn't consider the global visibility constraint.

Lee and Park (2000) considered the scannability constraints by calculating the locally accessible directions (LAD) for each mesh point. Then the scanning directions that cover the entire part surface are determined by performing Boolean intersection operations among LADs, where the result of these operations are called the sets of globally accessible directions (GAD). The number of GAD will decide the number of scans for scanning the entire surface.

Bernhard and Veron (2000) proposed an application and adaptation of the visibility theory to the automatic determination of the scanning strategies for the digitization of 3D complex parts using a laser sensor.

3.2.2 Visibility Constraints Analysis

Because the laser probe scanning depends on the location of the laser scanner viewpoint from which the surface is visible, the scanning planning for laser scanner could be presented as a problem where the laser-scanner viewpoint must satisfy all the visibility constraints simultaneously. First of all, the analysis of visibility constraints and
limitations in laser scanning is the first step of planning. Many researchers have
proposed methods and algorithms to analyze and model the constraints (Funtowicz &
Zussman, 1999; Funtowicz, Zussman and Meltser, 1998; Lamb, Baird and Greenspan,
1999; Zussman, Schuler and Seliger, 1994). The constraints could be categorized into
different groups according to their dependencies.

3.2.2.1 Sensor-dependent Constraints:

(1) View angle, constraint on the angle between the incident laser beam and the
surface normal. Otherwise the reflected beam won't be detected by CCD. The
constraint of view angle can be described by a view cone model (in Figure 3.1).

(2) Field of View (FOV), the surface being scanned should be within the width of a
laser stripe (see Figure 3.2).

(3) Depth of View (DOV), the scanned surface should be within a specified range of
distance from the laser source (see Figure 3.2).

Figure 3.1: Constraint of View Angle
3.2.2.2 Object-Related Limitations:

(1) The incident beam as well as the reflected beam should not interfere with the part
or the probe itself to avoid shadows and occlusions (shown in Figure 3.3).

Figure 3.2: Measurement Plane

Figure 3.3: The Shadow and Occlusion Effect
(2) Invisibility of laser scanner for some parts of the object (the parts with volumetric features such as slots, steps, blind holes, irregular cavities, bosses, protrusions and notches) subject to sensor limitations.

![Diagram of sensor and invisible features](image)

Figure 3.4: Invisibility of Some Features for Laser Scanner

### 3.2.3 Feature Differentiation

Due to the constraints and limitations discussed above, the laser scanning technique may face some difficulties when acquiring points on complex exterior surface having deep concavities, such as deep holes, pockets, and slots. This will lead the scan data to contain many voids or gaps in the surfaces.

#### 3.2.3.1 Background

In 1994, Concurrent Technologies Corporation (CTC), Johnstown PA, conducted an extensive study on re-engineering mechanical components using laser scanning (Chow, 1997). The study classified mechanical parts, with respect to re-engineering, into three categories:
Category I consists of parts with simple linear or curvilinear 2D features where the 3D object is constructed by fully extruding these features. The bounding surfaces require simple mathematical definitions, such as planar and cylindrical equations.

Category II consists of parts with volumetric features such as slots, steps, blind holes, irregular cavities, bosses, protrusions and notches. The bounding surfaces require either simple or complex mathematical definitions, such as planar, cylindrical, and simultaneous high-order polynomial equations.

Category III consists of parts with convex features without any volumetric feature definition. The bounding surfaces of these parts are generally difficult to represent mathematically and are represented by complex equations. Examples of parts in this category are turbines, and moulds and dies for automotive parts.

CTC used a wide range of commercial laser scanning hardware and software products to study the applicability of the laser-scanning process to re-engineer and remanufacture mechanical parts. They found that the use of laser scanning to re-engineering parts in categories I and III was a relatively simple process and resulted in significant time and cost savings. However, laser scanning and the subsequent modeling of parts in category II, which is the category that most aircraft structural components fall into, was a cumbersome and labor intensive process. One of the main reasons for the difficulties is that multiple scanning of the part and then merging of the multiple scans
into a complete model are required. One of the common geometric features in structural components, such as vertical walls, also presents some serious problem to laser scanning.

Tarbox (1995) presented a series of three planning algorithms for finding a set of sensing operations for completely measuring the exposed surface of an object to be inspected. In the study case of coffee cup, they also found out that the coffee cup was extremely difficult to inspect due to the deep concavity inside.

Therefore, it is necessary that these features can be differentiated and identified for other more appropriate inspection methods, such as CMM tactile probing process in order to reduce the unnecessary effort for some impossible-to-view, even hard-to-view regions. In this research, an algorithm based on the ray tracing method to perform the feature differentiation is presented.

3.2.3.2 The Ray Tracing Algorithm

Ray tracing has been used in a variety of applications: visual realism of solid to generate line drawings with hidden solids removed, animation of solids, and shading and rendering (Zeid, 1990). The ray tracing algorithm used in this research is going to tell if there are intersections between rays and entity. A ray can be described and constructed by three parameters, the source position, the direction vector and radius.

Based on the surface point sampling method, each ray model is constructed by taking the position of the sampled point as ray source position, the normal vector of the sampled
point as ray direction vector. If there is an intersection between a ray and entity, we consider that there is a hit between the ray and entity. From analysis of the features that contain deep concavities, the sampled points could be classified into two categories using the ray tracing method (Figure 3.5).

(1) Open position: the ray from the position along the normal vector of position has only one hit with the entity;

(2) Close position: the ray from the position along the normal vector of position has more that one hits with the entity, which means the ray has intersections with the entity.

![Ray Model and Ray Tracing Method](image)

**Figure 3.5: Ray Model and Ray Tracing Method**

This algorithm is implemented and simulated using the ACIS Solid Modeler 6.0 (Spatial Technology, 1999) and C++. The positions, where the rays with more than one hit are sent, will be separated for other appropriate methods, such CMM probing. The algorithm is shown in the Table 3.1.
Table 3.1: Ray Tracing Algorithm

**Input:**
- \( S(u, v) \), input surface;
- \( P_k \), measurement point \( k \), \( 1 < k < N \);
- \( V_k \), normal vector at the measurement point;
- \( R_k \), testing ray for each sampled point \( k \), \( 1 < k < N \);
- \( r \), the radius of test ray;
- \( H(S(u,v), R_k) \), the function to calculate the number of hits between surface, \( S(u,v) \), and testing ray, \( R_k \).

**Output:**
- \( \Omega \), set of points for laser scanning;
- \( \Psi \), set of points for other techniques;

**Algorithm:**

Initialization
\[
\Omega = \{}; \Psi = \{}
\]

Iteration
for each \( P_k \), \( 1 \leq k \leq N \) do
- Construct \( R_k \) with starting position at \( P_k \), direction of \( V_k \), and radius of \( r \)
- If \( (H(S(u,v), R_k) > 2) \)
  \[ \Psi = \Psi \cup \{P_k\} \]
end
\[ \Omega = \{P_1...P_N\} - \Psi \]

### 3.2.3.3 Examples

Figure 3.6 shows a free form surface with deep concavity features. 150 uniformly-sampled points and their normal vectors are taken as inputs to construct the testing rays
(Figure 3.7 (a)). By using ray tracing algorithm, 12 positions from which the rays have more than one hits were detected (shown in Figure 3.7(b)). These points will be selected for other appropriate inspection methods. The output is the list of points from which testing rays have hits with the object. The list is: 14, 15, 23, 28, 29, 30, 33, 34, 35, 36, 38, 53.

Figure 3.6: Free Form Surface with Deep Concavities

Figure 3.7: Example of Ray Tracing Method
(a) : The sampled positions and the ray models
(b) : The positions segregated by ray tracing
3.3 ACCURACY

For the current application of laser scanning technique in the 3D data acquisition, it is almost impossible to reach the accuracy obtained by a CMM equipped with a contact probe, which is lower than the micron. For a laser scanner mounted on a CMM, the accuracy is about 25 microns at best. The 3D laser sensors, delivering information about the object surface, all work according to a common principle: emitting a laser beam (incidental ray) from a laser diode, and then getting and analyzing the reflected ray. The optics laws require that the laser rays be normal to the surface for maximum reflected energy. This necessitates that the laser beam should be kept as normal as possible to the queried surface.

Smith and Zheng (1998) conducted accuracy analysis of point laser triangulation (PLT) probes by using simulation techniques. They developed the probe model and simulated observed measurement errors. The effects of sensor-to-surface orientation, specula reflection, and component placement and orientation were analyzed using simulation program.

Prieto, et al. (1999) modeled the accuracy of the NRC 3D laser sensor as a function proportional to the distance between the sensor and the surface and to the incident angle. They achieved 128 measurements in different positions for distance and orientation of the laser sensor with respect to a reference surface. They found the best scanner placement range as 170mm ~ 240mm and the dispersion of experiment variance is smaller when the incident angle is near to zero, or normal to the surface.
Xi, et al. (2000) addressed error compensation analysis for the 3-D line laser scanning data. They considered the angle between the scanning direction and the surface normal, and the scan depth as two error-influencing factors. An empirical compensation formula was obtained through error characterization. The error formula obtained from the least square fitting is given as:

$$\hat{\epsilon} = (-0.00016\alpha + 0.0033)(0.25d - 40.85) + 0.11$$ (3.1)

where $\hat{\epsilon}$ denotes the estimated error, $\alpha$ denotes the view angle in degrees between -40 and 40, and $d$ denotes the depth of view in mm between 106 and 154, corresponding to the top and bottom of field of view (FOV), respectively. The standoff distance of the laser scanner used is 106 mm.

Rolls (2001) also discussed the uncertainties in laser scanning data collection. A number of major sources of uncertainties encountered during single view digitization using the Hymarc Hyscan 45C laser scanner were identified and quantified. Those uncertainties are ranging distance, time, and the angle between the scanning axis and object surface normal. The results show that significant uncertainty exists with variation in the ranging distance, and a clear and significant increase in the digitization error, particularly when the angular misalignment within the scanner FOV exceeds 20°.

The uncertainty and accuracy analysis in laser scanning data collection lays the foundation for the error compensation methodology, and also the results can be utilized in the automated planning task for laser scanning in order to reach the required accuracy. In this research work, the following two main factors have been considered:
- View angle between surface normal and scanning direction;
- Distance between sensor and surface.

The view angle as the first criterion in clustering algorithm is used to ensure that both the visibility and accuracy requirements are met. Distance between the sensor and surface is represented by two parameters, Depth of View (DOV) and standoff distance. These three parameters: view angle, depth of view, and standoff distance can be input by users for the special accuracy requirement.

### 3.4 EFFICIENCY

One of the important objectives of scanning planning is to increase the efficiency of laser scanning process. The laser scanning process mainly involves the orientation alignment, re-orientation setup and scanner moves. There are two factors that affect the time and cost of the laser scanning process.

#### 3.4.1 The Number of Orientations

During the laser scanning process, the most costly process is the orientation changes because each re-orientation of the probe requires re-alignment process and stopping the machine to change the orientation before the scanner can be used again. Therefore, it is vital to minimize the number of orientations in order to measure a given component as efficiently as possible.
The clustering algorithm based on the view angle is used to cluster the sampled points into different groups. Each group includes as many points as possible as long as all points in one group can be viewed by laser scanner using one orientation.

3.4.2 The Sequence of Moving Path

For the movements involved in the scanning process, there are two kinds of moves. One is within the cluster, which performs the cloud data collection. Traditional zig-zag path plan is chosen to control the moves within the cluster and the moving speed can also be determined for the better digitization effect. For the move among the clusters, there is no data collection, so the scanner can move faster and choose the better sequence for saving the time and traveling distance.

In order to reduce the number of changing orientations and moving distance among clusters, the moving path search algorithm starts from the current cluster and searches for the closest cluster. If there are more than one cluster that need the same orientation, the scanning will be done for the clusters which require the same orientation first to avoid the change of orientation, then goes to the next closest cluster.

3.5 DISCUSSION

This chapter identified and analyzed some factors which affect the laser scanning process. These factors are taken into consideration in the scanning planning method developed in the next chapter. The feature differentiation method separated positions and
normal vectors into two groups, one of which are taken as input for the laser scanner planning task.
Chapter 4 SCANNING PLANNING FOR LASER SCANNER

The objective of the Feature Differentiation (FD) approach presented in the Chapter 3 is to form two sets of points for planning. A CMM planning system, called Computer-Aided Tactile Inspection Planning (CATIP), was developed by Limaiem and ElMaraghy (1999). In this chapter, a computer-aided scanning planning system for laser scanner is presented. Figure 4.1 shows the structure of the new system.

![Diagram of scanning planning system]

**Figure 4.1:** Structure of Scanning Planning for Laser Scanner

4.1 CLUSTERING ALGORITHM

Based on the sampled points and normal vectors of the surfaces, the aim of the clustering algorithm is to divide all the sampled points into different clusters according to the constraints of view angle of laser scanner. Then the scanning direction for each
cluster will be computed. At the same time, the number of clusters is necessary to be minimized for the efficient digitizing process of the surface.

4.1.1 The Normal Cone and Normal Map

Kim, et al, (1995) discussed the definitions and properties of three types of cones on Bezier surfaces, i.e., tangent, normal and visibility cones. There are many applications of these cones in robotics, machining planning, and sensing planning.

**Definition 1:** Let a point set \( S = \{p_i \mid i = 1 \ldots k, p_i \in \mathbb{R}^3 \} \). Then the set of points is the affine set generated by \( S \). When \( \alpha_i \geq 0 \), the affine set becomes the convex set generated by \( S \).

\[
\{ p \mid p = \sum_{i=1}^{k} \alpha_i p_i, \alpha_i \in \mathbb{R}, \sum_{i=1}^{k} \alpha_i = 1 \}
\]  

(4.1)

**Definition 2:** \( \sigma \) is a sphere with unit radius centered at the origin, \( O \), of \( \mathbb{R}^3 \).

**Definition 3:** A cone \( C \) is said to be generated by \( S \) if

\[
C = \{ p \mid p = \lambda q, q \in S, \forall \lambda \geq 0 \}
\]

(4.2)

When the boundary of \( C \cap \sigma \) is a small circle, the cone is called a circular cone. When \( \lambda = 0 \) in particular, \( p \) is called an apex of the cone.

**Definition 4:** Bezier surface of degree \( m \times n \) are defined by an equation

\[
b^{m,n}(u,v) = \sum_{i=0}^{m} \sum_{j=0}^{n} b_i B^m_i(u)B^n_j(v), \quad u, v \in [0,1]
\]

(4.3)

A normal cone, \( N \), is a set of points in \( \mathbb{R}^2 \), such that a position vector of a point in \( N \) corresponds to a normal vector on the surface, at some \( u \) and \( v \). It is defined as

\[
N = \{ p \mid p = \lambda n, \forall \lambda \geq 0, \quad u, v \in [0,1] \}
\]

(4.4)
Where \( p \in \mathbb{R}^3 \) and \( n \) is a normal vector on \( b^{m,n}(u, \nu) \).

Figure 4.2: Normal Cone and Normal Map of A Planar Curve

A normal map, \( N \), is defined as \( N = \mathbb{R} \otimes \sigma \). A normal map for a surface \( b^{m,n}(u, \nu) \) is denoted as \( N(b^{m,n}(u, \nu)) \). A normal map is also known as the Gauss map (O'Neill, 1966). Figure 4.2 illustrates an example of a normal cone and a corresponding normal map for a planar curve.

A normal cone, \( N \), of a Bezier surface can be computed using a normal surface, \( N(u,r) \), which is defined as

\[
N(u,r) = H_u \times H_v = \begin{vmatrix} i & j & k \\ \partial_u x & \partial_u y & \partial_u z \\ \partial_v x & \partial_v y & \partial_v z \end{vmatrix}
\]

\[
= (\partial_u y \partial_v z - \partial_u z \partial_v y)i + (\partial_u z \partial_v x - \partial_u x \partial_v z)j + (\partial_u x \partial_v y - \partial_u y \partial_v x)k \tag{4.5}
\]

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4.1.2 The Clustering Algorithm Based on View Angle

According to the constraint analysis, the utilization of optical triangulation imposes a limit on the angle between the incident beam from the scanner and the normal of surface. Denote by $\angle ab$, the angle between two vectors $a$ and $b$, we can express the view angle constraint as:

Assume a given scanning direction $V$, and the view angle limit is $\alpha$. We say that a point $p_0$ is locally visible from $V$ if and only if the angle between normal vector of the point, $n_{p0}$ and scanning direction, $\angle n_{p0} V \leq \alpha$. Further, a region $R$ is said to be locally visible for the direction $V$ if and only if every point $p_k$ in region $R$ satisfies $\angle n_{pk} V \leq \alpha$.

Figure 4.3: Local Visibility from Scanning Direction

Figure 4.3 illustrates the local visibility of positions on a 2D curve. The angle between $n_{p1}$ and scanning direction ($V$) is less than the view angle limit, so is the angle between $n_{p2}$ and $V$. $P_1$ and $P_2$ are locally visible from the scanning direction $V$. Therefore, they can be clustered in one group, which means they can be scanned using the
same scanning direction. Since the angle between $n_{p3}$ and $V$ is larger the view angle limit, $P_3$ is not visible from $V$ and it needs another scanning direction.

In order to cluster all sampled points, a cone algorithm is presented. From the cone properties, we know that if the major angle is $2\alpha$, the angle between any two vectors which stays inside the cone is less than or equal to $2\alpha$. In other words, the angle between cone axis and any vector which stays inside the cone is less than or equal to $\alpha$. The cone provides a good description of view angle constraint (Figure 4.4). The objective of the cone algorithm is to search the normal vectors of sampled points, which can fit in the cone with major angle of $2\alpha$. Then the axis of cone will be returned as the scanning direction for the cluster so that the angle between the scanning direction, which is represented by cone axis, and any vector inside the cone is guaranteed to be less than or equal to view angle limit, $\alpha$.

![Cone Diagram](image)

**Figure 4.4: View Angle Constraint Represented by Cone Algorithm**

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The following processes describe how the cone algorithm works:

(1) The algorithm first calculates the angle between every two normal vectors.

(2) Starting from the first vectors, the algorithm searches all other vectors and finds a vector list in which each vector has the angle with the first vector less than $2\alpha$. Then the angle between every two vectors in this list will be evaluated, some vectors which have angle larger than $2\alpha$ will be deleted from the list. The average value of angles between every two vectors in the list is also calculated.

(3) Step (1) will execute for the second vector till the last one.

(4) Sort all the lists which resulted from step (2) and (3) according to their average value of angles. The list with the smallest average value of angle will be output as one of the final clusters. The normal vectors included in the clusters will be taken out from the original normal vector list.

(5) For the remaining normal vectors, steps (2)-(4) are repeated until all normal vectors have been clustered.

The pseudo-code is described in Table 4.1.
**Table 4.1: The Clustering Algorithm Based on View Angle**

**Input:**
- \( N \), number of sampled points;
- \( k \), sampled point index, \( 1 < k < N \);
- \( V_k \), normal vector at the sampled point \( k \);
- \( \alpha \), angle limit between incident beam and surface normal.

**Output:**
- \( N\text{Cluster} \), number of clusters;
- \( \text{ClusterSet}[n] \), set of points in cluster \( n \), \( n = 1 \ldots N\text{Cluster} \);

**Algorithm:**

Initialization
- \( N\text{Cluster} = 0 \);

\[ \text{TempSet} = \{1, 2, \ldots, N\}; \] // index of the sampled points

\[ \text{SizeTempSet} = N; \] //The number of points in \( \text{TempSet} \)

\( \text{TempClusterSet}[j] \); // array to record the intermediate sets of point index;

for every two vectors, \( V_i, V_j, 1 \leq i \leq N, 1 \leq j \leq N \) do

compute the angle between \( V_i \) and \( V_j \), \( \text{angle_between}[i][j] \)

Do while (\( \text{SizeTempSet} ! = 0 \))

\( \text{TempClusterSet}[\text{SizeTempSet}] \);

for \( (i=1; i < \text{SizeTempSet} + 1; i++) \)

- construct the \( \text{TempClusterSet}[i] \) from \( \text{TempSet} \) with the criteria:
  - Starting from \( V_i \);
  - \( \forall p, q \in \text{TempClusterSet}[i], \text{angle_between}[p][q] \leq 2^\circ \alpha \)
  - \( \text{TempClusterSet}[i] \) should include qualified vectors as many as possible
  - Calculating the average \( \text{angle_between} \) in \( \text{TempClusterSet}[i] \);

endfor

sort the \( \text{TempClusterSet} \) according to the average \( \text{angle_between} \),

return the \( \text{TempClusterSet}[m] \) with the smallest average \( \text{angle_between} \);

\( \text{ClusterSet}[N\text{Cluster}] = \text{TempClusterSet}[m] \);

\( \text{TempSet} = \text{TempSet} - \text{TempClusterSet}[m] \);

\( N\text{Cluster}++ \);

endo
4.1.3 Calculation of Scanning Direction for Each Cluster

For each cluster, the cone algorithm will be used to calculate the scanning direction. According to the clustering algorithm, the angle between every two vectors that are in one cluster is guaranteed less than $2\alpha$. Table 4.2 shows the pseudo-code of the calculation of scanning direction. Figure 4.5 illustrates the calculation of two scanning directions for two clusters using the cone algorithm.

<table>
<thead>
<tr>
<th>Table 4.2: Calculation of Scanning Direction for Cluster</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input:</strong></td>
</tr>
<tr>
<td>$N$, number of sampled points;</td>
</tr>
<tr>
<td>$N_{Cluster}$, number of clusters;</td>
</tr>
<tr>
<td>$Cluster_{Set_k}$, set of point number in cluster $k$, $1 \leq k \leq N_{Cluster}$;</td>
</tr>
<tr>
<td>$P_t$, sampled point $t$, $1 \leq t \leq N$ and $t \in Cluster_{Set_k}$;</td>
</tr>
<tr>
<td>$V_t$, normal vector at the sampled point $P_t$;</td>
</tr>
<tr>
<td><strong>Output:</strong></td>
</tr>
<tr>
<td>$SV_k$, scanning vector (direction) for cluster $k$, $1 \leq k \leq N_{Cluster}$;</td>
</tr>
<tr>
<td><strong>Algorithm:</strong></td>
</tr>
<tr>
<td>Initialization</td>
</tr>
<tr>
<td>Iteration</td>
</tr>
<tr>
<td>for $1 \leq k \leq N_{Cluster}$ do</td>
</tr>
<tr>
<td>for every point in $Cluster_{Set_k}$ do</td>
</tr>
<tr>
<td>search two points, whose have the largest between-angle in the cluster, $\angle V_aV_b$</td>
</tr>
<tr>
<td>construct the cone with major angle $= \angle V_aV_b$</td>
</tr>
<tr>
<td>return the axis of cone as $SV_k$</td>
</tr>
<tr>
<td>end</td>
</tr>
<tr>
<td>end</td>
</tr>
</tbody>
</table>
4.1.4 Example: Hoof-Shaped Surface

A hoof-shaped surface is used to show the result of applying the clustering algorithm based on the view angle constraint. Figure 4.6 (a) shows the 3D model in ACIS SAT file. 198 points and normal vectors were generated in Imageware Surfacer 9.0 by using uniform sampling method. The view angle limit is input in the degree of 33. There are three clusters generated from the clustering algorithm. The unit vector of scanning direction for each cluster is also calculated as follow:

0.3532 0.8214 -0.4478,
0.5120 -0.2551 -0.8202,
0.3044 -0.8325 -0.4630
(a): 3D Model of the Hoof-Shaped Surface;
(b): The Sampled Points and Normal Vectors
(c): Clusters and Scanning Directions;

Figure 4.6: Result of Applying the Clustering Algorithm Based on View Angle Constraint

4.1.5 Global Accessibility and Occlusion Check

In order to guarantee the global accessibility of the defined scanning direction, the incident and reflected beams have to be checked for shadows and occlusions caused by the object itself. This has been done by using ray-tracing algorithm for both incident and reflected beams as shown in Figure 4.7. Two testing rays are sent from each point. One ray follows the opposite direction of the incident beam, and the other follows the direction of the reflected beam. All testing rays are checked for the intersections with the object itself. As shown in Figure 4.7, the testing ray following the opposite direction of incident beam from point P2 has intersections with the surface, which means the incident beam will not reach position P2 due to the interference with the surface.
4.2 SCANNER PLACEMENT

4.2.1 Clustering Based on The Depth of View (DOV)

After the scanning directions are determined for each cluster, there is another parameter that needs to be decided. That is the distance along the scanning direction from the scanning device to the surface to be scanned. Actually the parameter is a range of distance because the laser scanner allows certain range of distance along the laser beam, called Depth of View (DOV), which is dependent on the scanning device. Therefore it is not necessary to determine standoff distance for each sampled point. The scanner placement is also based on the clustering algorithm. As long as the points using
the same scanning direction fall into the specific range of distance along the scanning direction, they can be clustered into one group and be set at the same standoff distance for the scanner. Figure 4.8 illustrates how to calculate the distance difference between two positions along the scanning direction.

![Diagram](image)

**Figure 4.8: The Distance Difference between Two Positions**

Two points, \( P_1 \) and \( P_2 \) on the surface, are in the same cluster which means they can be scanned along the same scanning direction. Through the point \( P_1 \), the plane perpendicular to the scanning direction, \( P_s \), is constructed. Then the distance from position \( P_2 \) to the plane \( P_s \) is computed as the difference \( \Delta D \) between \( P_1 \) and \( P_2 \). \( \Delta D \) is checked to ensure that it is within the allowable DOV; otherwise \( P_1 \) and \( P_2 \) will be in two different groups which have different scanner placements.
Figure 4.9: Clustering Based on The DOV

Figure 4.9 shows one cluster of points that fall within the DOV along the scanning direction.

4.2.2 Virtual Scanner Move Plane

A virtual scanner move plane is used to represent the spatial position plane which contains the laser scanner movement. When points are grouped into one cluster according to the allowable DOV (Figure 4.9), a center plane between the two planes, which contain all points between them and are perpendicular to the scanning direction, will be determined by taking the cluster orientation as normal vector (shown in Figure 4.10). The virtual plane is obtained by translating the center plane along the normal vector (the cluster orientation) by the standoff distance.
\[ P_{VM} = \text{Trans} \ (T_S \ V_C) \ P_C \]  \hspace{1cm} (4.6)

Where:

\( P_{VM} \): Virtual Scanner Movement Plane;

\( P_C \): Center Plane

\( V_C \): Cluster Orientation;

\( T_S \): Standoff Distance

Figure 4.10 shows how to determine the virtual scanner move plane.

Figure 4.10: Point Projection onto Virtual Scanner Moving Plane

In order to plan the scanner motion based on the clusters, the points in one cluster are projected onto the virtual scanner movement plane to form the certain pattern that is
represented by the projected points. Figure 4.11 shows the projected points on the virtual scanner move plane from the View T in Figure 4.10.

Figure 4.11: Projected Point Pattern from View T

Figure 4.12 shows the projected points on the virtual scanner movement planes based on the result of clustering shown in Figure 4.6 for hoof-shaped surface.

Figure 4.12: Projected Points on Virtual Move Planes of the Hoof-Shaped Surface
4.3 PATCH-BASED PATH PLANNING

After the scanning direction and scanner placement are determined, the point pattern for each cluster is generated on the virtual scanner plane by the projection procedure (Figure 4.10). These point patterns will be used to form different patches from which the scanning paths will be generated.

4.3.1 Envelop of Point Pattern

In order to form a patch from one point pattern, a bounding rectangle, which envelops the point pattern, is found. The following algorithm describes how to generate the bounding rectangle for one point pattern.

Table 4.3: The Algorithm to Find Bounding Rectangle (BR)

<table>
<thead>
<tr>
<th>Input:</th>
</tr>
</thead>
<tbody>
<tr>
<td>ProjPoint, projected points in one cluster;</td>
</tr>
<tr>
<td>Pvm, virtual scanner moving plane;</td>
</tr>
<tr>
<td>Px: yz plane (1,0,0)</td>
</tr>
<tr>
<td>Py: xz plane (0,1,0)</td>
</tr>
<tr>
<td>Px: xy plane (0,0,1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output:</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR, bounding rectangle for ProjPoint;</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Algorithm:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculate:</td>
</tr>
<tr>
<td>Dist_X: The distance of point pattern, ProjPoint, along axis X;</td>
</tr>
<tr>
<td>Dist_Y: The distance of point pattern, ProjPoint, along axis Y;</td>
</tr>
<tr>
<td>Dist_Z: The distance of point pattern, ProjPoint, along axis Z;</td>
</tr>
</tbody>
</table>
\textbf{Min}_X: The point in \texttt{ProjPoint} with minimum X-coordinate;
\textbf{Max}_X: The point in \texttt{ProjPoint} with maximum X-coordinate;
\textbf{Min}_Y: The point in \texttt{ProjPoint} with minimum Y-coordinate;
\textbf{Max}_Y: The point in \texttt{ProjPoint} with maximum Y-coordinate;
\textbf{Min}_Z: The point in \texttt{ProjPoint} with minimum Z-coordinate;
\textbf{Max}_Z: The point in \texttt{ProjPoint} with maximum Z-coordinate;

If (Dist\_X >= Dist\_Y >= Dist\_Z)
   Through \texttt{Max\_Y} construct plane, \texttt{P}$_{\text{max}}$ \parallel \texttt{P}$_Y$;
   Through \texttt{Min\_Y} construct plane, \texttt{P}$_{\text{min}}$ \parallel \texttt{P}$_Y$;
   Construct the straight line, \texttt{L}$_1$, by intersecting \texttt{P}$_{\text{max}}$ and \texttt{P}$_{\text{min}}$.
   
   \texttt{L}$_1$ = \texttt{INTERSECT}(\texttt{P}$_{\text{max}}$, \texttt{P}$_{\text{min}}$)
   
   \texttt{L}$_2$ = \texttt{INTERSECT}(\texttt{P}$_{\text{min}}$, \texttt{P}$_{\text{vil}}$)

   Through \texttt{Max\_X}, construct the line, \texttt{L}$_3$ \perp \texttt{L}$_1$
   Through \texttt{Min\_X}, construct the line, \texttt{L}$_4$ \perp \texttt{L}$_1$
   Return the bounding rectangle, \texttt{BR} (\texttt{L}$_1$, \texttt{L}$_2$, \texttt{L}$_3$, \texttt{L}$_4$).

If (Dist\_X >= Dist\_Z >= Dist\_Y)
   
   .......
   
   .......

\subsection{4.3.2 Scanner Moving Lines Generation}

Scanner moving lines represent the moving path when laser scanner sweeps over the surface. The linear scanner moving lines for one patch are generated from the bounding rectangle, \texttt{BR}, which is obtained from the above algorithm. Because the \texttt{BR} envelops all projected points in one cluster, now the problem becomes how to generate scanner-moving lines to cover the bounding rectangle, \texttt{BR}. In order to reduce the number of
scanner moving line in one patch, the longer edge of the BR is taken as the movement
direction of laser scanner. The number of scanner moving lines in one patch is
determined by the width of BR, W, and the width of laser strip. In Equation 4.7, function
\( \text{CEILING()} \) rounds a number up to an integer.

\[
\text{NoScanLines} = \text{CEILING}(\frac{\text{WidthOf Bounding Rectangle}}{\text{WidthOf LaserStripe}})
\]  \hspace{1cm} (4.7)

Another parameter, ScanLineOffset, which provides the extra distance before the
scanning starts, is used to determine the anchor points of scanner moving lines. Each line
has two anchor points representing the starting and ending position of the scanner.
Figure 4.13 shows how to generate the scanner moving lines for patches. The output will
be the number of scanner moving lines and their anchor points for each patch. Figure
4.14 shows the generated scanner moving lines for the hoof-shaped surface.

![Diagram](image)

**Figure 4.13:** Scanner Moving Lines for Patches

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4.3.3 Generation of Zig-Zag Path Within a Patch

After generating scanner moving lines for each patch, the zig-zag path method is applied to generate the paths among moving lines in one patch. In order to represent the patch scanner-moving line, the following structure is used in the algorithm (Table 4.4). Four anchor points of the two outmost moving lines of the patch represent four vertexes of each patch. The starting point could be any one of four vertexes. As long as the starting position is determined, the ending position is determined by the number of scans according to the property of zig-zag path.
Table 4.4: The Data Structure of Patch Scanner Moving Lines

Struct PatchScanLines
{
    int NoScanLine; // Number of scanner moving lines in one patch;
    int vert1;      // the point index number of the first vertex
    int vert2;      // the point index number of the second vertex
    int vert3;      // the point index number of the third vertex
    int vert4;      // the point index number of the forth vertex
    int startPoint; // the index number of the starting point of each patch
}

Figure 4.15: Zig-Zag Path in One Patch
As shown in Figure 4.15, the patch on the left side has only one scanner moving line. In this case, the vertex 1 overlaps with vertex 3, so does vertex 2 with vertex 4. The patch on the right side of Figure 4.15 has three scanner moving lines. The figure shows that the patch is taking vertex 1 as the starting position, and the number of scanner moving lines is three (odd), so the ending position will be vertex 4. Therefore, when the starting position in one patch is determined, the zig-zag path within the patch is also determined, and so is the ending position.

4.3.4 Movement between Patches

For the movement path between the current patch and next patch, the algorithm starts from the ending position of the current patch and searches for the closest vertex among the vertexes of all remaining patches. If there is more than one patch having the same patch normal vector (which means there are more than two patches that can be scanned using the one direction), the search will be done among the patches with the same normal first, followed by the next closest patch. The found closest vertex will be considered as the starting position of the found patch. The graphic simulation in ACIS SAT file is shown in Figure 4.16. As displayed in Figure 4.16, three patches are connected with the linear zig-zag paths to cover the whole hoof-shaped surface.
Figure 4.16: Zigzag Scanning Path Generated for the Hoof-shaped Surface

Table 4.5 shows the final output file which contains the patch and path information for the example. Some input information, such as number of points and normal vectors, is recorded in the file and so are the user-defined parameters, such as the view angle limit, allowable DOV, the standoff distance, the scan width, and scan length offset. The patch and path information includes the number of patches, the number of scanner moving lines, the scanning direction for each patch, and the anchor points of scans.
Table 4.5: Final Output Plan for the Hoof-Shaped Surface

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sampled positions</td>
<td>198</td>
</tr>
<tr>
<td>Number of normal vectors</td>
<td>198</td>
</tr>
<tr>
<td>Number of positions detected by ray-tracing</td>
<td>0</td>
</tr>
<tr>
<td>The view angle limit</td>
<td>33.0</td>
</tr>
<tr>
<td>The No. of clusters based on view angle</td>
<td>3</td>
</tr>
<tr>
<td>The allowable DOV</td>
<td>40.0</td>
</tr>
<tr>
<td>The No. of patches based on the DOV</td>
<td>3</td>
</tr>
<tr>
<td>The standoff distance</td>
<td>165.0</td>
</tr>
<tr>
<td>The scan width</td>
<td>70.0</td>
</tr>
<tr>
<td>The scan length offset</td>
<td>40.0</td>
</tr>
<tr>
<td>No of Patches</td>
<td>3</td>
</tr>
<tr>
<td>No of Scans</td>
<td>6</td>
</tr>
</tbody>
</table>

Patch No. 1
- No of Scans: 2
- The scanning direction: 0.3532 0.8214 -0.4478
- Angle with X, Y, Z Axis: 69.3 34.8 116.6
- The anchor points of scans:
  - 303.31 -184.88 -63.97
  - 529.63 -184.88 114.54
  - 505.64 -157.98 144.96
  - 279.32 -157.98 -33.55

Patch No. 2
- No of Scans: 2
- The scanning direction: 0.5120 -0.2551 -0.8202
- Angle with X, Y, Z Axis: 59.2 104.8 145.1
- The anchor points of scans:
  - 232.70 26.64 48.46
  - 517.28 26.64 226.10
  - 523.87 73.80 215.55
  - 239.29 73.80 37.91

Patch No. 3
- No of Scans: 2
- The scanning direction: 0.3044 -0.8325 -0.4630
- Angle with X, Y, Z Axis: 72.3 146.4 117.6
- The anchor points of scans:
  - 338.34 197.46 -21.56
  - 541.28 197.46 111.87
  - 565.01 226.21 75.77
  - 362.07 226.21 -57.66

The total path traveling distance: 2257.58
4.4 DISCUSSION

This chapter presented a computer-aided scanning planning method based on the object CAD model and sampled points.

The clustering algorithm based on the view angle limit decomposes all the sampled points into different clusters. Each cluster can be scanned using one direction. For each cluster, Depth of View (DOV) is used to determine the scanner position; one cluster may have more than one placement for the scanner due to the DOV constraint.

All points in one cluster are projected on a virtual plane which contains the laser scanner move positions. Projected points form certain point pattern, and one bounding rectangle that envelops the point pattern is determined to form the patch.

Zig-zag scanning paths are generated to cover each patch, and a search algorithm which find the next closest patch is used to produce the paths between patches. The final output plan includes the number of patches, scanning directions, scanner moving lines, and scanner moving paths. Examples were also provided to show the planning results.
Chapter 5 SIMULATION AND EXPERIMENTAL TEST

A Computer-Aided Laser-scanning Planner (CALP) system, based on the proposed planning method, has been implemented in ACIS 3D Toolkit and C++. In order to test the proposed method, both computer simulation and experimental testing using the Hymarc laser scanner and CMM were applied in this research. Figure 5.1 shows the structure of the implementation and simulation system.

5.1 COMPUTER SIMULATION

ACIS 3D Toolkit and optional husks are also used in this research as geometric modeling and simulation platform. ACIS 3D Toolkit (ACIS) is an object-oriented three-dimensional geometric modeling engine from Spatial Technology Inc. It is designed for use as the geometric foundation within many end user 3D modeling application. ACIS, written in C++, provides an open architecture framework for wireframe, surface, and solid modeling from a common, unified data structure.

The simulation module is to display intermediate and final results of path planning system. The display includes:

1. The surface, the sampled points, the normal vectors and the configuration of the transportation (e.g. laser scanner mounted on the CMM);
2. Results of the ray tracing for feature differentiation;
3. The normal vectors in different cluster after the view angle clustering;
4. The scanning direction for each cluster;
Figure 5.1: The Structure of Implementation and Simulation of CALP
(5) Projected positions (to form the patch) on the virtual scanner movement plane after the DOV clustering;

(6) Linear scanner moving lines for each patch; and

(7) Zig-zag path lines, which connect all patches.

5.1.1 Simulation Case #1

The first example is a car light lens which has simple free-form surface. The 3D surface model is shown in Figure 5.2(a). 145 positions were sampled by using uniform sampling technique in Imageware Surfer 9.0, and 145 normal vectors were also generated at sampled positions. The ray tracing module tested all positions and normal vectors, and no vectors were found to have intersections with surface itself. Three view angle limit values; 15°, 20° and 25° are respectively applied to test the planning results. Some other input parameters are:

(1) The allowable DOV is: 40.0mm

(2) The scan width is: 70.0mm

(3) The scan length offset is: 40.0mm

Figure 5.2 (b-d) presents the three planning results based on the different view angle limit values. The detailed comparison is given in Table 5.1. From the results of planning, it is noted that when the 15° view angle limit is applied, there is one more cluster based on DOV than on view angle. That means there is two clusters using the same scanning orientation but two different scanner placements due to the DOV constraint. The simulation results also show that when the view angle constraint is

77
relaxed (i.e. 20° to 25°), the total traveling distance is greatly reduced due to the reduced number of patches.

**Figure 5.2: Simulation Case #1: Car Light Lens**

- **a**: 3D surface model
- **b**: Path and Scanning Directions (View Angle Limit = 15°)
- **c**: Path and Scanning Directions (View Angle Limit = 20°)
- **d**: Path and Scanning Directions (View Angle Limit = 25°)
Table 5.1: Comparison of Planning Results with Different View Angle Limits for Car

<table>
<thead>
<tr>
<th>View Angle limit (Degree)</th>
<th>No. of Points Detected by Ray-tracing</th>
<th>Clusters (Base on View Angle)</th>
<th>Clusters (Based on DOV)</th>
<th>No. of Patches</th>
<th>No. of Scans</th>
<th>Total Traveling Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 (b)</td>
<td>0</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>2862.91</td>
</tr>
<tr>
<td>20 (c)</td>
<td>0</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>2682.81</td>
</tr>
<tr>
<td>25 (d)</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>1876.03</td>
</tr>
</tbody>
</table>

5.1.2 Simulation Case #2

Simulation case #2 has combined features of free form surface, steps, and holes. The 3D model was built in SDRC I-DEAS MS7 shown in Figure 5.3(a). The IGES file was imported to Imageware Surfacer 9.0 and the surfaces were sampled by using uniform sampling method. There are 300 sampled positions and their normal vectors, generated from Imageware Surfacer, are shown in Figure 5.3 (b). The ACIS model, sampled points, and normal vectors were input to CALP and first to segregate the certain positions on features which are not suitable for laser scanning. Figure 5.3 (c) shows the result of feature differentiation using ray tracing method. Points on the walls of two through holes were separated from the other points. The remaining points and normal vectors were input to CALP to automatically generate the scanning plan for laser scanner. Figure 5.3 (d) presents the result of clustering method based on the view angle constraint of 20°: five clusters were generated. Figure 5.3 (e) illustrates the scanning lines for each cluster and zig-zag path to cover the surfaces.
Figure 5.3: The Simulation Case #2

a: 3D model of simulation case #1  
b: Sampled points and normal vectors

c: Result of feature differentiation using ray tracing method

d: Clusters based on the view angle limit  
e: Zig-zag path for laser scanning of object
5.1.3 Simulation Case #3

Simulation case #3 was chosen to illustrate the effects when different view angle limits apply. The 3D model was constructed in ACIS by ACIS-Scheme interface. Appendix I shows the Scheme code for simulation case #3.

Simulation case #3 presents some complex features, such as free form surface, concavity features, and vertical walls (shown in Figure 5.4 (a)). Figure 5.4 (b) shows 151 sampled positions and their normal vectors, which are generated in Imageware Surfacer 9.0. 53 positions on the vertical wall are differentiated by the ray tracing algorithm first before scanning planning for laser scanner (shown in Figure 5.4 (c)).

Three different view angle limit values were applied to the scanning planner system respectively. The simulated moving path and scanning directions are shown in Figure 5.4 (d,e,f). The simulation demonstrated that the ray tracing algorithm successfully detected the positions on the vertical walls which are hard for laser scanner to scan. Table 5.2 shows the final outputs of planning work for two view angle limits and other system parameters keep the same. It also shows that the number of clusters based on view angle changed from three to four due to the tighter view angle constraint of 15°. From the detailed comparison shown in Table 5.3, it is noted that 20° makes the least number of scans and the least total traveling distance. When the view angle limit increases to 25°, one cluster includes more points, which makes the patch bigger and needs more scans and traveling distance to cover the patch.
Figure 5.4: Simulation Case #3

a: 3D model in ACIS SAT file;  
b: Sample points and normal vectors;

c: Result of feature differentiation;  
d: Final path with view angle limit of 15°

e: Final path with view angle limit of 20°;  
f: Final path with view angle limit of 25°
Table 5.2: The Output Files Based on Two Different View Angle Limits for Simulation

Case #3

<table>
<thead>
<tr>
<th>The angle limit is: <strong>25.0</strong></th>
<th>The angle limit is: <strong>15.0</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The No. of clusters based on view angle: 3</td>
<td>The No. of clusters based on view angle: 4</td>
</tr>
<tr>
<td>The standoff distance is: 165.0</td>
<td>The standoff distance is: 165.0</td>
</tr>
<tr>
<td>The allowable DOV range is: 40.0</td>
<td>The allowable DOV range is: 40.0</td>
</tr>
<tr>
<td>The No. of patches based on the DOV: 3</td>
<td>The No. of patches based on the DOV: 4</td>
</tr>
<tr>
<td>The scan width is: 70.0</td>
<td>The scan width is: 70.0</td>
</tr>
<tr>
<td>The scan length offset is: 40.0</td>
<td>The scan length offset is: 40.0</td>
</tr>
<tr>
<td>No of Patches: 3</td>
<td>No of Patches: 4</td>
</tr>
<tr>
<td>No of Scans: 7</td>
<td>No of Scans: 7</td>
</tr>
<tr>
<td>Patch No. 1</td>
<td>Patch No. 1</td>
</tr>
<tr>
<td>No of Scans: 3</td>
<td>No of Scans: 3</td>
</tr>
<tr>
<td>The patch normal: -0.0372 -0.0394 -0.9985</td>
<td>The patch normal: -0.0590 -0.2365 -0.9698</td>
</tr>
<tr>
<td>Angle with X, Y, Z Axis: 92.1 92.3 176.9</td>
<td>Angle with X, Y, Z Axis: 93.4 103.7 165.9</td>
</tr>
<tr>
<td>The anchor points of scans:</td>
<td>The anchor points of scans:</td>
</tr>
<tr>
<td>59.51 -116.42 182.04</td>
<td>63.44 -81.80 203.48</td>
</tr>
<tr>
<td>59.51 128.80 172.36</td>
<td>63.44 156.95 145.25</td>
</tr>
<tr>
<td>6.20 128.88 174.35</td>
<td>10.17 157.70 148.31</td>
</tr>
<tr>
<td>6.20 -116.34 184.03</td>
<td>10.17 -81.05 206.53</td>
</tr>
<tr>
<td>-47.12 -116.26 186.01</td>
<td>-43.09 -80.31 209.59</td>
</tr>
<tr>
<td>-47.12 128.96 176.34</td>
<td>-43.09 158.44 151.37</td>
</tr>
<tr>
<td>... ...</td>
<td>... ...</td>
</tr>
</tbody>
</table>

Table 5.3: Comparison of Planning Results with Different Angle Limits for Simulation

Case #3

<table>
<thead>
<tr>
<th>View Angle limit (Degree)</th>
<th>No. of Clusters (View Angle)</th>
<th>No. of Clusters (DOV)</th>
<th>No. of Patches</th>
<th>No. of Scans</th>
<th>Total Traveling Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>1822.31</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>1394.22</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>6</td>
<td>1650.19</td>
</tr>
</tbody>
</table>
5.2 EXPERIMENTAL TEST

5.2.1 Experiment Setup

5.2.1.1 Experimental Equipment and Software

The proposed algorithms of Computer-Aided Laser-scanning Planner (CALP) were demonstrated by experiments using example surfaces at the laboratories of Intelligent Manufacturing System Center (IMS), University of Windsor (Figure 5.5). The experimental hardware and software consist of:

(1) Hyscan 45C 3D laser scanning system: the laser scanning probe, the controller, and Hyscan Indy software - Xhyscan. The user interface is run on a Silicon Graphics Indy workstation with 32 MB memory, 535 MB HDD and an upgraded 20" color monitor.

(2) DEA Mistral coordinate measuring machine with Cartesian bridge configuration.

(3) The CMM software interface is TUTOR for Windows\textsuperscript{TM} Version 2.02, running on a 486 DX2/66 PC under Windows 3.11.

(4) The 15-degree incremental trunnion mount, which connects the Hyscan 45C laser scanner to the DEA Mistral CMM.

(5) Imageware Surfacer 9.0, which 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 within Surfacer.
5.2.1.2 Configuration-Related Limitations:

In the experiment, there are some limitations related to the configuration of Hyscan 45C laser scanner mounted on the Mistral CMM.

(1) Limited working volume. The real working volume is limited because the laser scanner works in the non-contact status and has to keep a certain standoff distance from the scanned surface when scanning.

(2) Limited available positions and orientations of laser scanner mounted on transportation system. For example, the laser scanner mounted on CMM by using incremental trunnion mount could have different orientations in two axes (Figure 5.6).
(3) The orientations are changed manually.

Figure 5.6: Orientations of the Hyscan Digitizer Incremental Trunnion Mount (Hymarc Ltd., 1998)

5.2.1.3 Reference System Setup

When Hyscan 45C scanner is mounted on the CMM, the laser scanner is working on its own coordinate reference system, whose origin position is the center of alignment sphere. This alignment is done by scanning the sphere every time when the laser probe changes the orientation position. For the CMM, the home position is right at the top-left corner of CMM rams. Figure 5.7 shows the relation between the home position of CMM and the origin of laser scanner.
Since the laser scanner will be driven by CMM, the CMM coordinate system has to conform to the reference system of laser scanner. When the alignment sphere is positioned, the CMM probes the sphere and obtains the center point coordinates. The reference system can be setup in TUTOR by loading the reference system whose origin is the center of alignment sphere.

Figure 5.7: The Setup of Reference Coordinate System

5.2.1.4 Path Transformation from CMM Probe to Laser Scanner Probe

The scanner moving paths obtained from the path planning module can not be used directly to write the offline CMM program and automatically drive the laser scanner to conduct the scanning task because the offline CMM program actually controls the trajectory of the CMM probe tip, not the scanner probe. When Hyscan is mounted on the CMM, there is coordinate difference between the two probes depending on the geometry
of the mount. Figure 5.8 shows the difference between CMM tactile probe and the laser scanner where the Hymarc incremental trunnion mount is used. The generated paths from CALP will be transformed from position $B$ to position $A$ as follows:

\[
X_A = X_B - LW \tag{5.1}
\]
\[
Y_A = Y_B - LM \times \sin(\theta) \tag{5.2}
\]
\[
Z_A = Z_B - CL + LH + LM \times \cos(\theta) \tag{5.3}
\]

Where:

- **B**: The point from which the laser beams shoot (considered as the center point of bottom edge of the laser scanner, see Figure 5.8 (b) and (c)).
- **$\theta$**: The rotation angle of the laser scanner with the trunnion mount along X-axis.
- **CL**: The distance from the center of tip to the lower edge of CMM arm.
- **LH**: The distance from the mount center to the lower edge of CMM arm.
- **LW**: The distance from the laser scanner to the axis of CMM arm (along the axis of mount).
- **LM**: The distance from $B$ to the axis of the trunnion mount when the laser scanner is at the 0 degree position.

The generated paths will be transformed by Equation (5.1), (5.2) and (5.3) before being used to program and drive the CMM.
Figure 5.8: Coordinates of CMM Probe and Laser Scanner Probe

5.2.2 Offline Programming in DEAPPL

DEA Part Programming Language (DEAPPL) is an off-line sequential part program language for CMM provided by Brown & Sharpe Inc. A sequential part program consists of four parts:

- opening (heading), with the PROGRAM keyword, followed by the program name;
- declaration part, with the declaration of all variables that will be used in the program;
- execution part (executable part), with the sequence of all instructions of the
  program;
- closing, with the **ENDSTAT** and **END_PROGRAM** keywords.

The execution part consists of a variety of functions that operate the probe
management, part management, geometric tolerance, output control, and move control,
etc. The source file (.TSC extension) of part program can be written and edited in a text
editor. When the source file is complied by the TUTOR compiler, the executable file
(having .TEC extension name), that includes the instructions of the part program, is
automatically generated. Because the CMM path file from the path-planning module
consists of all the points of scanner moving lines and the moves among them, these points
can be written into the source file to form the motion instructions, which guide the
rectilinear movements of a NC measuring machine. Another very important movement
parameter is the motion speed. As we know, all movements include two kinds of moves.
One is the move when the laser scanner is scanning and the other is the move connecting
two scanner moving lines. Different motion speeds should be set for those two different
moves. In DEAPPL, this can be done using the **FEED** instruction to set the different
speed of the carriage and of the ram.

The interaction among the offline program, CMM, user and Hyscan laser scanner
system is shown in Figure 5.9. The motion of CMM is controlled by the offline program,
and the changing of laser scanner orientation is completed manually by the user.
5.2.3 Test Case: Block Artifact

The artifact in Figure 5.10 (a) was used to demonstrate the result of the developed laser scanner inspection planning system. The block has five surfaces, and the angle between two intersecting surfaces is 45 degree. If the view angle threshold is set less than 22.5 degree, the surface will have five clusters (shown in Figure 5.10 (b)) according to the algorithm of clustering based on the view angle. Moreover, if we setup the block
along the X-axis, the orientations (the direction of incident laser beam) resulting from the system will be (shown in Appendix II, the final output from CALP)

- Patch 1 normal: 0.0087 1.0000 0.0013; angle with (-Z): 90 degree
- Patch 2 normal: 0.0031 0.7080 -0.7062; angle with (-Z): 45 degree
- Patch 3 normal: -0.0043 0.0013 -1.0000; angle with (-Z): 0 degree
- Patch 4 normal: -0.0092 -0.7061 -0.7080; angle with (-Z): -45 degree
- Patch 5 normal: -0.0087 -1.0000 -0.0013; angle with (-Z): -90 degree

These five orientations are available from the 15-degree incremental trunnion mount that is used to mount Hyscan laser scanner on the CMM. The final path plan shown in Appendix II needs to be transformed using Equation (5.1)-(5.3). The path file after transformation is shown in Appendix III, which will be used to write the CMM offline program in DEAPPL.

Figure 5.10 (c) also shows the zig-zag path of laser scanner to cover the surfaces. The DEAPPL source program (.TSC) is written according to the generated patch and path plan (after transformation) shown in Appendix III, and compiled using TUTOR to generate the executable file (.TEC) which can be run in TUTOR to drive the CMM along the zig-zag path in CNC motion mode. The source code is shown in Appendix VI. During the program execution, the user will be asked to change the scanner orientation and to set up the corresponding angle alignment for each plane on the block.
Figure 5.10: Test Case: Block Artifact

(a): 3D model of block artifact
(b): Clusters and scanning directions
(c): Zig-zag path

Figure 5.11 shows the reference object model and scanned point cloud with Hyscan 45C scanner using the scan plan in Appendix II for the registration process in Imageware Surfacer. Although each of the five scanning lines is planned to just cover one plane, the
laser scanner actually will obtain more data points from adjacent planes because the sweeping width of laser scanner is larger than the width of plane. However, the data points obtained from the adjacent planes are not as accurate as data from the targeted plane due to the larger view angle between the scanning direction and the normal of those adjacent planes. Therefore, the data obtained from each of the scanner orientations should be trimmed to the width of the respective surface in order to eliminate points with off-normal digitization error. The trimming of the scanned point cloud can be achieved using Imageware Surfacer software. The surface-cloud difference analysis can be done in Imageware Surfacer Inspection function. The error map, which illustrates the difference between reference surface and scanned cloud, is shown in Figure 5.12.

![Figure 5.11: CAD Model and Scanned Data Cloud for Registration Process](image)
The operational time was also recorded for the manual operation and automatically planned inspection. The result shows that the automated scanning planning helps save 20-30% time of manual operation, in which most of the time is spent to determine the proper scanner position to meet the visibility requirement. It is rather easy for the operator to determine the orientations in this case, however, when surfaces become more complex, computer-aided scanning planning will have more advantages in generating more accurate and more efficient inspection plan.

5.3 DISCUSSION

This chapter presented both computer simulations and experiments to test the developed Computer-Aided Laser-scanning Planner (CALP). Three simulation case studies were performed. Different view angle limits were also applied to test the
capabilities of Computer-Aided Laser-scanning Planner (CALP). The ACIS SAT models displayed the intermediate and final results of the system.

An experimental test with a block artifact was executed at the laboratories of the Intelligent Manufacturing Systems (IMS) center. The final inspection plan generated from developed system (CALP) was converted to DEAPPL code which can drive the CMM to complete the scanning coverage automatically.
Chapter 6 CONCLUSIONS AND FUTURE WORK

6.1 CONCLUSIONS

This research presented a method for computer-aided laser-scanning planning based on the CAD model. The method integrated three planning criteria, visibility, efficiency, and accuracy into planning. A feature differentiation method, based on the ray tracing algorithm, is proposed and applied to detect vertical walls of certain deep concavity features, such as slots, holes, pockets, which are very hard to reach for laser scanning but are suitable for CMM probing.

The method automatically generates a consistent and efficient scanning plan that can avoid the unnecessary trials in manual operations and reduce the effect on accuracy due to different human operators. The generated scanning plan includes the number of patches, the number of scanner orientations, scanning directions, scanner placements, scanning lines, and moving paths. The experiment has demonstrated that the laser scanning plan can be integrated to the CMM and used to automate the scanning process. The computer simulation case studies have shown that CALP can automatically generate the scanning plans under visibility and accuracy constraints.

6.2 CONTRIBUTIONS

This research has made the following contributions to the field of laser scanner inspection planning:
(1) A feature differentiation method based on the ray tracing algorithm was proposed and implemented. This innovative method helps the scanning planning system to detect and segregate certain features which are hard or impossible to reach for laser scanner before planning the scanning process.

(2) Factors that affect the laser scanning process were analyzed in this research. Three planning criteria, visibility, accuracy and efficiency, were modeled and integrated into the scanning planning methods and algorithms. This ensures that the generated sensor parameters guarantee the laser scanner can reach the areas to be scanned, the point data obtained by generated scanning plan meet the accuracy requirement, and the scanner movement to cover the whole surface is efficient.

(3) A computer-aided Laser-scanning Planner (CALP) system was developed and implemented using ACIS 6.0 (Spatial Inc.) and C++. Extensive simulation studies and experimental test as well have been conducted to test the developed CALP system.

6.3 FUTURE WORK

There are a number of issues which provide future research opportunities related to this research.

6.3.1 Improving the Current CALP System

Current research presents an effective method to solve the planning problem for laser scanners. The effectiveness of the algorithms used in current system has been
demonstrated through both experiments and simulations. These algorithms are mainly based on heuristics, but they are not optimized.

The proposed laser scanning planning method is mainly based on the use of sampled points and their normal vectors. The density and distribution of sampled points will affect the planning process. The sampling methods for different kinds of surfaces need further investigation and evaluation.

The feature differentiation method is efficient, but rather simple for complex parts. More intelligent algorithms which can recognize the different features may need to be developed.

The developed planning method is actually a patch-based scanning planning. The whole surface is divided into different patches due to certain constraints. However, when the width of generated patch is less than the sweeping width of laser scan, more unexpected and unwanted data from adjacent patches could also be obtained, but these data are not guaranteed to meet the accuracy requirement. One solution is to trim the scanned data cloud according to the patch width to ensure that the scanned data are from the specific patch. This highlights the need for more research on post-processing of scanned data cloud.
6.3.2 Sampling Method in Inspection Planning for Laser Scanner

The uniform sampling method applied in this research provides simple and direct information about the surface. However, the density and distribution of sampled points may affect the results of scanning planning. A computer-aided sampling approach to meet the requirements of laser scanner planning task needs to be developed. ElKott and ElMaraghy (1999, 2000) developed an automatic sampling system for CMM inspection planning of free form surfaces.

6.3.3 Intelligent Hybrid Inspection by CMM Probing and Laser Scanning

According to the comparison analysis of CMM probing and laser scanning techniques, both inspection methods have their own advantages and disadvantages. The possibility to perform hybrid inspection using both techniques presents a significant research opportunity. One of the important issues in hybrid inspection is to detect the appropriate features for each inspection method. The feature differentiation based on ray tracing algorithm in this research provided a simple way to detect the vertical walls of concavity features. An intelligent feature differentiation algorithm is vital for automated hybrid inspection method.

In addition, the strategic functions of two different inspection techniques in hybrid method will be interesting issues. The following schemes provide the possible solutions.
(1) Free form surface scanning by laser scanner. CMM probing works as supplementary digitization method for hard to view or impossible to view areas using laser scanner.

(2) CMM probing works as more accurate inspection method for high tolerance and high precision requirements.

(3) CMM probing works as support to guide laser scanner for recognizing the working volume and positioning.

(4) Laser scanning guided CMM inspection. In case where the CAD model is not available, the laser-scanned data can generate an approximate surface, which may guide subsequent CMM inspection.

6.3.4 Integration of Multi-sensor Inspection Planning

The development of an integrated system that supports multiple sensor integration for high precision, highly automated, high speed, 3D coordinate acquisition will be a very interesting and exciting research work. The multi sensors could include tactile probe, laser-based sensor, and 3D active vision system. Much work on CMM tactile probe path planning, and collision avoidance has been achieved. Little work has been done in the inspection planning for laser scanner. The inspection planning method presented in this work can be used as a candidate to be integrated to a multi-sensor inspection planning module.
REFERENCES


APPENDIX I: SCHEME CODE FOR SIMULATION CASE

#3

(view:dl 0 0 400 400)
(part:clear)
(iges:init "C:/Program Files/acis/iges/igac/iges_04.dbt")
(define c (solid:cylinder (position -50 0 40) (position 50 0 40 40))
(iso)
(zoom-all)

(define sw (solid:wiggle 200 200 45 -2 -2 2 1))
(define part1 (solid:subtract sw c))

(define block1 (solid:block (position -200 -150 -40) (position 200 150 40))
(define block2 (solid:block (position -100 -100 -10) (position 100 100 70))
(define block3 (solid:subtract block1 block2))

(define part2 (solid:unite part1 block3))

(blend:entities part2 2 "fix")

(iso)
(zoom-all)
(part:save-selection part2 "c:/yang/catip/simupart2/part.sat")
(iges:write "c:/yang/catip/simupart2/part.igs" "logfile" part2)
APPENDIX II: THE PATCH AND PATH FILE FOR

ARTIFACT BLOCK

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of sampled positions</td>
<td>48</td>
</tr>
<tr>
<td>Number of normal vectors</td>
<td>48</td>
</tr>
<tr>
<td>Number of positions detected by ray-tracing</td>
<td>0</td>
</tr>
<tr>
<td>The view angle limit</td>
<td>20.0</td>
</tr>
<tr>
<td>The No. of clusters based on view angle</td>
<td>5</td>
</tr>
<tr>
<td>The allowable DOV</td>
<td>40.0</td>
</tr>
<tr>
<td>The No. of patches based on the DOV</td>
<td>5</td>
</tr>
<tr>
<td>The standoff distance</td>
<td>165.0</td>
</tr>
<tr>
<td>The scan width</td>
<td>70.0</td>
</tr>
<tr>
<td>The scan length offset</td>
<td>40.0</td>
</tr>
<tr>
<td>No of Patches</td>
<td>5</td>
</tr>
<tr>
<td>No of Scans</td>
<td>5</td>
</tr>
</tbody>
</table>

Patch No. 1
No of Scans: 1
The scanning direction: 0.0090 1.0000 0.0010
Angle with X, Y, Z Axis: 89.5 0.5 89.9
The anchor points of scans:
119.26 -194.73 -14.42
299.33 -196.35 -14.42

Patch No. 2
No of Scans: 1
The scanning direction: 0.0030 0.7081 -0.7061
Angle with X, Y, Z Axis: 89.8 44.9 134.9
The anchor points of scans:
300.50 -139.92 130.14
120.43 -139.92 129.37

Patch No. 3
No of Scans: 1
The scanning direction: -0.0040 0.0010 -1.0000
Angle with X, Y, Z Axis: 90.2 89.9 179.8
The anchor points of scans:
121.81 -0.76 186.14
301.89 -0.76 185.42
Patch No. 4
No of Scans: 1
The scanning direction: -0.0090 -0.7061 -0.7081
Angle with X, Y, Z Axis: 90.5 134.9 135.1
The anchor points of scans:
302.88 138.42 129.00
122.81 138.42 131.29

Patch No. 5
No of Scans: 1
The scanning direction: -0.0090 -1.0000 -0.0010
Angle with X, Y, Z Axis: 90.5 179.5 90.1
The anchor points of scans:
122.75 195.25 -14.02
302.82 193.63 -14.02

The total path traveling distance: 1512.09
APPENDIX III: THE PATCH AND CMM PATH FILE FOR ARTIFACT BLOCK (AFTER TRANSFORMATION)

No of Patches: 5
No of Scans: 5

Patch No. 1
No of Scans: 1
The scanning direction: 0.0090 1.0000 0.0010
Angle with X, Y, Z Axis: 89.5 0.5 89.9
The anchor points of scans:
-15.74 -259.72 -119.48
164.33 -261.34 -119.48
Angle with -Z: 90.06

Patch No. 2
No of Scans: 1
The scanning direction: 0.0030 0.7081 -0.7061
Angle with X, Y, Z Axis: 89.8 44.9 134.9
The anchor points of scans:
165.50 -193.01 73.96
-14.57 -193.01 73.19
Angle with -Z: 45.08

Patch No. 3
No of Scans: 1
The scanning direction: -0.0040 0.0010 -1.0000
Angle with X, Y, Z Axis: 90.2 89.9 179.8
The anchor points of scans:
-13.19 -11.03 156.10
166.89 -11.03 155.38
Angle with -Z: 0.24

Patch No. 4
No of Scans: 1
The scanning direction: -0.0090 -0.7061 -0.7081
Angle with X, Y, Z Axis: 90.5 134.9 135.1
The anchor points of scans:
167.88 177.24 87.09
-12.19 177.24 89.38
Angle with -Z: -44.92

Patch No. 5
No of Scans: 1
The scanning direction: -0.0090 -1.0000 -0.0010
Angle with X, Y, Z Axis: 90.5 179.5 90.1
The anchor points of scans:
-12.25 260.24 -98.96
167.82 258.62 -98.96
Angle with -Z: -89.94

The total traveling distance: 1512.09
APPENDIX IV: THE DEAPPL CMM PATH PROGRAM

FOR ARTIFACT BLOCK

program MATT1[WM1,WM2]
  element_array MEMORY[300]
  STRING inp[1]
  ncmove
  DY ("The laser scanner is moving to the starting position!")
  feed 25
  move (X=-5.47, Y=-250, Z=120)
  DY ("Setup the orientation(+90) for the first scan.")
  DY ("Setup the alignment file of +90 from Xhyscan.")
  DY ("When you are done and ready, PRESS y, others end the program.")
  read(inp)
  IF inp EQ "y" THEN
    move (X=-15.74, Y=-259.72, Z=-119.48)
    feed 4
    DY("Prepare to press the SCAN button...")
    DY("Scanning in process...")
    DY("Prepare to press the STOP button...")
    move (X=164.33, Y=-261.34, Z=-119.48)
    DY ("The first scan finished.")
    feed 25
    move (X=165.50, Y=-193.01, Z=73.96)
    DY ("Setup the orientation(+45) for the second scan.")
    DY ("Setup the alignment file of +45 from Xhyscan.")
    DY ("When you are done and ready, PRESS y, others end the program.")
    read(inp)
    IF inp EQ "y" THEN
      feed 4
      DY("Prepare to press the SCAN button...")
      DY("Scanning in process...")
      DY("Prepare to press the STOP button...")
      move (X=-14.57, Y=-193.01, Z=73.19)
      DY ("The second scan finished.")
      feed 25
      move (X=-13.19, Y=-11.03, Z=156.10)
      DY ("Setup the orientation(0) for the third scan.")
      DY ("Setup the alignment file of 0 from Xhyscan.")
      DY ("When you are done and ready, PRESS y, others end the program.")
      read(inp)
      IF inp EQ "y" THEN
        feed 4
        DY("Prepare to press the SCAN button...")
        DY("Scanning in process...")
        DY("Prepare to press the STOP button...")
        move (X=166.89, Y=-11.03, Z=155.38

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DY ("The third scan finished.")

feed 25
move (X=167.88,Y=177.24,Z =87.09)
DY ("Setup the orientation(-45) for the third scan.")
DY ("Setup the alignment file of -45 from Xhyscan.")
DY ("When you are done and ready, PRESS y, others end the program.")
read(inp)
IF inp EQ "y" THEN
  feed 4
  DY("Prepare to press the SCAN button...")
  DY("Scanning in process...")
  DY("Prepare to press the STOP button...")
  move (X=-12.19,Y=177.24,Z =89.38)
  DY ("The forth scan finished.")

feed 25
move (X=-12.25,Y=260.24,Z =-98.96)
DY ("Setup the orientation(-90) for the third scan.")
DY ("Setup the alignment file of -90 from Xhyscan.")
DY ("When you are done and ready, PRESS y, others end the program.")
read(inp)
IF inp EQ "y" THEN
  feed 4
  DY("Prepare to press the SCAN button...")
  DY("Scanning in process...")
  DY("Prepare to press the STOP button...")
  move (X=167.82,Y=258.62,Z =-98.96)
  DY ("The fifth scan finished.")
END_IF
END_IF
END_IF
END_IF
END_IF
DY ("Program ends successfully.")
endstat
end_program
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