OPTIMAL TRAVERSAL OF SURFACE AREA WITH CONSTRAINTS

A Project Report

Submitted by

Mohitesh Kumar 121642014

in fulfillment for the award of the degree
of

M.Tech (Information Security)

Under the guidance of
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**DEPARTMENT OF COMPUTER ENGINEERING AND INFORMATION TECHNOLOGY,
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May, 2011

A Dissertation Stage-I Report On

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[2017-2018]

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CERTIFICATE

This is to certify that, **Mohitesh Kumar** is studying in M.Tech Computer Engineering course in SEM-III and he has successfully completed and submitted the seminar-I, entitled **' Optimal Traversal of Surface Area with Constraints '**. This study is a partial fulfillment of the degree of Masters of Technology in Computer Engineering of College Of Engineering Pune, during the academic year 2017-2018.

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Acknowledgments

- It is matter of great pleasure for me to submit this dissertation stage I report on **“ OPTIMAL TRAVERSAL OF SURFACE AREA WITH CONSTRAINTS ”** as a part of curriculum for award of “ Master in Computer Technology ” degree of College Of Engineering Pune.

- Firstly I would like to express my gratitude to my guide **Mrs. A. B. Patil**, for her inspiration, adroit guidance, constant supervision, direction and discussion in successful completion of dissertation stage I.

- Also , I would like to thank my industry guide **Mr. N Sreenivasan**, for his guidance, supervision and for creating a mental model of the project in my head.

- I am thankful to Head Of Department **Dr. Mrs. V. S. Inamdar**, for his valuable support and guidance.

- Also I extend my thanks to all my colleagues those who have helped me directly or indirectly in completion of dissertation stage I and last but not least, I am thankful to my parents, who had inspired me with their blessings.

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Contents

1 Abstract

1.1 Problem Definition

This thesis aims to identify a strategy to compute a single connected path that completely traces a surface area with some constraints.

1.2 Problem Description

To understand the problem definition, consider an irregular surface. For e.g. consider a fancy mobile case with holes for camera and volume buttons and being irregular in terms of its shape. Such a surface must be divided into parts and separate scans must be defined on each of the parts which is cumbersome. So, we need to identify a strategy to compute a single connected path that completely traces the surface area. Consider it similar to be painting a surface completely with a fixed size brush, not allowed to lift off the surface of the canvas. The brush has to follow certain constraints such as, the handle of the brush cannot cut into the surface.

Moving the traditional 3-axes of the CMM is slower and lowers precision of measurement. Hence, we need to minimize the motion of the 3 huge axes (in our painting example, it refers to minimizing

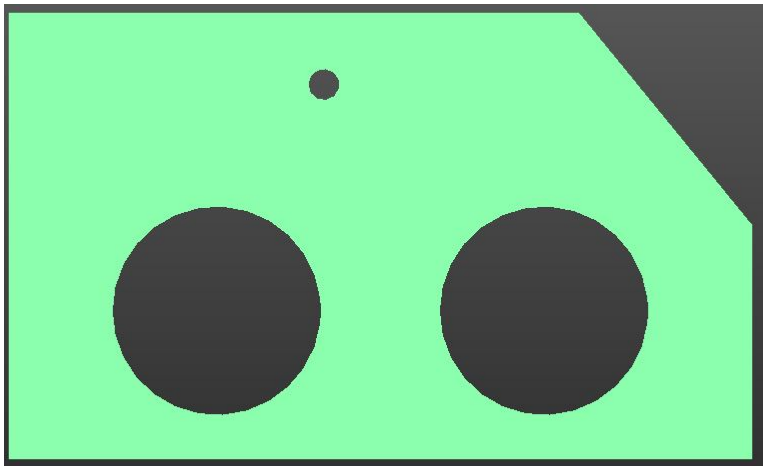

Figure 1: Surface With Constraints

the motion of our hand holding the brush). So we need to define an automatic curve computer which scans the entire surface on a pre-defined path with constraints while keeping the path optimal and the movement of the 3 axes at a minimum.

2 Introduction

A Coordinate Measuring Machine (CMM) is a general-purpose measuring machine, used to measure physical and geometrical characteristics of an object. Compared with the traditional 3-axis CMM, a 5-axis CMM equipped with the capability of continuous sweep scanning can provide much denser data points while taking much shorter time and lesser energy. This report presents an automatic sweep scan path planning system which, on given an input in the form of a guide curve, calculates the best possible path, the CMM head should take to generate data points for the object under consideration. The algorithm aims at improving the scanning efficiency by utilizing the advantages of the two rotary axes which have very low moment of inertia , to cover a larger area while reducing the speed and acceleration demand on traditional axes which have larger inertia. The algorithm will take care of constraints(contour of the surface area)and the path planned by it will be calculated to be optimal. The approach taken to solve the problem is a voxelized one.

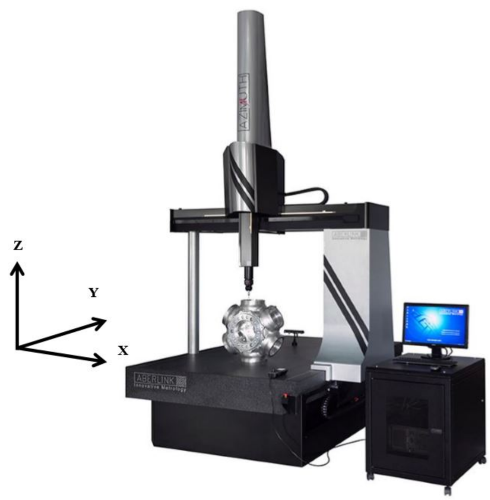

Figure 2: The Co-ordinate measuring machine

3 Hardware Specification

This section aims to explain all the hardware and technologies which will be required. The components are:

3.1 Co-ordinate Measuring Machine

3.1.1 Definition

A coordinate measuring machine (CMM) is a device for measuring the physical geometrical characteristics of an object. Measurements are defined by a probe attached to the third moving axis of this machine. The given Figure 2, is that of a traditional 3-axis CMM designed to move mechanically in 3 directions.

3.1.2 Renishaw's 5- axis measurement system

Renishaw's REVO system uses synchronized motion and 5-axis measurement technology to minimize the dynamic effects of CMM motion at ultra high measurement speeds. This can be achieved by letting the REVO-2 head do the fast-demanding motion while CMM moves linearly slow. The use of a flexible tip-sensing probe further adds to the system's accuracy and performance.

Given below are the parts which together make up the 5 - axis measurement system:

- REVO-2 head: Figure 3 shows the CMM head that is attached to the 3-axis CMM to give it 2 extra movement directions(A and B). It is obvious from the figures that the 3-axis movement is done by large moving joints and levers which apart from being energy in-efficient is also poor precision wise. 5 - axis technology that can minimize the dynamic effects of CMM motion at high measuring speeds which increases measurement output.
- REVO-2 probe options:

Figure 3: Renishaw's REVO-2 CMM head

- RSP2: RSP2 is a dedicated lightweight probe for use on REVO systems, capable of 2D-scanning (x, y) and 3D touch-trigger measurement (x, y, z). The RSP2 has a universal body to which a number of different length stylus holders can be fitted.
- RSP3: RSP3 complements the RSP2 probe, providing the REVO system with 3D-scanning (x,y,z) and crank stylus capabilities. It is used for 3-axis scanning, such as with a fixed REVO head angle during measurement.
- SFP2: This makes surface finish inspection an integral part of the CMM measurement procedure, which was earlier done using hand held sensors. There are more probe op-

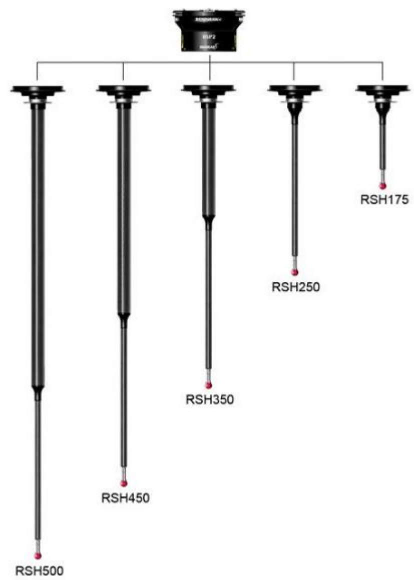

Figure 4: RSP2 probe option

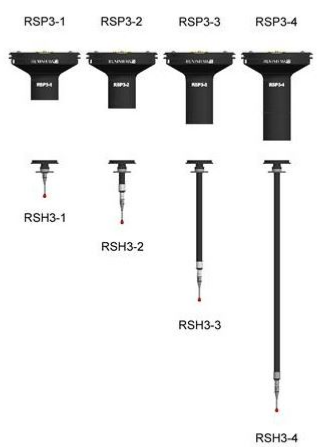

Figure 5: RSP3 probe option

Figure 6: SFP2 probe option

tions, but for the purpose of this report, these are enough.

- Controller System: The 5-axis measurement technology is embedded in Renishaw's UCC S5 CMM controller which forms the basis of the 5-axis measurement system – 3 machine axes plus the 2 rotary axes of the head. Patented technology within the UCC S5 provides unique motion commands, synchronization and 5-axis metrology capability.
- REVO system change rack: It is designed to allow automatic probe and stylus holder changing on a CMM. The primary purpose of the system is to improve flexibility with the ability to use and store longer styli and large star stylus configurations.

Figure 7: REVO system change rack

4 Software Specification

4.1 Workstation Configuration

The program is written on a Windows 10 Enterprise, 64 bit machine with 6 GB RAM and Quad Core CPU. The coding environment used was Visual Studio 2013.

4.2 Additional Libraries

The program uses proprietary software library from Renishaw called Geometric Modelling Library(GML). It consists of over 7,500 functions developed to resolve many complex geometric problems. GML also has a fully extendable API and a fully customisable GUI. The library includes 6 main geometric entity types, as well as a large selection of algorithms for manipulating these entities. There are algorithms for registration, fitting, surfacing, error analysis, extraction, data reduction, infilling and more. GML GUI provides a “sandbox” environment where you are free to use and test complex geometrical algorithms before they are incorporated into applications for distribution. This is where the algorithm was developed and tested.

4.3 Memory usage

GML while running the algorithm uses 28 MB of system memory(RAM) and utilizes about 18% of CPU.

5 Problem Definition

5.1 Curve Scan and Sweep Scan

To properly define the problem, sweep scan and curve scan have to be explained in the context of CMM's.

- Sweep Scan: Capturing data points over a surface can be accomplished by utilizing the REVO-2 drive system to sweep back and forth. It uses a sweeping motion of the head obtained by the combination of A and B rotational head angles keeping the CMM motion along a linear path with constant speed. This process minimizes the inherent inaccuracies of the CMM structure while scanning the surface at high speeds.Figure 5.1 will help to understand better.

- Curve Scan: A curve scan scans the surface along a predefined curve. Although it can scan any area based on a formula, the scanning is slow compared to sweep scan. The purpose of this report is to create a tool which can automatically compute curve scans to attain a full coverage of any surface.

5.2 Objectives

- To find out an optimal guiding path along which the probe head is supposed to move.
- To automatically compute curve scans to attain a full coverage of any surface with constraints
- To maximize efficiency by reducing redundancy.
- To minimize the time required to take a measurement.

5.3 Methodology

- Understanding the measurement techniques, equipment, working of RSP3 and RSP2 and metrological concepts. Understanding the procedure of calibration and inspection for RSP3 and RSP2 Probe sensors.
- Review of literature to prove the novelty of research work.

- Forming an approach based on designing a voxel model for any free form surface.
- Generating a guide line for the CMM head to move on.
- Writing a program for the the movement of stylus head in such a manner that all voxels are covered.
- Taking care of constraints that might be on the surface or other physical constraints that might be introduced due to the big moving parts of CMM.
- Test the output of the program by offline simulation and check to see if actually the movement covers the entire surface .
- Create an interactive user interface to above program to display the results in a graphical format.
- Conduct an experiment on a simulation to check how this algorithm compares to other previously working algorithms.
- Writing a full report of the research work.

6 Literature Survey

The current manufacturing systems are flexible and give high throughput in short period of time. The use of numerical control in a manufacturing process leads to high quality products with less wastage. The quality of product is decided by measurement and inspection systems. The developments in measurement and inspection system as compared to manufacturing system are not at high rate. The uncertainty in a measurement and in inspection systems arises due to many factors like manufacturing process, sampling and inspection strategy, dynamic structure of measuring systems, data acquisition and data fitting. These factors affect the measurement and inspection system capability and leads to an error in a measurement and further leads to wastage.

Many researchers have directed their efforts to improve the performance of Coordinate Measuring Machines by optimizing various measurement process parameters. But, most past research on the subject of surface measurement using CMM has been about the traditional 3-axis CMM inspection, and with a focus point on sample points' selection. The focus of this review is on developments in a various inspection strategy and in evaluation methods. The review contains various techniques in brief from the past two decades in inspection strategy and flatness error evaluation. The technologies are examined from the view point of an inspection engineer.

Zhou,Zhang and tang have given an approach [**?**] in which a method for planning sweep scan path for free-form surfaces on a 5-axis CMM is proposed. They have also performed experiments which showed significant improvement in scanning efficiency compared to some existing methods. They have created an algorithm for traversing a free-form surface without constraints on a guide path which is given as input. The efficiency lies in planning the movement of the stylus keeping the head motion along a single line/curve. 8.

Figure 8: Sweep Scan path in [**?**]'s approach

While this approach might work for a continuous free-form surface as shown in Figure 8,it will have problems to deal with in this problem. For sweep scan to work, we need to have a guide path which is equidistant from both sides of the surface so that sweep scan can be performed. But in a surface with constraints, it is difficult to make a guide path unless it is overlapped which is again a problem as it has to be equidistant at all times which is not possible for all cases. Let us even assume a possible case, then also there can be multiple points on the guide path which can reach the same point on the surface.

S. M. Stojadinovic et al. [?] proposed a model of intelligent inspection of prismatic parts. The CAD model is used for offline simulation of measurement process and inspection plan is validate by conducting experiment on prismatic parts using ZEISS CMM UMM500. The simulation has algorithm for sampling strategy, probe path planning, collision avoidance and probe accessibility analysis which gives optimum measuring process parameters. The optimal path is compared experimentally with online CMM program and program designed with software Pro/Engineer. The result shows the reduction in measurement time if proposed model used as it generates path with minimum length.

G. Mansour [?] developed an algorithm to find minimum number of points to define the curves by which the free form of blades is defined with certain allowable deviation for three-dimensional scanning. The algorithm is written in MATLAB language and applied on 2 different blades. The algorithm approximates curves by 3rd degree polynomial with certain allowable deviation. The test time is reduced as the algorithm reduces number of points that are required for scanning the blades on CMM

Zhang, Tang and Hu were also involved in another paper [?], wherein a similar approach of a guide path(called inspection path in this paper) is used. However, [?]'s work depends on humans to specify the guiding curve and the curve sampling accuracy cannot be controlled. Using complex mathematics, this paper tries to generate a guide path for CMM motion, given the surface. The lack of thought for contours is an issue with this paper.

After studying these techniques, I came across a paper on Graphics based path planning [?]. This paper discussed a new tool path planning approach based on ray-casting and voxel models. Until this paper, voxel models were used in virtual machining simulation but were been used to generate tool paths. The graphics concept of ray tracing was used to generate the cutter contact points based on intersections with the voxelized part. This path planning exercise was not meant for measurement but it could be modified a bit to suit measurement demands.

6.1 Comments on Literature Survey

By reviewing the above given literature, it seems that the focus of researchers is on the minimizing inspection time of CMM which is based on the measurement path, probe path. Some research is done surrounding the guide path mentality, while a little research is done on using voxelized surfaces for path planning. Considering all of the above given approaches, it is found that no research is done on using a voxelized surface for path planning using a guide line as the basis.

7 Voxels and Params

7.1 Voxels

The best way to understand a voxel (Fig 9) is by first imagining a 3D pixel. A voxel is a volume element much like a pixel is a picture element.[**?**] It represents a value on a regular grid in three-dimensional space. As with pixels in a bitmap, voxels themselves do not typically have their position (their coordinates) explicitly encoded along with their values. Instead, rendering systems infer the position of a voxel based upon its position relative to other voxels. Voxels are frequently used in the visualization and analysis of medical and scientific data and in representation of terrain in games and simulations.

7.1.1 Voxelization

Voxelization is the process of transforming an object into a volume element.The surface is voxelized for the twofold purpose of fast intersection detection with the rays and fast calculations on the voxel volume. Surface intersection is drastically simplified by using a voxel model. However, this speed comes at the expense of large memory

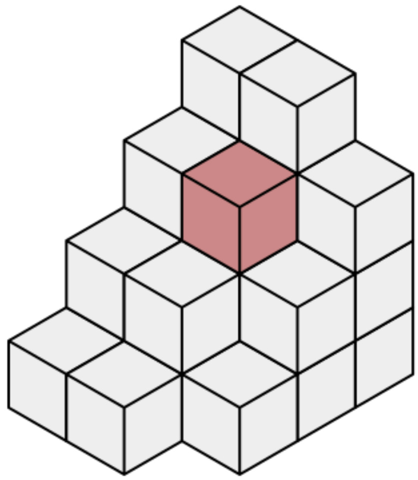

Figure 9: A series of voxels in a stack with a single voxel shaded

consumption(but memory is not a big problem these days).

A voxelized model has a very simple topology that makes it easily implementable for path-finding. Other 3D representations like the commonly used boundary representation (b-rep) lack this topology and require an additional step before path-finding can be applied. Besides that, certain operations are very easily and efficiently performed on a voxelized model. A path-finding method might utilize these operations for efficient path-finding. Three of such operations are listed below.

- Distance transform: A distance field is a derived volumetric model in which each voxel indicates the distance to a closest point. This closest point might for example be a point on a wall.

- Skeletonization: A skeleton is minimal representation of a model in which the geometry is thinned to a thickness of one voxel. Although the geometry of the model is heavily changed, the internal topology of the model remains the same. This skeleton is very suitable for path-finding for multiple reasons. Firstly, it contains topology. Secondly, it reduces the number of voxels that can be traversed. Thirdly, it guarantees a path through the center of the space.

- Dilation: Dilation adds a buffer around voxels of an object. Such a buffer can be used in path-finding to consider the size of the CMM parts.

7.1.2 Normal Vector to the Voxel

A voxel is 3D pixel, most generally a cuboid. The representation of a digitized cloud of points as a voxel-map allows the identification of empty or surface voxels. In this paper, the concept of voxel-space introduced in [3] is adopted. Therefore it is possible to attach attributes, such as the normal or the barycenter, to each voxel in function of the surface portion included inside. As the CAD model is known, it is easy to retrieve the STL representation of the surface. A surface voxel includes a portion of the object surface that means a discrete number of facets. The vector normal is defined considering the mean value of the normal vectors to each facet included in the voxel. 10

7.1.3 Dicretization of Surface

The voxel model is built by discretization of the surface. In this process, those voxels which would lie on the contour are eliminated or modified accordingly. The process of doing so is explained in 10.

7.2 Guide Curve

The process of voxelization is done so that, after visiting each voxel, we can call the surface traversal of an area complete. Simply visiting voxels, though is not the only criterion. We need to minimize the probe head movement and for that purpose, we need to move it along a guiding curve. The guide curve has to be minimalist and should be relative to the direction of voxels. Voxels will be reachable using certain points on the guide curve. These points are called params.

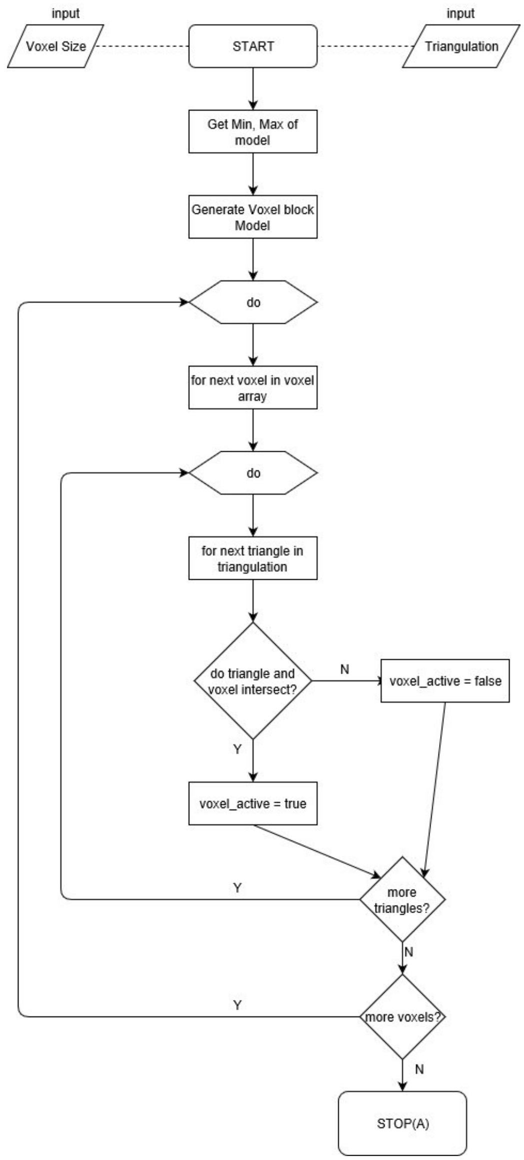

Figure 10: Discretization of Surface

The process of selecting params is given below.

- First, the guide curve is created as a set of points joint together.
- Next, each two consecutive points are connected to form a line and doing the same for the entire pointset gives us a lineset.
- Now a two way check has to performed. A sphere is drawn keeping each voxel center as its center and radius equal to stylus length. The points where the sphere intersects individual line segments is marked and are called param points. If a voxel does not intersect any point on the guide lines, a new guiding curve will have to be drawn. A 'voxel info' array is made using this information, wherein each voxel is stored along with its intersecting param points.
- After checking that all voxels are reachable, we create a list of all param points. A sphere is drawn from each param point and a sphere is made at each voxel(with radius as voxel radius and center as voxel center). Intersection between the two spheres are marked correspondingly and a map is made with each param point related to the voxel spheres it could intersect. This information is stored in the 'param info' array.

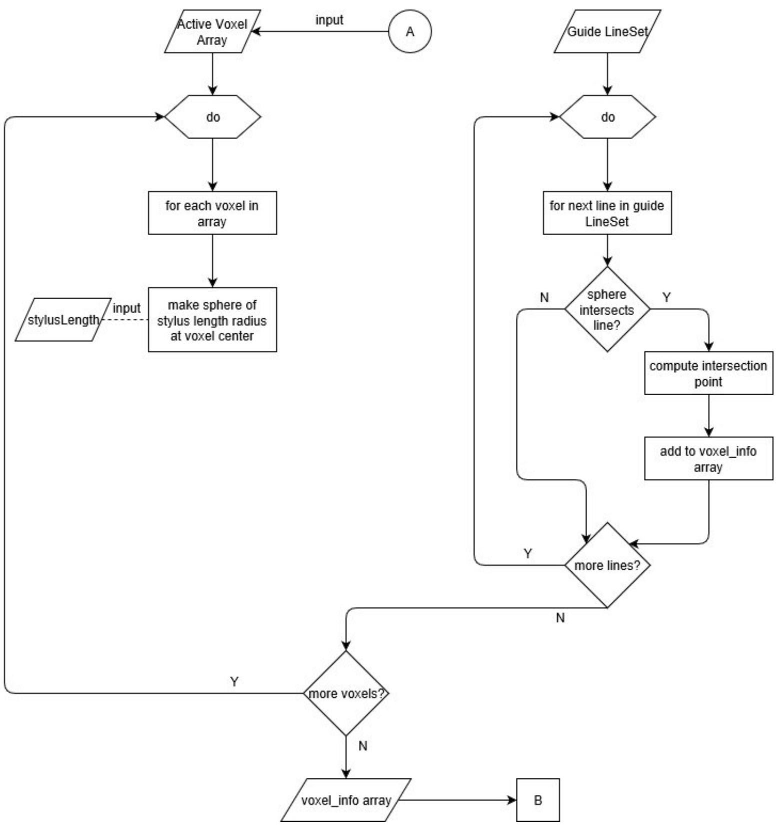

Figure 11: Flowchart for calculating ´voxel_info´ array

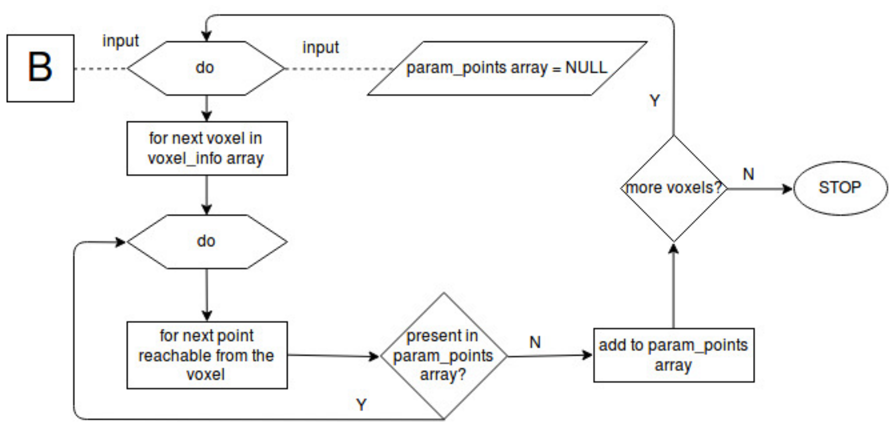

Figure 12: Filling up ´param_points´ array

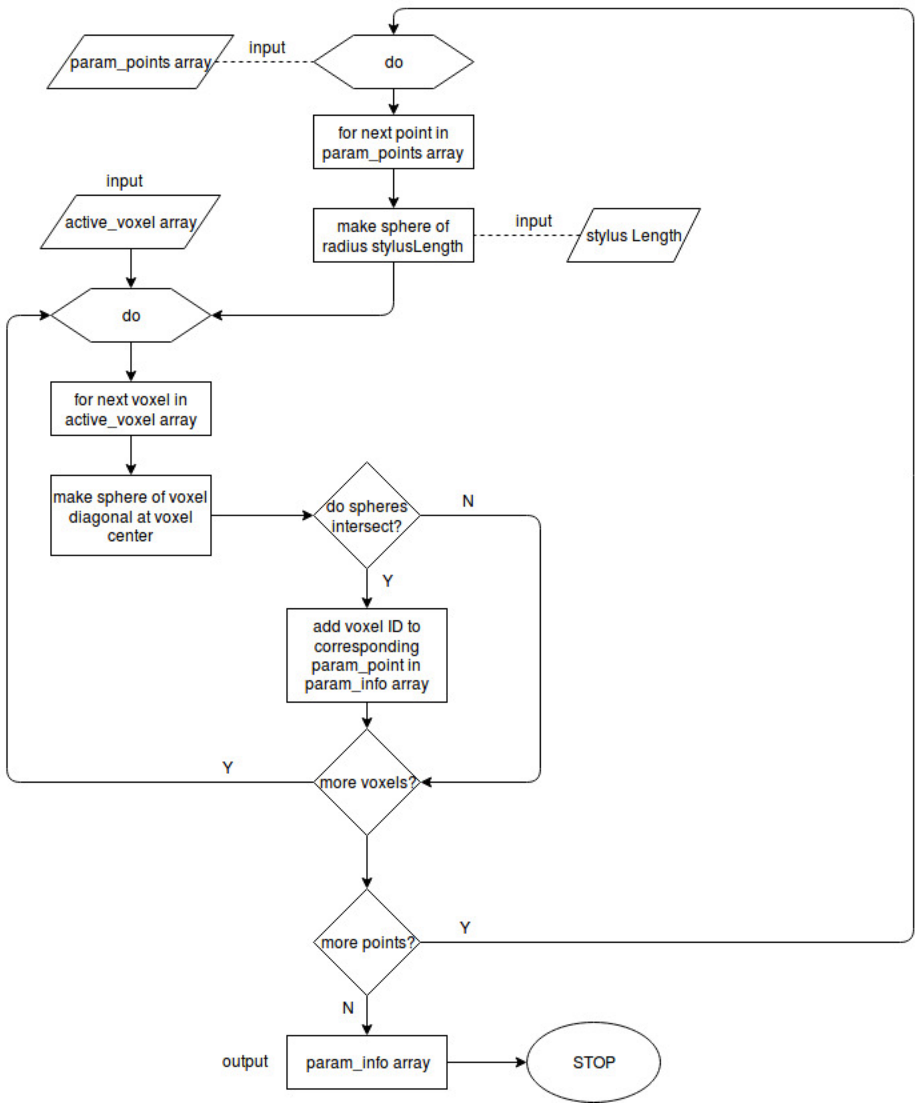

Figure 13: Filling up ṕaram_info´ array

8 Path Planning

A lot of research has been done on path-finding methods and their applications.Each path-finding method has different characteristics like the model it operates on and its notion of the best path. These characteristics depend on the application of the path-finding method. For example, the fastest path and a graph network would suffice for outdoor car navigation while a shortest path and a grid would suffice for indoor robotic navigation.

8.1 Shortest Path Algorithms

Shortest path algorithms lie at the basis of path finding. These algorithms are used to compute the shortest path through an environment while avoiding any obstacles. Some common shortest path algorithms are described below:

- BFS Algorithm: One of the simplest implementations is the breadth-first search algorithm which is also called the "Bush fire algorithm" or "Flood fill algorithm". This algorithm works by expanding a region from a starting point until the ending point falls within this region. Each cell in this region is assigned the number of steps from the starting point. The shortest path is found by traversing the cells from ending point to starting point by visiting neighboring cells with the lowest assigned number.

- Dijkstra's algorithm : This algorithm is meant for graphs and is technically the same to breadth first search when applied to a grid.

  Breadth-first search and Dijkstra both guarantee to give the shortest path, but they are not computationally efficient because they only consider the distance to the starting point and not the distance to the ending point.

- A* algorithm: This algorithm considers the distance to the ending point by using a heuristic function. This heuristic is an estimation of the distance and can for example be the Euclidean distance or Manhattan distance. The sum of the travelled distance and the heuristic function is used to determine which neighboring cell should be visited. This sum should be minimum. A* greatly reduces the number of cells to visit making it much more efficient than breadth-first search and Dijkstra's algorithm.

- Ant Colony Algorithm: The ant colony optimization algorithm (ACO) is a probabilistic technique for solving computational problems which can be reduced to finding good paths through graphs. The algorithm searches for optimal path in the graph based on behaviour of ants seeking a path between their colony and source of food. It has been used to produce near-optimal solutions to the travelling salesman problem.

9 Proposed Methodology

This section lists the proposed method to complete the task at hand in detail. It is an extension to section 5.3. The parameters for successful path planning are:

1. All voxels must be visited.
2. The head should move only in one direction and should not turn back.

The following is how the voxelized approach is supposed to find out the best path. There are various steps involved in this process:

- The two maps, i.e. 'voxel info' and 'param info' must be ready before this step.
- The two maps should now be made consistent. This means that if voxel A can be visited by param i,j and k in the voxel info array, then only param i,j and k should have voxel A mapped along with them. No more params should hold this voxel. This should also rule out guiding curves which leave some voxels unreachable by any param.
- The preference of one voxel over the other has to be defined in

such a way that it does not lead to loops and does not leave voxels uncovered.

1. First preference has to be given to unvisited voxels. So we start from the first voxel in the first param and find out its unvisited neighbors and visit it. If there are one or more than one unvisited neighbors, go to step 2. If there are no unvisited neighbors, goto step 6.

2. Now we need to rule out those voxels which , if visited would cause a problem for visiting other voxels. A heuristic function is written for the same, which finds out voxels which can be safely visited. In case of multiple 'visitable' voxels, goto step 3, in case of single voxel, visit it. If no visitable voxels, goto step 6.

3. Now, make a list of all voxels with their maximum params. Select the least maximum param from among them. This makes sure that voxels whose params will get over sooner are visited first. In case of multiple least max param candidates, goto step 4. In case of single candidate, visit it. In case of no candidates, goto step 6.

4. Choose a candidate which on selection will be directed towards the previous voxel shift direction. This means that the next voxel will be in the same direction as before. This is not a necessary condition, but it makes for an efficient sweeping motion of the stylus. In case no voxel is in the same direction, goto step 5. If a neighbor is found in the same direction, visit it.

5. Choose any random candidate from the list as both are equally capable and visit it. Goto step 11.

6. Find out visited neighbors of the voxel. Goto step 7.

7. Among the visited neighbors, find out those which can be visited, based on the previous heuristic. Goto step 8.

8. Shortlist candidates with a higher param than current param. Select those candidates which have the smallest param among the shortlisted ones. If such a selection returns no candidates, goto step 9. If it return a single candidate, visit it. If multiple candidates are returned, goto step 10

9. Shortlist candidates with param higher or equal to current param. Select candidates having least param among the

shortlisted ones. If multiple candidates, goto step 10.

10. Make a list of all candidates with their corresponding max param ID. Select candidates with highest max param ID. In case of multiple candidates, goto step 4. In case of single candidate visit it and goto step 11.

11. If the number of unvisited voxels is 0, goto step 12, else goto step 1.

12. Stop program.

9.1 Flowchart

This is the first phase in which the basic approach of solving the problem is selected. The overall structure and style of the project is shown here. The entire project can be divided into three parts which are shown below. The flowchart captures the essence of the project.

- Compute an array which holds the information of all voxels and the points on the guide line from where they can be accessed. Call this array ´voxel_info´. Similarly compute a ´param_info´ array.(Figure 10,Figure 11, Figure 12) and Figure 13)

- Find a path by which all voxels can be accessed.(Figure 14, 15, 16, 17)

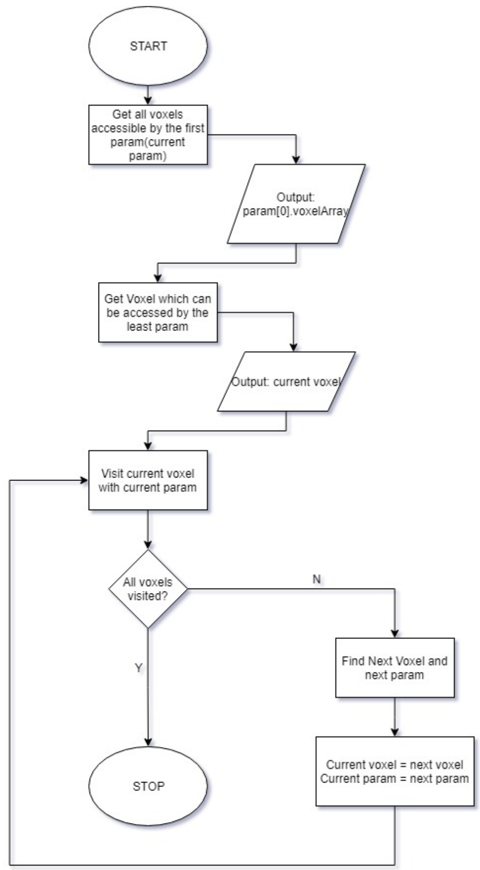

Figure 14: Flowchart for finding path

- Optimize the path to achieve faster speeds, minimize CMM motions, remove collisions etc.(Figure **??**)

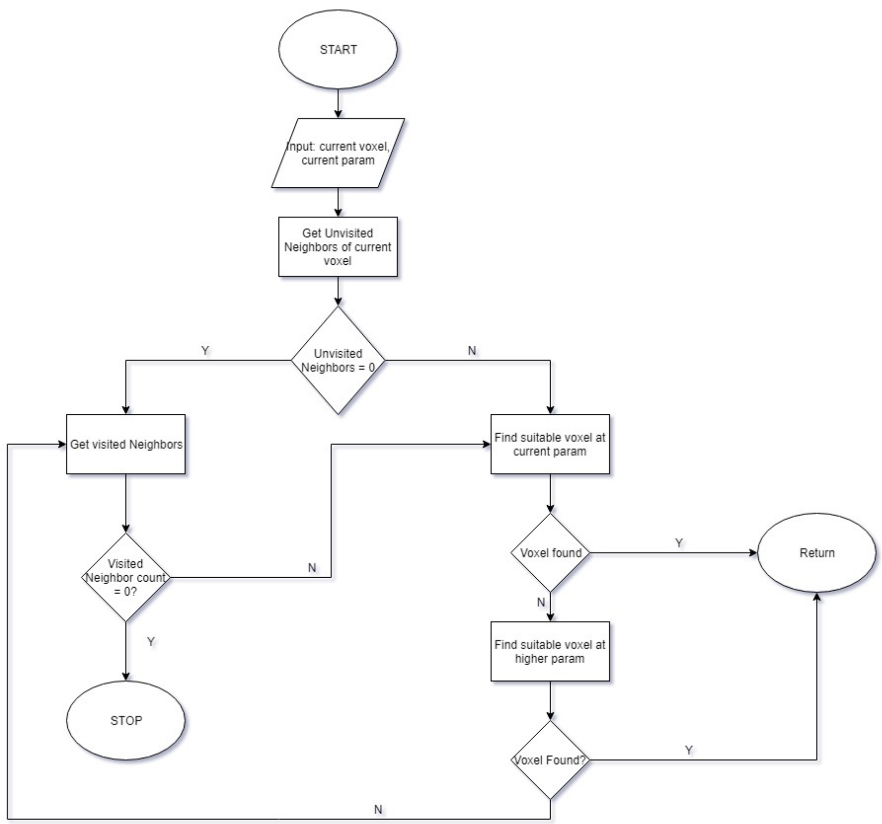

Figure 15: Flowchart for finding next voxel

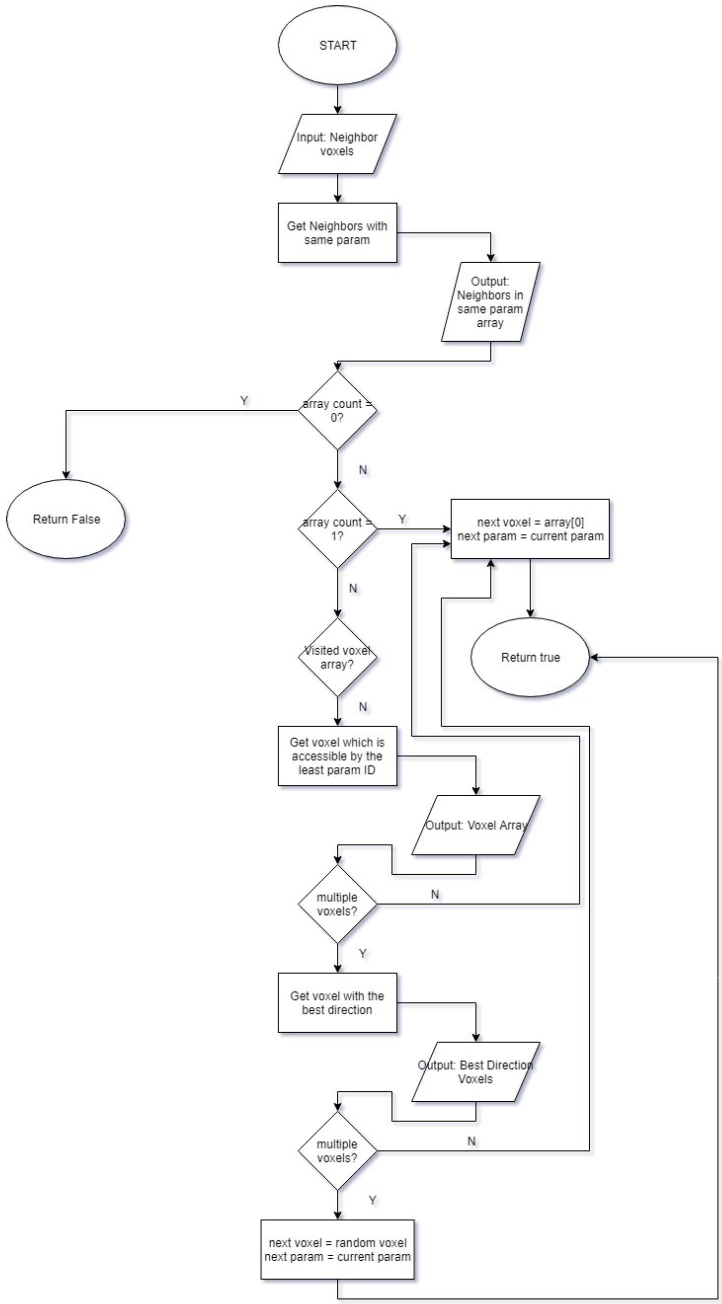

Figure 16: Flowchart for finding next voxel at same param

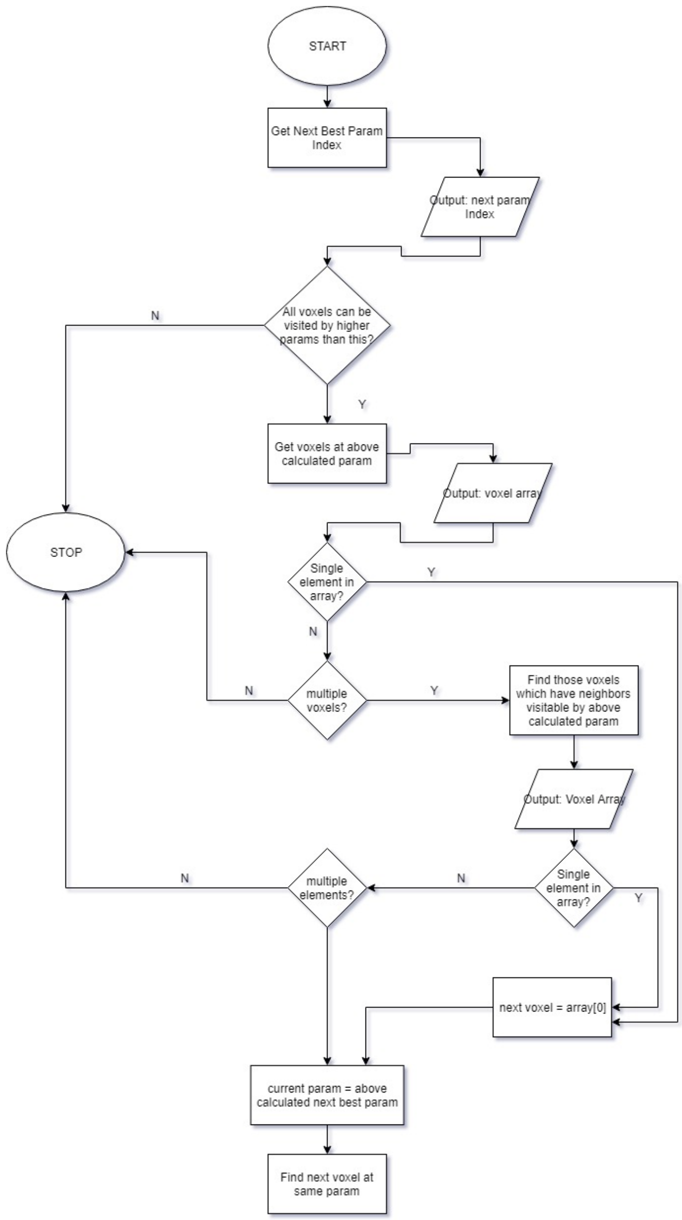

Figure 17: Flowchart for finding next voxel at higher param

9.2 Data Flow Diagram

A Data Flow Diagram(DFD) is a graphical representation of the flow of data through an information system. DFD's can also be used for the visualization of a structured design. Below are given three DFD's, analogous to the three parts constituting the project.

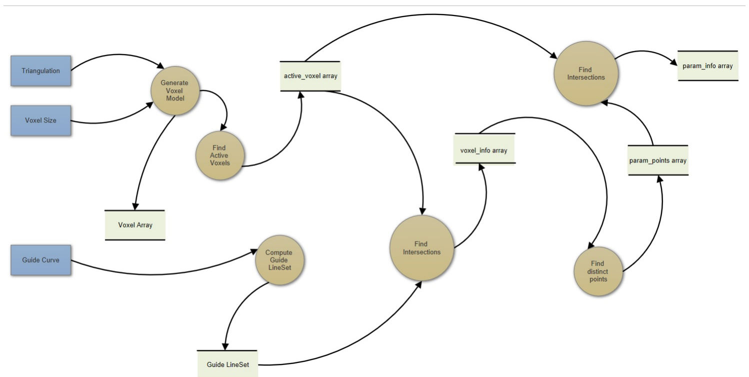

Figure 18: DFD to find voxel info and param info arrays

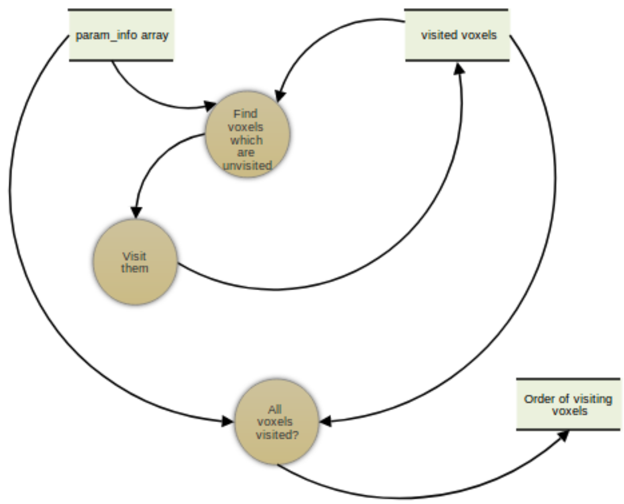

Figure 19: DFD for finding out path

10 Observations and Results

Implementation of the algorithm was done on two faces of Renishaw's demo box. It is a cubical structure marked by multiple contours of different shapes. It is used by Renishaw to test CMM capabilities. Given below are the two faces of the Renishaw's cube along with the final path returned after executing the algorithm. Given 20 is an image of Renishaw's demo cube block depicting 2 sides used for traversal.

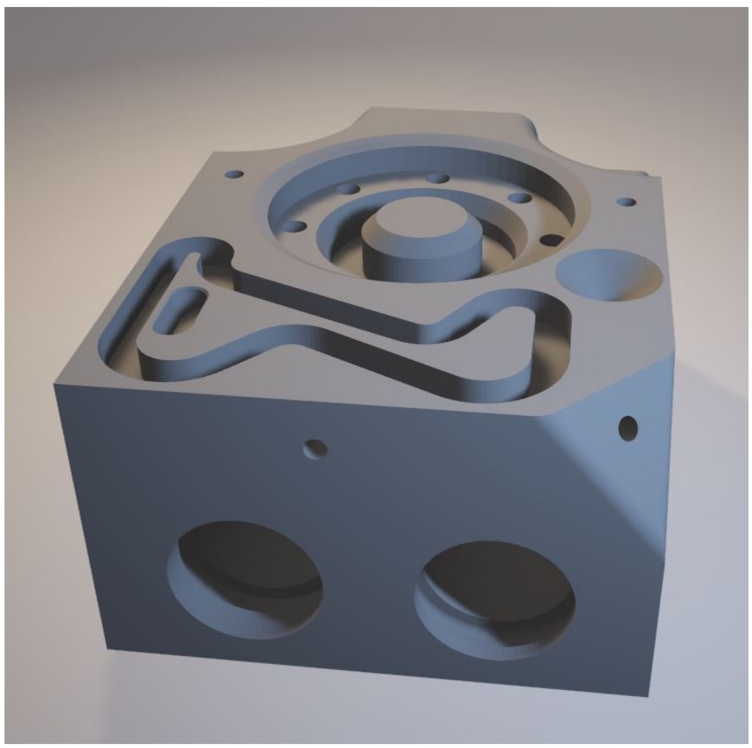

Figure 20: Renishaw's demo cube block

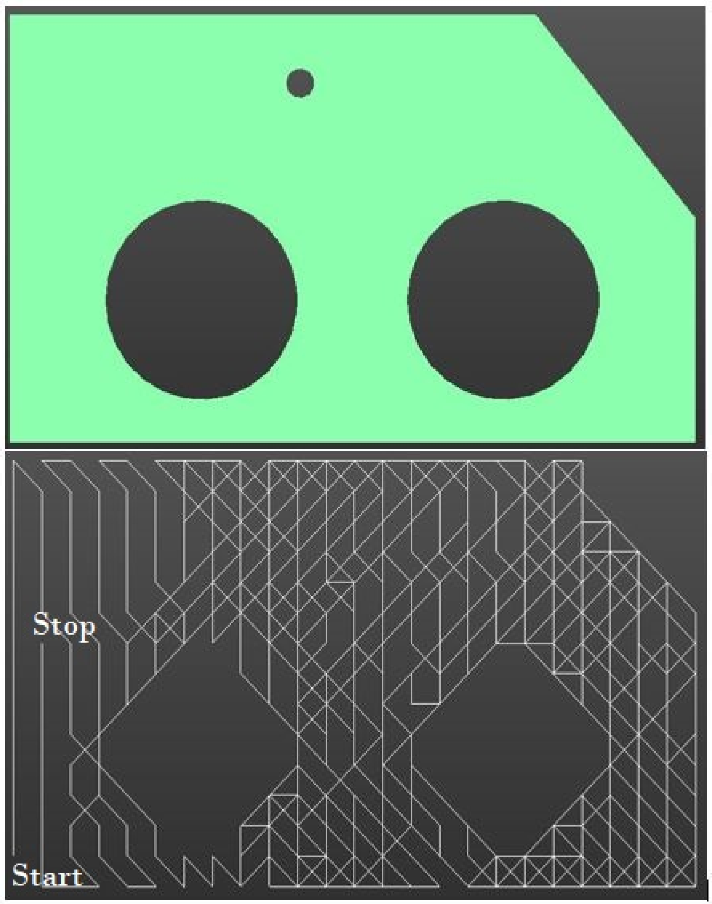

Figure 21: First Surface With traversal map

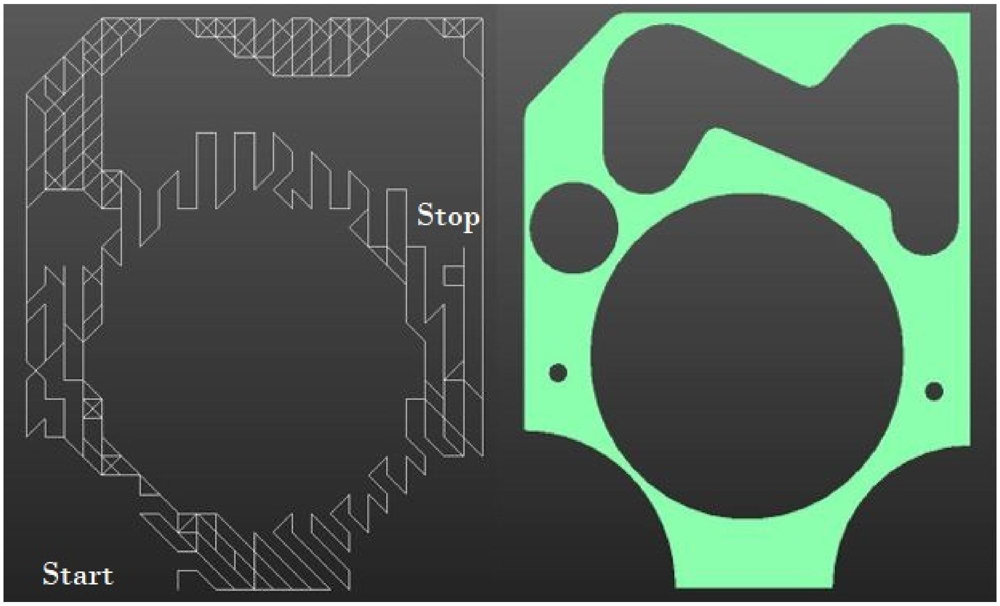

Figure 22: Second Surface With traversal map

10.1 Observations

11 Conclusion

This paper presents a new method to automatically generate a sweep scan path for performing continuous scanning inspection of an arbitrary free-form surface on 5-axis CMM.The proposed method fully utilizes the superb kinematic advantages of the 5-axis CMM (i.e., the two rotary axes have extremely low moment of inertia) and should be able to generate a sweep scan path that in general, should be more efficient the existing methods.

On the deficiency of the proposed method, although it can generate a viable curve scan path automatically, significant user involvement is still required. Another major limitation is that the quality of the generated curve scan path crucially depends on the guide curve, which currently is provided by the user instead of being automatically determined by the system.

List of Figures

References