## CHAPTER-1

**INTRODUCTION**

**1.1 Free Form Surfaces**

Freeform surfaces, also called sculptured surfaces, have been widely used in aerospace, automobile, consumer products and the die/mold industry. Freeform surfaces are usually designed to meet or improve an aesthetic and/or functional requirement. The definitions of freeform or sculptured surfaces are intuitive rather than formal. Often they are defined as surfaces containing one or more non-planar non-quadratic surfaces generally represented by parametric and/or tessellated models. Due to increase demand on this features and ever growing quality requirements concerning new products such as functionality, ergonomics as well as appearance demand of complex 3D forms need accuracy. Such parts are shaped by surfaces that are impossible to be described by simple mathematical equations. The accuracy control, in such cases, consists in digitizing the analyzed object (coordinate measurement by scanning) and comparing the obtained coordinate measurement points with the CAD model.

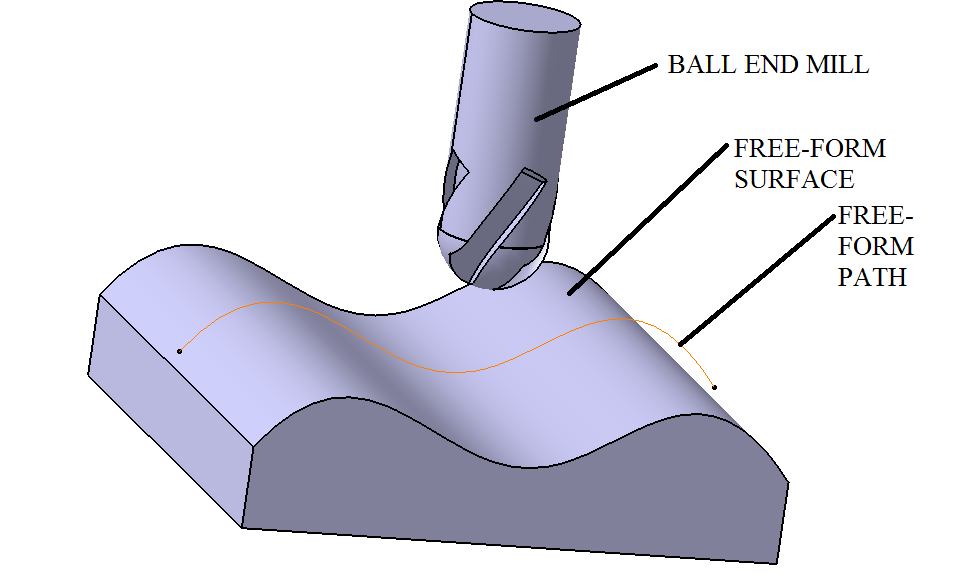


Fig 1.1: Schematic diagram of free from surface

3- axis and 5-axis CNC machines have been most widely used in machining freeform surfaces. Five motions can be continuously and simultaneously controlled in a 5-axis machine. Translational motions in the X, Y and Z directions and two rotational motions are either applied to the tool holder or the machine table or both. Compared to 3-axis machines, 5-axis machines can produce complex surfaces with better quality and efficiency. 3 1/2 1/2 machines have also been used due to a lower initial and operational cost. They have better stiffness compared to 5-axis machines because the rotary axes are locked during the cutting movement of the tool . However unlike 5-axis machines, in 3 1/2 1/2 machines orientation cannot be continuously adjusted during cutting process, thus requiring longer machining time. Stages to complete free form surface machining are usually classified into rough, semi-finish, finish, clean-up and final polishing and treatment. In rough cutting, most of the material is removed from the surface to generate an approximate shape of the surface. Shoulders left from the roughing stage by large machine tools are removed in semi-finishing to yield a continuous offset surface for finishing. At the finishing stage, the rough surface is transformed into the exact shape. Another method classified the stages as rough, finish and clean-up.

Machine parts composed of free-form 3D surfaces are more and more often designed. In designing, producing and measuring such surfaces, CAD/CAM techniques are applied. The accuracy inspection consists in digitalizing the workpiece under research, followed by comparing the obtained coordinates of the measurement points with the CAD design (model). There are generally two types of measurement data acquisition methods: contact measurement using a coordinate measuring machine (CMM) and non-contact measurement by using an optical/laser scanner. Numerically-controlled CMMs equipped with a ball-end touch trigger or scanning probes, are mainly used for workpiece validation in manufacturing.

As a result of the measurement, a set of discrete data is obtained in the form of the coordinates of the measurement points. To research on geometric deviations of free-form surfaces, the methods of creating a solid model of scanned free form surface and measure it by CMM for discrete points, by combining this data point set we create the 2D surface and then 3D model which is we need to generate the NC code for machining of the free form surface for verification.

**1.2 B - Splines**

B-splines, short for basis splines, are a type of mathematical curve used in computer graphics, 3D modeling, and animation. They are defined by a set of control points and a degree, and can be used to create smooth curves and surfaces.

B-splines are made up of a set of basis functions, which are piecewise polynomials that define the shape of the curve. These basis functions are defined recursively, using a set of control points and a degree value. The degree of a B-spline curve determines the order of the polynomials used in the basis functions, and higher-degree B-splines can produce more complex curves.

One of the advantages of B-splines is that they can be easily manipulated and modified by adjusting the control points. This allows designers and animators to create complex curves and surfaces with a high degree of control and precision.

B-splines are commonly used in computer graphics and animation software, such as Autodesk Maya and Blender, where they are used to create smooth curves for objects and characters. They are also used in engineering and design applications, such as CAD software, where they can be used to create complex curves and surfaces for objects and structures.

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## Fig 1.2: B-spline

## 1.3 Cubic Splines

## Cubic splines are a type of spline curve used in computer graphics, engineering, and other fields. They are a specific type of B-spline curve where the degree of the polynomial used in the basis functions is 3.

## Cubic splines are defined by a set of control points and a set of cubic polynomials that connect them. The curve is smooth at each control point, and the slope and curvature of the curve can be controlled by adjusting the location of the control points.

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## Fig 1.3: Cubic-spline

## One of the advantages of cubic splines is that they provide a balance between smoothness and flexibility. They are smoother than linear or quadratic splines, but are not as complex as higher-degree B-splines. This makes them a popular choice for creating curves and surfaces in computer graphics and engineering applications.

## Cubic splines can be used to create a wide range of curves, including shapes with loops, bends, and twists. They are commonly used in computer graphics and animation software, where they are used to create smooth curves for objects and characters. They are also used in engineering and design applications, such as CAD software, where they can be used to create complex curves and surfaces for objects and structures. In engineering and design applications, such as CAD software, where they can be used to create complex curves and surfaces for objects and structures.

## 1.4 NURBS

## NURBS stands for Non-Uniform Rational B-Splines, and they are a type of mathematical curve used in computer graphics, 3D modeling, and animation. NURBS are a generalization of B-spline curves that provide more flexibility and precision in representing complex shapes. These curves are generated through a mathematical formula. In simple terms, it is a mathematical representation of complex 3D geometry. NURBS cannot be referred to as surfaces, but you can create NURBS surfaces by interjecting a surface amid NURB splines.

## NURBS curves are defined by a set of control points, a degree, and a set of weights. The weights allow for the curve to be weighted towards certain control points, which can be used to create complex shapes with varying levels of smoothness and curvature.

## What are Nurbs?

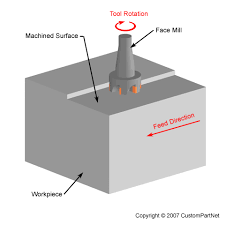
## Fig 1.4: Non-Uniform Rational B-Splines

## NURBS curves are highly versatile and can be used to create a wide range of curves and surfaces. They are commonly used in computer graphics and animation software, such as Autodesk Maya and Rhino 3D, where they are used to create smooth curves and surfaces for objects and characters. They are also used in engineering and design applications, such as CAD software, where they can be used to create complex curves and surfaces for objects and structures.

## One of the main advantages of NURBS curves is that they can represent complex shapes with a relatively small number of control points. This makes them highly efficient for representing complex shapes in computer graphics and engineering applications. Additionally, NURBS curves are highly adaptable and can be modified easily by changing the location of control points or adjusting the degree and weights of the curve.

## 1.5 Milling

**Milling** is a process performed with a machine in which the cutters rotate to remove the material from the work piece present in the direction of the angle with the tool axis. With the help of the milling machines one can perform many operations and functions starting from small objects to large ones.



## Fig 1.5: Schematic diagram of milling machining

**Milling machining** is one of the very common manufacturing processes used in machinery shops and industries to manufacture high precision products and parts in different shapes and sizes.

## ****1.5.1 Milling Machine****

The milling machines are also known as the multi-tasking machines (MTMs) which are multi-purpose machines capable of milling and turning the materials as well. The milling machine has got the cutter installed up on it which helps in removing the material from the surface of the work piece. When the material gets cooled down then it is removed from the milling machine.

The two main configurations of the milling machining operations are the types of milling machines. These are the vertical mill and the horizontal mill.

### **1.5.1.1 Vertical Milling Machines**

The vertical mill has a vertically arranged spindle axis and rotate by staying at the same axis. The spindle can also be extended and performing functions such as drilling and cutting. Vertical mill has got two further categories as well: turret mill and bed mill.

The turret mill has got a table that moves perpendicularly and parallel to the spindle axis in order to cut the material. The spindle is, however, stationary. Two cutting methods can be performed with this by moving the knee and by lowering or raising the quill.

The other is the bed mill in which the table moves perpendicular to the axis of the spindle and the spindle moves parallel to its axis.

### **1.5.1.2 Horizontal Milling Machines**

The horizontal mill is also the similar cutter but their cutters are placed on a horizontal arbor. A lot of horizontal mills have got rotary tables that help in milling in various angles. These tables are called the universal tables. Apart from this all the tools that are used in a vertical mill can also be used in the horizontal mill.

## CHAPTER-2

**LITERATURE REVIEW**

## 2.1 REVIEW IN THE LITERATURE

**Kim BH, Choi BK[1] and El-Midany et al.[2]**compared the machining time for direction- and contour-parallel paths by considering the feed rate acceleration and deceleration. In both researches, the machining times for different direction- and contour-parallel paths were compared by using a linear feed rate acceleration/deceleration model. El-Midany et al. concluded that the selection of the optimal path topology depends on the geometry of the surface’s boundary and the cutting conditions. Kim and Choi mentioned that although pure zigzag path (with sharp corners) results in a longer machining time compared to contour parallel path, it is practically preferred to contour parallel in die and mold machining because of enhanced constant cutting loads.

An investigation of optimal path pattern selection for layer by-layer rough cutting has been carried out by **Li H. et al [3] (1994).** In this method, the optimal path topology for each layer was selected by fuzzy pattern analysis among a variety of topologies in a path topology database. So for each roughing process, more than one pattern could be selected to machine all layers based on the geometry of these layers.

**Cox JJ et al. (1994)[4]** introduced the space filling curves (SFCs) for finish tool path generation of free form surfaces considering that parallel or spiral line pattern is not the best way of traversing the tool in an area. They used truncated Palmer’s and Moore’s curves to avoid overlapping and crossing points in the generated tool paths. However this truncation method doubles the number of lines to be traversed and sharp edges still remain in the tool paths.

In the research by **Han ZL et al. (2001) [5],** a free form surface was approximated by a ruled surface based on the isophote method. Iso-inclination curves were used as generators for the ruled surface and also as the boundary curves for the tool path generation.

**Choi BK et al. (1997)[6]** and **Morishige et al.(1997) [7]** employed the configuration space (C-space) technique in tool path generation. The configuration space (C-space) of a rigid object with a certain degrees of freedom is defined as the space of the parameters corresponding to the degrees of freedom. Each point in the C-space represents one configuration. By considering the design tolerance and mapping the obstacles corresponding to the local and global gouges in the C-space, the problem of tool path planning can be converted into the problem of planning the movements of a point in the C-space. The 2D C-space of the tool at the CC point is constructed by only considering two orientation parameters of the tool (α and ω) and removing the configurations with collision from the available space. Then the optimal parameters are selected in the C-space based on the maximum .machining efficiency.

**Hosseinkhani Y. et al. (2007) [8]** developed a method called the penetration–elimination method (PEM) for rear gouging avoidance. Similar as RBM and AIM, the PEM is only applicable to open face collision-free areas. A new concept for gouge quantification was introduced based on radial and axial depths of gouge. If a point is inside the tool area, it is assigned a negative radial depth of gouge. The gouging intensity function is defined as the multiplication of radial and axial depths of gouge. Hence, a point in the gouge area has a negative gouge intensity value. The penetration–elimination is conducted by incremental checking of the tool shadow area and adjusting the tilt angle, while each time the points calculated with positive gouge intensity values are deleted from the checking seed points. Together with an optimized root finding method, this method greatly reduces the calculation time by dynamically removing the safe areas out of the calculation loop.

Approximation of rear gouging area by a quadric surface has been used by **Fan J et al.(2008) [9]** for the tool orientation in 5-axis machining. A major advantage is the computational efficiency of fitting and distance calculation and the applicability to implicit, polyhedral and point based surfaces. However the required sample point patterns exaggerate the gouge prone area under the tool shadow, and hence increase the time of gouge checking. Another group of methods tends to locate the work piece in a few setups by using tilt/rotary tables. Note that this is different from 5-axis machining when the tool rotations are controlled by the machine table. In these methods, setups are generated based on partitioning the surfaces into a few areas and then machining by a multi-axis machine. This partitioning process has been conducted by the shape classification and machinability in, accessibility domain analysis in and G-map (Gaussian map) based area normal matching. Then tool orientation is adjusted in every setup by tilt/rotary table to machine with 3, 3 1/2 1/2, or 4 axis NC machine.

**Shuai He, et al. [10]** established an accurate freeform surface topography model considering geometric errors, tracking errors, and cutting forces. Regarding geometric errors, based on the theory of multibody systems and homogeneous coordinate transformation, the transfer relationship between various geometric errors and the tool error in the workpiece coordinate system is described. Using the continuous acceleration Position-Velocity-Time (PVT) interpolation method, the offset discrete points caused by geometric errors are interpolated and rediscretized, and the accurate mathematical model between the tool errors (position and posture) in the workpiece coordinate system and the topography of the freeform surface is established. Based on the model, the influence of geometric errors on the contour errors of freeform surfaces is accurately calculated, and the contribution and similarity of the effects of various geometric errors on the contour errors of freeform surfaces are analyzed. For dynamic-dependent factors, a second-order system with two degrees of freedom on the X or Z axis is established. According to the simplified result of the equivalent system, the contour error of the freeform surface caused by the tracking error and cutting force is analyzed. For the tracking error, under the condition of constant rotation velocity of the spindle, the change of the slope of the freeform surface along the circumferential direction causes the change in the velocity and acceleration of the motion axis; thus, the corresponding area of the surface has a larger contour error. For cutting force, the change of the slope of the freeform surface along the circumferential direction changes the tool working rake angle, the tool working clearance angle, and the shearing angle, resulting in a change in the cutting force. Moreover, the change of cutting speed is accompanied by the change of cutting force. An experiment verifies the effectiveness of the proposed modelling method. In addition, the modelling method provides an effective solution for the calculation of the contribution rate of different error sources to the contour error of the freeform surface.

**P J Scott et al. [11]** The specification and characterisation of freeform surfaces is immature: many CAD packages only allow the nominal freeform geometry to be specified. To control manufacturing and function, the allowable geometric variability also needs to be specified. Currently International standards specify allowable geometry through geometrical tolerancing. Geometrical tolerancing has proved to be a very blunt instrument with many cases, particularly in the aerospace and biomedical industries, of failure of the function of freeform surfaces due to inadequate specification. The paper begins by discussing the importance of the decomposition of the surface geometry into different scales for both specification and characterisation. The three main types of geometrical decomposition: linear, morphological and segmentation are briefly discussed. The Laplace-Beltrami operator (LBO) is the generalization of the Laplace operator to manifolds (i.e. freeform surfaces). By taking Eigenfunctions/Eigenvalues of the LBO a spectral decomposition of the freeform geometry can be realized. The Eigenfunctions are called manifold harmonics and are a direct generalization of Fourier harmonics for freeform surfaces. Tolerancing the Eigenfunctions provides a very powerful and flexible system to control geometrical variability of freeform surfaces; extending the geometrical tolerancing system by allowing decomposition of the geometrical shapes within tolerance zones. Further a generalized Gaussian filter can also be realized by Gaussian weighting the LBO spectra and reconstructing the weighted Eigenfunctions.

**Xinyu Liu et al. [12]** A data point calculation method that does not require the use of Fermat′s principle and a simple and general design method of starting points of freeform off-axis multi-mirror optical systems are proposed in this paper, which aim to promote the realization of high-performance reflective systems containing freeform surfaces. Taking a planar system and the required parameters as the input, a good starting point for a freeform off-axis multi-mirror system can be automatically obtained using the proposed method. The design of a freeform off-axis five-mirror system with a low F-number is taken as an example to show the effectiveness of the proposed method. The method can also be used for the design of freeform reflective systems with other numbers of mirrors.

**Hongxiang Pan et al. [13]** demonstrated a method of how to construct a freeform surface directly in an off-axis reflective image system is proposed. The method includes both the seed curve extension algorithm and simulated annealing algorithm. Firstly, the sample points on the unkown freeform surface were be obtained quickly by the seed curve extension algorithm. Then the continuity of the freeform surface is evaluated by calculating the angle between the normal vectors at the adjacent sample points. At last the freeform surface was fitted to an extended polynomials using simulated annealing algorithm. The method is employed to construct a freeform surface directly which is used as a primary mirror in an initial layout of an off-axis two-mirror system.

**Damian Groch et al. [14]** introduced method to simulate and predict the accuracy of fitting two freeform surfaces. For this purpose, the CAD models of both actual surfaces should be determined on the basis of coordinate measurement data obtained in measurements along regular grids of points in the UV space. The NURBS regression surfaces are modeled on the measurement data. Adequate regression models are sought with the iterative procedure. In the following steps of the procedure, the number of control points and/or the degree of the surface is/are changed, and the autocorrelation of residuals from the models is tested using the spatial statistics methods. The designated models are optimal CAD representations of the actual surfaces. Tests of the accuracy of fitting the surfaces are carried out virtually by fitting together both models in the CAD software. The outcome of the study is a spatial model of the gap between the studied surfaces. The obtained model was verified experimentally by measuring the dimensions of the actual gap between the surfaces, applying a measuring microscope. The proposed method is a useful tool in analyzing and improving the accuracy of injection molds machining.

**HaoyuLyu et al.[15]** Conjunctive multi-freeform surfaces play an important role in many advanced optical systems. The position and posture accuracy of freeform surfaces are the key to system performance. However, there is no effective method of measuring the positions and postures of multiple freeform surfaces. In this study, a conjunctive multi-freeform surface measurement system based on multi-sensors is developed, and a trust region registration based on the least squares method is proposed, with the aim of registering multiple freeform surfaces at different positions and postures. The performance of the proposed system was analyzed and the errors were calibrated. The calculation accuracy of the registration method was within 20 nm at Φ50 mm in terms of root-mean-of-squares (RMS) values. The positioning accuracy of the freeform surface measurement system proved to be 1.2 μm within the area of 120 mm × 120 mm; the related uncertainty was also analyzed. The proposed measurement approach provides a comprehensive solution to optical conjunctive multi-freeform surfaces.

**Wei Zhang et al. [16]** constructed a small-scale, lightweight structure with complex freeform surfaces via parametricdesign. First, the method of freeform surface modelling and parametric design were introduced, and combined into the parametric design aided freeform surface modelling. Then, the parametric design and software forcomplex surface structure were determined. On this basis, the small-scale structure was conceptualized andthe model was improved in the design phase. The PP sheet was selected as the final simulation material andthe model was established according to the specified method. The stress deformation of the structure wassimulated to correct the stress defects in the design, while the airflow impact was simulated to verify therationality of the structural form. The results show that the parametric design helps apply complex freeformnsurface to small and light structure and assist the generation of the designed form. The research findings shednew light on the application of parametric design in the field of structure.

**Julius Muschaweck [17]** Tailoring freeform surfaces for illumination with point sources is an established method to generate near-arbitrary illuminance distributions with high detail using a single freeform surface. Real, non-laser sources are not point sources, however. Replacing a point source in a tailored freeform system with an extended source blurs the point-source distribution. Accordingly, extended sources are often treated as a perturbation within a pointsource tailoring algorithm, which may work well for small sources. However, important applications like street lighting, wall-washing and automotive front lighting require some peak intensity in certain directions, which can only be achieved with a given source luminance when nearly the whole aperture contributes to that peak intensity. Then, the tenet of point source tailoring – a one-to-one relation of surface points to target points – breaks down. In this paper, we embrace extended sources instead of treating them as a perturbation: Illuminance at several target points is computed by integrating the luminance of the virtual source image over its finite projected solid angle in a noise-free, non-Monte-Carlo way. The freeform surface is parametrized; the shape of the distorted virtual source image, and thus the illuminance at the target points, becomes a function of the freeform surface parameters, leading to a system of nonlinear equations, which are solved iteratively. Using a solved-example problem, it is possible to provide answers to whether solutions exist and are unique.

**Jiancheng Hao et al. [18]** When machining a complex freeform part, using a non-spherical tool could significantly improve the machining efficiency, as one can adaptively adjust the tool posture to maximize its contact area with the part surface. However, since adjusting the tool posture requires changing the tool orientation, a five-axis machine tool is needed, which is extremely expensive as compared to a conventional three-axis machine tool. Moreover, for a complex freeform surface with high curvature variation, to match its curvature change, the tool axis has to drastically change accordingly, thus inducing high velocity and acceleration on the machine tool’s rotary axes. To address these issues, in this paper we propose a partition-based 3 + 2-axis strategy for machining a general complex freeform surface with a non-spherical tool. As only a finite small number of distinct tool orientations are needed for 3 + 2-axis machining, an indexed three-axis machine tool suffices, thus relieving the need of an expensive five-axis machine tool. In addition, the much-increased rigidity of the three linear axes of the machine tool will greatly improve the kinematics and dynamics of the machine tool and thus enhance the machining accuracy. Experiments in both computer simulation and physical machining are carried out, whose results confirm that, when compared to using a conventional spherical cutter, by using a non-spherical cutter and adaptively adjusting the contacting tool posture and the feed direction, significant improvement in machining efficiency could be achieved, e.g., more than 50% achieved in our experiments.

**Lingbao Kong et al. [19]** Compound freeform surfaces are widely used in bionic and optical applications. The manufacturing and measurement of such surfaces are challenging due to the complex geometry with multi-scale features in a high precision level with sub-micrometer form accuracy and nanometer surface finish. This article presents a study of ultra-precision machining and characterization of compound freeform surfaces. A hybrid machining process by combining slow slide servo and fast tool servo is proposed to machine compound freeform surfaces. The machining process for this hybrid tool servo is explained, and tool path generation is presented. Then, a normal template-based matching and characterization method is proposed to evaluate such compound freeform surfaces. Experimental studies are undertaken to machine a compound freeform surface using the proposed method based on a four-axis ultra-precision machine tool. The machined compound freeform surface is also measured and characterized by the proposed analysis and characterization method. The experimental results are presented, and the machining errors for compound freeform surfaces are also discussed.

**YassirArezki et al. [20]** Improvement in metrology of asphere and freeform surfaces is requested in many sectors and industries. ISO standards of Geometrical Product Specifications recommend the usage of the infinite norm L∞ (min-max) to determine the minimum zone (MZ). This is performed by directly minimizing the peak-to-valley (PV) which is the difference between maximum and minimum deviations of the dataset and the reference surface. Performing data fitting according to L∞ remains a major challenge when considering complex geometries such as aspheres and freeform surfaces. In this work, two algorithms for aspheres minimum zone fitting were implemented and compared on generated reference and measured datasets, namely the Exponential Penalty Function and Primal-Dual Interior Point Method The obtained results show that both methods give accurate values of minimum zone. When the number of points increases, a decay in the latter method’ performances was also noticed especially for calculation time and accuracy of returned minimum zone values.

**YassirArezki et al. [21]** Ultra-high precision measuring machines enable to measure aspheric shapes with an uncertainty of few tens of nanometres. The resulting clouds of points are then associated to theoretical model at the same level of accuracy so as to obtain parameters that indicate about form error. Minimum zone (MZ), defined as the least value of peak to valley (PV), is widely used to assess form error. Least squares method (L2) is often used to determine MZ but the resulting value is usually overestimated. For this reason, L2 is replaced by L∞ norm because it gives a more accurate value of MZ since it directly minimizes PV. Using L∞ norm results in a non-smooth optimization problem and consequently its resolution becomes more challenging compared to L2.In this paper, a novel minimax fitting method for accurate metrology of aspheres and freeform based on a hybrid trust region algorithm (HTR) is proposed. To assess performance of the introduced method, it was compared to an available minimax fitting algorithm based on a smoothing technique: exponential penalty function (EPF). The choice of EPF is justified by superior performances in comparison to existing techniques. Comparison was conducted on reference data, data available in literature and data gathered form measurements of a real optical high quality asphere. Results show superiority of HTR over EPF in both returned PV values and execution time.

**W. Gao et al. [22]** On-machine and in-process surface metrology are important for quality control in manufacturing of precision surfaces. The classifications, requirements and tasks of on-machine and in-process surface metrology are addressed. The state-of-the-art on-machine and in-process measurement systems and sensor technologies are presented. Error separation algorithms for removing machine tool errors, which is specially required in on-machine and in-process surface metrology, are overviewed, followed by a discussion on calibration and traceability. Advanced techniques on sampling strategies, measurement systems-machine tools interface, data flow and analysis as well as feedbacks for compensation manufacturing are then demonstrated. Future challenges and developing trends are also discussed.

**C. Brecher et al. [23]** The machining of ultra-precision optical components with form tolerances in the sub-micron range requires a close interaction between the machine tool, the process and the procedure for the NC tool path generation. Especially for the optical free-form machining the choice of a data-format for the surface description as well as the calculation of the tool path is crucial for the overall achievable quality of the work piece. This paper presents the layout of a tool path calculation based on the NURBS data format that has been developed at the Fraunhofer IPT. In addition the interfaces and the hardware and software for the realisation of a NURBS based control unit for Fast Tool Servo turning and local corrective polishing operations are described.

**L.B. Kong, et al. [24]** Due to the geometry complexity and high precision requirement, there still possess a lot of challenges in the design, manufacturing and measurement of ultra-precision micro-structured freeform surfaces (e.g. micro lens array) with sub micrometer form accuracy and surface finish in nanometer range. Successful manufacturing of ultra-precision micro-structured freeform surface not only relies on the high precision of machine tools, but also largely depends on comprehensive consideration of advanced optics design, modelling and optimization of the machining process, freeform surface measurement and characterization. This paper presents the theoretical basis for the establishment of an integrated platform for design, fabrication, and measurement of ultra-precision micro-structured freeform surfaces. The platform mainly consists of four key modules, which are Optics Design Module, Data Exchange Module, Machining Process Simulation and Optimization Module and Freeform Measurement and Evaluation Module. A series of experiments have been conducted to evaluate the performance of the platform and its capability is realized through a trial implementation in design, fabricating and measurement of a micro lens array. The results predicted by the system are found to agree well with the experimental results. These show that the proposed integrated platform not only helps to shorten the cycle time for the development of micro lens array components but also provides an important means for optimization of the surface quality in ultra-precision machining of micro-structured surfaces. With this successful development of the system, optimal machining parameters, the best cutting strategy, and optimization of the surface quality of the ultra-precision freeform surfaces can be obtained without the need for conducting time-consuming and expensive cutting tests.

**Chen, J., et. al. [25]** Contour parallel tool paths have been proved to be a preferred machining strategy for their advantage of less tool retractions and less sharp turns. The traditional geometrical algorithm-based tool path generation method often makes it hard to simply and simultaneously solve the problems of self-intersection, no residual, and smoothness at the same time due to their contradictions. To address this issue, a contoured parallel tool path generation method for pocket machining is developed in this study. It is based on sound field synthesis theory inspired by the phenomenon of sound wave propagation. Firstly, the simplified medial axis (SMA) tree of the pocket is extracted and the propagation direction of each SMA segment is calculated on account of the geometric characteristics of the pocket boundary. Secondly, the final tool path is obtained through the synthesis of the sound field. Finally, the novel method is verified on five different pockets to generate a contoured parallel milling tool path. After machining these pockets and measuring the machining time, roughness, and cutting force, the experimental results demonstrate that the tool path obtained by the novel method has advantages in improving machining quality and efficiency.

**Li, Y., et. al. [26]** In order to quantitatively evaluate and improve the sustainability of machining systems, this paper presents an emergy (the amount of energy consumed in direct and indirect transformations to make a product or service) based sustainability evaluation and improvement method for machining systems, contributing to the improvement of energy efficiency, resource efficiency and environmental performance, and realizing the sustainability development. First, the driver and challenge are studied, and the scope and hypothesis of the sustainable machining system are illustrated. Then, the emergy-based conversion efficiency model is proposed, which are (1) effective emergy utilization rate (EEUR), (2) emergy efficiency of unit product (EEUP) and (3) emergy conversion efficiency (ECE), to measure and evaluate the sustainable machining system from the perspectives of energy, resource and environment. Finally, the proposed model is applied to a vehicle-bridge machining process, and the results show that this paper provides the theoretical and method support for evaluating and improving the sustainable machining processes to decouple the resources and development of the manufacturing industry.

**Zhang, X., et. al. [27]** Five-axis machining of free-form surfaces has one major advantage over three-axis machining, i.e. a greater degree of flexibility in positioning the cutting tool relative to the surface. In five-axis machining of free-form surfaces there are three major phases in creating the tool path: (i) generation of the cutter contact (CC) points; (ii) formation of the cutter location (CL) points that define the path followed by the cutting tool reference point; and (iii) the creation of the specific machine tool part program (G-code file). In this paper, the free-form surface is defined as a triangular polyhedral mesh. The CC-points are created from the surface mesh definition employing a cutting plane technique. Additionally, the CC points are positioned based on an examination of several important factors: geometric constraints derived from the machine tool axis limits, gouging (undercutting) of the free-form surface by the cutting tool and collision of the tool with either the machining stock or machine. The CL points can then be generated along the resulting CC points by consideration of specific machining strategies, such as cusp height and a smooth change in tool posture. The critical issues addressed in this work concern the avoidance of machining problems (machine limit, collision, and gouging) in the tool-path generation phase. Therefore, this technique avoids inefficient five-axis machining practices by automatically creating and verifying a feasible tool-path prior to the actual metal cutting..

**Wang, X., et. al. [28]** In order to ensure machining stability, curvature continuity and smooth cutting force are very important so as to meet the constraints of both cutting force and kinematics of machine tools. For five-axis flank milling, it is difficult to meet both of the constraints because tool path points and tool axis vectors interact with each other. In this paper, multiple relationships between tool path points and tool axis vectors with cutting force and kinematics of machine tools are established, and the strategies of corner-looping milling and clothoidal spirals are combined so as to find feasible solutions under both of the constraints. Tool path parameters are iterated by considering the maximum cutting force and the feasible range of the tool axis vector, and eventually a curvature continuity five-axis flank milling tool path with smooth cutting force is generated. Machining experimental results show that the conditions of cutting force are satisfied, vibration during the process of machining is reduced, and the machining quality of the surface is improved.

**Zhang, J., et. al. [29]** Tool path generation is a fundamental problem in 5-axis CNC machining, which consists of tool orientation planning and cutter-contact (CC) point planning. The planning strategy highly depends on the type of tool cutters. For ball-end cutters, the tool orientation and CC point location can be planned separately; while for flat end cutters, the two are highly dependent on each other. This paper generates a smooth tool path of workpiece surfaces for flat end mills from two stages: Computing smooth tool orientations on the surface without gouging and collisions and then designing the CC point path. By solving the tool posture optimization problem the authors achieve both the path smoothness and the machining efficiency. Experimental results are provided to show the effectiveness of the method.

**Xu, L., et. al. [30]** Five-axis machining of free-form surfaces has one major advantage over three-axis machining, i.e. a greater degree of flexibility in positioning the cutting tool relative to the surface. In five-axis machining of free-form surfaces there are three major phases in creating the tool path: (i) generation of the cutter contact (CC) points; (ii) formation of the cutter location (CL) points that define the path followed by the cutting tool reference point; and (iii) the creation of the specific machine tool part program (G-code file). In this paper, the free-form surface is defined as a triangular polyhedral mesh. The CC-points are created from the surface mesh definition employing a cutting plane technique. Additionally, the CC points are positioned based on an examination of several important factors: geometric constraints derived from the machine tool axis limits, gouging (undercutting) of the free-form surface by the cutting tool and collision of the tool with either the machining stock or machine. The CL points can then be generated along the resulting CC points by consideration of specific machining strategies, such as cusp height and a smooth change in tool posture. The critical issues addressed in this work concern the avoidance of machining problems (machine limit, collision, and gouging) in the tool-path generation phase. Therefore, this technique avoids inefficient five-axis machining practices by automatically creating and verifying a feasible tool-path prior to the actual metal cutting.

**Zheng, Jet. al .[31]** An improved tool path generation method for five-axis machining of free-form surfaces is proposed. The method first divides the surface into a series of patches, and then uses a local feature analysis algorithm to determine the optimal tool orientation for each patch. The toolpath is then generated by connecting the tool orientation for each patch. The effectiveness of the proposed method is demonstrated through several numerical experiments, and the results show that the proposed method can effectively reduce the machining time and improve the surface quality of the machined parts.

**Park, J. Y., et. al. [32]** A new method for tool path generation in five-axis machining of free-form surfaces is proposed. The method first divides the surface into a series of patches, and then uses a local feature analysis algorithm to determine the optimal tool orientation for each patch. The toolpath is then generated by connecting the tool orientation for each patch. The effectiveness of the proposed method is demonstrated through several numerical experiments,

**Liu, H., et. al. [33]** An urgent challenge in the manufacturing industry is increasing efficiency while decreasing energy consumption and environmental impact. Past studies addressing these issues have mainly focused on tool path optimization only considering machining efficiency. In this paper, we present a methodology to optimize the tool path for high efficiency, low energy consumption and carbon footprint in milling process. Firstly, the description and influencing factors of tool path are introduced. Then, a multi objective tool path optimization model with maximum machining efficiency, minimum energy consumption and carbon emission is proposed. Furthermore, the solution of the proposed model is introduced, which including two steps, one is the calculation of the number of cutter contact points (CCP), the other is using adaptive dynamic GA to optimize the connection sequence and ways of each CCP. Finally, the effectiveness and practicability of the method are verified by the machining experiments.

**Huang, S., et. al. [34]** A novel approach for tool path generation in five-axis machining of free-form surfaces is proposed. The approach first divides the surface into a series of patches, and then uses a local feature analysis algorithm to determine the optimal tool orientation for each patch. The toolpath is then generated by connecting the tool orientation for each patch. The effectiveness of the proposed approach is demonstrated through several numerical experiments, and the results show that the proposed approach can effectively reduce the machining time and improve the surface quality of the machined parts.

**Li, J., et. al. [35]** A tool path planning approach for five-axis machining of free-form surfaces is proposed. The approach first divides the surface into a series of patches, and then uses a local feature analysis algorithm to determine the optimal tool orientation for each patch. The toolpath is then generated by connecting the tool orientation for each patch. The effectiveness of the proposed approach is demonstrated through several numerical experiments, and the results show that the proposed approach can effectively improve the machining efficiency and surface quality of the machined parts.

**Zhang, J., et. al. [36]** A tool path generation approach for five-axis NC machining of free-form surfaces is proposed. The approach first divides the surface into a series of patches, and then uses a local feature analysis algorithm to determine the optimal tool orientation for each patch. The toolpath is then generated by connecting the tool orientation for each patch. The effectiveness of the proposed approach is demonstrated through several numerical experiments, and the results show that the proposed approach can effectively reduce the machining time and improve the surface quality of the machined parts.

**Zhang, H., et. al. [37]** A new algorithm for tool path generation in five-axis machining of free-form surfaces is proposed. The algorithm first divides the surface into a series of patches, and then uses a local feature analysis algorithm to determine the optimal tool orientation for each patch. The toolpath is then generated by connecting the tool orientation for each patch. The effectiveness of the proposed algorithm

**Zou, L., et. al .[38]** A multi-objective optimization approach for tool path planning in five-axis flank milling of free-form surfaces is proposed. The approach takes into account both the machining efficiency and surface quality as the optimization objectives, and uses a genetic algorithm to search for the optimal tool path. The effectiveness of the proposed approach is demonstrated through several numerical experiments, and the results show that the proposed approach can effectively optimize the tool path and improve the machining efficiency and surface quality of the machined parts.

**Lin, Z., et. al. [39]** A novel optimization method for tool path generation in five-axis machining of free-form surfaces is proposed. The method uses a local feature analysis algorithm to determine the optimal tool orientation for each point on the surface, and then uses a genetic algorithm to search for the optimal tool path. The effectiveness of the proposed method is demonstrated through several numerical experiments, and the results show that the proposed method can effectively optimize the tool path and improve the machining efficiency and surface quality of the machined parts.

**Wu, Y., et. al. [40]** A novel optimization method for tool path generation in five-axis machining of free-form surfaces is proposed. The method uses a local feature analysis algorithm to determine the optimal tool orientation for each point on the surface, and then uses a genetic algorithm to search for the optimal tool path. The effectiveness of the proposed method is demonstrated through several numerical experiments, and the results show that the proposed method can effectively optimize the tool path and improve the machining efficiency and surface quality of the machined parts.

**Sun, L., et. al. [41]** An improved algorithm for tool path generation in five-axis machining of free-form surfaces is proposed. The algorithm first divides the surface into a series of patches, and then uses a local feature analysis algorithm to determine the optimal tool orientation for each patch. The toolpath is then generated by connecting the tool orientation for each patch. The effectiveness of the proposed algorithm is demonstrated through several numerical experiments, and the results show that the proposed algorithm can effectively reduce the machining time and improve the surface quality of the machined parts.

**Luo, Y., et. al.[42]** An efficient tool path planning method for five-axis machining of free-form surfaces is proposed based on surface decomposition. The method first decomposes the surface into a series of patches, and then uses a local feature analysis algorithm to determine the optimal tool orientation for each patch.

**Garg, A., et. al. [43]** A Freeform surfaces are widely used in industries such as aerospace, automotive, and biomedical. However, machining of freeform surfaces is a challenging task due to the complex geometries involved. In this paper, a comprehensive review of the literature on machining of freeform surfaces is presented, including the various methods, challenges, and future trends. The review provides a valuable resource for researchers and practitioners in the field.

**Nayak, A. K., et. Al. [44]** The Taguchi method is used to optimize machining parameters for minimizing surface roughness in ball-end milling of free-form surfaces. This study investigates the effects of cutting speed, feed rate, axial depth of cut, and radial depth of cut on surface roughness in milling operations. The Taguchi L9 orthogonal array is used to design the experiments, and signal-to-noise (S/N) ratios are used to evaluate the performance of the machining parameters. The results show that the cutting speed is the most significant factor affecting surface roughness, followed by the feed rate, axial depth of cut, and radial depth of cut. The optimal combination of machining parameters for minimizing surface roughness is determined. This study provides valuable insights into the optimization of machining parameters for ball-end milling of free-form surfaces, which can help improve the efficiency and quality of milling operations.

**Kumari, A., et. al. [45]** This study proposes a novel tool path generation method for five-axis machining of free-form surfaces using Delaunay triangulation. The proposed method utilizes a local Delaunay triangulation algorithm to generate tool paths for each facet of the surface, which can effectively reduce the computation time and memory usage. The tool path is optimized based on the characteristics of the surface curvature and tool accessibility, and the collision detection algorithm is applied to avoid collisions between the tool and the surface. The proposed method is validated using various examples of free-form surfaces, and the results show that the proposed method can generate smooth and efficient tool paths with a shorter computation time and lower memory usage compared to other methods. This study provides a practical and efficient tool path generation method for five-axis machining of free-form surfaces, which can help improve the accuracy and efficiency of machining operations.

**Panda, S. K., et. al. [46]** This study focuses on the optimization of machining parameters for ball-end milling of free-form surfaces using the Taguchi method. The effects of cutting speed, feed rate, axial depth of cut, and radial depth of cut on surface roughness are investigated using the Taguchi L9 orthogonal array. The signal-to-noise ratio (S/N) is used to evaluate the performance of the machining parameters. The results show that the cutting speed is the most significant factor affecting surface roughness, followed by the feed rate, axial depth of cut, and radial depth of cut. The optimal combination of machining parameters is determined to minimize surface roughness. The analysis of variance (ANOVA) is performed to determine the significance of the factors and their interactions. The results indicate that the cutting speed has the highest contribution to surface roughness, followed by the feed rate and the axial depth of cut. The proposed method can provide valuable insights into the optimization of machining parameters for ball-end milling of free-form surfaces, which can help improve the efficiency and quality of milling operations.

**Dehghani, A, et. al. [47]** This study proposes a hybrid approach for tool path generation in five-axis milling of free-form surfaces, which combines the advantages of both the iso-parametric and tri-parametric methods. The proposed method first decomposes the surface into small patches using the iso-parametric method and then applies the tri-parametric method to generate tool paths on each patch. The tool paths are optimized based on the surface curvature and tool accessibility, and collision detection algorithms are applied to avoid collisions between the tool and the surface. The proposed method is validated using various examples of free-form surfaces, and the results show that the proposed method can generate smooth and efficient tool paths with a shorter computation time compared to the iso-parametric and tri-parametric methods separately. This study provides a practical and efficient tool path generation method for five-axis milling of free-form surfaces, which can help improve the accuracy and efficiency of machining operations.

**Zhou, Y., et. al. [48]** This study presents an analytical approach for predicting tool deflection in five-axis milling of free-form surfaces. The proposed model considers the effects of cutting force, tool geometry, and workpiece geometry on tool deflection. The cutting force is calculated using a mechanistic cutting force model, and the tool geometry and workpiece geometry are modeled using a finite element method. The proposed model is validated using experimental data, and the results show good agreement with the experimental data. The proposed model is then applied to analyze the effects of cutting parameters on tool deflection. The results show that the cutting speed has the most significant effect on tool deflection, followed by the axial depth of cut and radial depth of cut. The proposed model can provide valuable insights into the optimization of cutting parameters for five-axis milling of free-form surfaces, which can help reduce tool deflection and improve the accuracy and efficiency of machining operations.

**Jeong, S. et. al. [49]** This study presents an analytical model for predicting tool path deviation in five-axis machining of freeform surfaces. The model considers the effects of tool geometry, machining parameters, and surface curvature on tool path deviation. The tool geometry is modeled using a virtual tool approach, and the surface curvature is estimated using a surface fitting algorithm. The proposed model is validated using experimental data, and the results show good agreement with the experimental data. The model is then used to analyze the effects of machining parameters on tool path deviation. The results show that the cutting speed has the most significant effect on tool path deviation, followed by the axial depth of cut and radial depth of cut. The proposed model can provide valuable insights into the optimization of machining parameters for five-axis machining of freeform surfaces, which can help reduce tool path deviation and improve the accuracy and efficiency of machining operations.

**Chen, Y., et. al. [50]** This study presents a Bayesian network model for predicting tool wear and surface roughness in milling of free-form surfaces. The proposed model considers the effects of cutting parameters, tool wear, and surface roughness on each other. The cutting parameters include cutting speed, feed rate, axial depth of cut, and radial depth of cut. The tool wear is modeled using a physical-based wear model, and the surface roughness is modeled using a mechanistic surface roughness model. The proposed model is validated using experimental data, and the results show good agreement with the experimental data. The model is then used to analyze the effects of cutting parameters on tool wear and surface roughness. The results show that the cutting speed has the most significant effect on tool wear and surface roughness, followed by the feed rate, axial depth of cut, and radial depth of cut. The proposed model can provide valuable insights into the optimization of cutting parameters for milling of free-form surfaces, which can help reduce tool wear and surface roughness and improve the accuracy and efficiency of machining operations.

**Fang, F., et. al. [51]** This study proposes a new method for tool path optimization in five-axis milling of free-form surfaces. The proposed method combines the advantages of both the genetic algorithm (GA) and the simulated annealing (SA) algorithm. The GA is used to generate initial solutions, and the SA is used to refine the solutions. The proposed method considers the effects of surface curvature, machining accuracy, and tool accessibility on tool path optimization. The proposed method is validated using various examples of free-form surfaces, and the results show that the proposed method can generate tool paths with better machining accuracy and shorter machining time compared to the traditional optimization methods. The proposed method can provide valuable insights into the optimization of tool paths for five-axis milling of free-form surfaces, which can help improve the accuracy and efficiency of machining operations

**Véron, et. al. [52]** This study presents the development of a robotized cell for deburring and finishing of free-form surfaces. The proposed cell consists of a six-axis robot, an end-effector, a vision system, and a force sensor. The vision system is used to locate the edges and features of the workpiece, and the force sensor is used to detect the contact between the end-effector and the workpiece. The proposed cell is programmed using a path planning algorithm to generate tool paths for deburring and finishing of the workpiece. The proposed cell is validated using various examples of free-form surfaces, and the results show that the proposed cell can effectively remove burrs and improve surface finish with high accuracy and consistency. The proposed cell can provide a practical solution for deburring and finishing of free-form surfaces, which can help improve the quality and efficiency of manufacturing operations.

**Bouchard, et. al. [53]** This study presents a model for predicting the optimal cutting parameters for 5-axis milling of free-form surfaces. The model considers the effects of cutting parameters such as cutting speed, feed rate, axial depth of cut, radial depth of cut, and tool diameter on surface roughness, machining time, and tool wear. The model is developed using a combination of a response surface methodology (RSM) and a genetic algorithm (GA). The RSM is used to model the relationships between the cutting parameters and the output variables, and the GA is used to optimize the cutting parameters. The proposed model is validated using experimental data, and the results show good agreement with the experimental data. The model is then used to analyze the effects of cutting parameters on surface roughness, machining time, and tool wear. The results show that the cutting speed and feed rate have the most significant effects on surface roughness, machining time, and tool wear, followed by the axial depth of cut, radial depth of cut, and tool diameter. The proposed model can provide valuable insights into the optimization of cutting parameters for 5-axis milling of free-form surfaces, which can help reduce surface roughness, machining time, and tool wear and improve the accuracy and efficiency of machining operations.

**Al-Musawi, et. al. [54]** This study presents an analytical model for predicting cutting forces in ball-end milling of free-form surfaces. The model considers the effects of cutting parameters such as cutting speed, feed rate, axial depth of cut, radial depth of cut, and tool geometry on cutting forces. The model is developed based on the mechanics of cutting and the geometry of the tool and workpiece. The proposed model is validated using experimental data, and the results show good agreement with the experimental data. The model is then used to analyze the effects of cutting parameters on cutting forces. The results show that the cutting speed and feed rate have the most significant effects on cutting forces, followed by the axial depth of cut, radial depth of cut, and tool geometry. The proposed model can provide valuable insights into the optimization of cutting parameters for ball-end milling of free-form surfaces, which can help reduce cutting forces and improve the accuracy and efficiency of machining operations.

**Monfroy, E et. al. [55]** This study proposes an efficient tool path optimization method for five-axis milling of free-form surfaces. The proposed method uses an adaptive sampling algorithm to generate a set of initial tool paths and then applies a genetic algorithm to optimize the tool paths. The proposed method considers the effects of cutting parameters such as cutting speed, feed rate, axial depth of cut, and radial depth of cut on tool path optimization. The proposed method is validated using various examples of free-form surfaces, and the results show that the proposed method can generate tool paths with better surface quality and shorter machining time compared to the traditional optimization methods. The proposed method can provide valuable insights into the optimization of tool paths for five-axis milling of free-form surfaces, which can help reduce machining time and improve the accuracy and efficiency of machining operations.

**Zhou, Y, et. al. [56]** This study presents a computational model for predicting surface roughness in 5-axis milling of free-form surfaces. The model considers the effects of cutting parameters such as cutting speed, feed rate, axial depth of cut, radial depth of cut, and tool diameter on surface roughness. The model is developed using a combination of a neural network and a genetic algorithm. The neural network is trained using experimental data, and the genetic algorithm is used to optimize the model parameters. The proposed model is validated using experimental data, and the results show good agreement with the experimental data. The model is then used to analyze the effects of cutting parameters on surface roughness. The results show that the cutting speed and feed rate have the most significant effects on surface roughness, followed by the axial depth of cut, radial depth of cut, and tool diameter. The proposed model can provide valuable insights into the optimization of cutting parameters for 5-axis milling of free-form surfaces, which can help reduce surface roughness and improve the accuracy and efficiency of machining operations.

**Ignatov, M. A., et. al. [57]** This study investigates the effect of tool wear on the accuracy of free-form surface milling. The study is conducted using a series of experiments with different levels of tool wear. The experiments are designed to investigate the effect of tool wear on surface roughness, form accuracy, and dimensional accuracy. The results show that as tool wear increases, surface roughness and form accuracy degrade, while dimensional accuracy is less affected. The study also investigates the relationship between tool wear and cutting parameters such as cutting speed, feed rate, and depth of cut. The results show that higher cutting speeds and feed rates lead to faster tool wear and degraded surface quality. The study concludes that tool wear has a significant impact on the accuracy of free-form surface milling and that proper tool maintenance and selection of appropriate cutting parameters are essential for achieving high surface quality and form accuracy. The findings of this study can provide valuable insights into the development of strategies for improving the accuracy of free-form surface milling in industrial applications.

**Yakovlev, et. al. [58]**, This study presents a multicriteria optimization approach for machining parameters in free-form surface milling. The approach uses the Taguchi method and the Grey Relational Analysis (GRA) to simultaneously optimize multiple machining criteria such as surface roughness, tool wear, and material removal rate. The proposed approach includes the identification of the significant machining parameters that affect the machining criteria, the optimization of the parameters using the Taguchi method, and the determination of the optimal parameter settings using the GRA. The proposed approach is validated through a series of experiments, and the results show that the proposed approach can effectively optimize the machining parameters for multiple criteria. The optimal parameter settings obtained through the proposed approach provide a balance between the machining criteria, which can help improve the overall machining performance. The proposed approach can provide valuable insights into the optimization of machining parameters for free-form surface milling, which can help improve the efficiency and accuracy of machining operations.

**Belyaev, et. al. [59]** This article presents a study on the use of virtual tools for analyzing the quality of machined surfaces. The study focuses on the development of a virtual machining simulation environment that allows for the analysis of surface quality based on the machining parameters and tool characteristics. The proposed approach includes the development of virtual tools such as virtual milling cutters and surface roughness measurement instruments that can be used to simulate the machining process and measure surface quality. The simulation results are compared with experimental results to validate the accuracy of the proposed approach. The study demonstrates that the proposed virtual tools can provide accurate predictions of surface quality and can be used to optimize the machining process parameters to improve surface quality. The proposed approach can help reduce the time and cost associated with physical experiments and can provide valuable insights into the optimization of machining processes. This study is published in the Russian Engineering Research journal.

**Pogorelov, et. al. [60]** The study presents an analysis of surface roughness in the milling of free-form surfaces using response surface methodology (RSM). The RSM is used to develop a mathematical model for predicting the surface roughness based on the machining parameters, such as cutting speed, feed rate, and depth of cut. The model is validated using experimental results obtained from milling of free-form surfaces, and the results show that the model can effectively predict the surface roughness with high accuracy. The study also investigates the effects of various machining parameters on the surface roughness, and provides guidelines for selecting the optimal cutting conditions for achieving the desired surface quality. The results showed that the cutting speed and feed rate have significant effects on the surface roughness, while the effect of the depth of cut is relatively small. The study concluded that the RSM can provide a reliable and effective tool for optimizing the machining parameters and improving the machining performance in the milling of free-form surfaces. The study also suggests that the RSM can be further developed and refined to include more complex machining processes and improve the accuracy of the predictions.

**Karpov, A., et. al .[61]** The study presents a mathematical model for predicting the surface roughness and machining accuracy in free-form surface machining by milling. The model is based on the geometric characteristics of the workpiece, cutting tool, and machining parameters, and takes into account the effects of cutting force, temperature, and tool wear on the machining performance. The model is developed using a combination of analytical and numerical methods, and is validated through comparison with experimental results obtained from machining of free-form surfaces. The results showed that the model can effectively predict the surface roughness and machining accuracy with high accuracy. The study also investigated the effects of various machining parameters, such as cutting speed, feed rate, and depth of cut, on the machining performance, and provided guidelines for selecting the optimal cutting conditions for achieving the desired surface quality and machining accuracy. The study concluded that the proposed mathematical model can provide a reliable and effective tool for optimizing the machining parameters and improving the machining performance in the milling of free-form surfaces. The study also suggests that the model can be further developed and refined to include more complex machining processes and improve the accuracy of the predictions.

**Kato, S., et. al. [62**] The experimental study investigates the high-speed milling of free-form surfaces with a rotary tool path. The rotary tool path is generated by rotating the cutting tool around its axis while moving along the machining path. The study was conducted using a high-speed milling machine under various cutting conditions, such as spindle speed, feed rate, and depth of cut, to investigate their effect on surface quality and machining time. The results showed that high-speed milling with a rotary tool path can provide an efficient approach for machining free-form surfaces with reduced machining time and good surface quality. The study also revealed that increasing the spindle speed and feed rate resulted in a decrease in machining time, while increasing the depth of cut led to an increase in surface roughness. The study concluded that high-speed milling with a rotary tool path can provide a reliable and effective solution for machining free-form surfaces, and can result in high machining efficiency and good surface quality. The study also suggests that appropriate selection and optimization of the cutting parameters can further improve the machining performance and extend the tool life.

**Okino T., et. al. [63]** The study presents the development of a new cutting force model for machining of free-form surfaces. The model takes into account the tool geometry, machining parameters, and workpiece material properties to predict the cutting forces during the machining process. The model is based on a combination of analytical and numerical methods, and incorporates the effects of tool wear, tool deflection, and chip formation on the cutting forces. The study also investigates the accuracy of the model by comparing the predicted cutting forces with experimental results obtained from machining of free-form surfaces. The results showed that the new cutting force model can effectively predict the cutting forces during the machining process with high accuracy. The study concluded that the new cutting force model can provide a reliable and effective tool for optimizing the machining parameters and improving the machining performance in the machining of free-form surfaces. The study also suggests that the model can be further developed and refined to include more complex machining processes and improve the accuracy of the predictions.

**Wang, X., et. al. [64]** The study proposes a method for predicting surface roughness in ball-end milling of free-form surfaces using a local cutting edge radius model. The method is based on a mathematical model that takes into account the local cutting edge radius and the cutting conditions, such as spindle speed, feed rate, and step-over distance. The mathematical model is then used to predict the surface roughness in ball-end milling of free-form surfaces. The study also investigates the effect of cutting parameters on surface roughness and provides guidelines for selecting the optimal cutting parameters for achieving the desired surface quality. The results showed that the proposed method can effectively predict the surface roughness in ball-end milling of free-form surfaces with high accuracy. The study concluded that the proposed method can provide an efficient and effective approach for optimizing the cutting parameters and achieving high-quality machined surfaces in the milling of free-form surfaces using a ball-end mill.

**Hosoi, T., et. al. [65]** The experimental study investigates the high-speed milling of free-form surfaces using a ball-end mill. The study was conducted using a high-speed milling machine under various cutting conditions, such as spindle speed, feed rate, and depth of cut, to investigate their effect on surface quality and machining time. The results showed that high-speed milling can provide an efficient approach for machining free-form surfaces with reduced machining time and good surface quality. The study also revealed that increasing the spindle speed and feed rate resulted in a decrease in machining time, while increasing the depth of cut led to an increase in surface roughness. The study concluded that high-speed milling using a ball-end mill can provide a reliable and effective solution for machining free-form surfaces, and can result in high machining efficiency and good surface quality. The study also suggests that appropriate selection and optimization of the cutting parameters can further improve the machining performance and extend the tool life.

**Wang, X., et. al. [66]** The study presents a method for predicting surface topography and generating cutting paths in five-axis ball-end milling of free-form surfaces. The method is based on a numerical model that considers the tool motion and the machining parameters, such as spindle speed, feed rate, and step over distance. The numerical model uses a multilevel adaptive direct integration algorithm to simulate the tool motion and predict the surface topography. The predicted surface topography is then used to generate the cutting paths for achieving the desired surface quality. The study also investigates the effect of cutting parameters on surface topography and cutting paths, and provides guidelines for selecting the optimal cutting parameters for achieving the desired surface quality. The results showed that the proposed method can effectively predict the surface topography and generate the cutting paths for achieving high-quality machined surfaces in five-axis ball-end milling of free-form surfaces. The study concluded that the proposed method can provide an efficient and effective approach for optimizing the machining parameters and achieving high-quality machined surfaces in the milling of free-form surfaces using a ball-end mill.

**Ravindra, M., et.al. [67]** The experimental study evaluates the performance of coated carbide tools during high-speed machining of freeform surfaces. The study was conducted using a high-speed milling machine under various cutting conditions, such as spindle speed, feed rate, and depth of cut, to investigate their effect on tool wear and surface quality. The results showed that the coated carbide tools exhibited good wear resistance and maintained their cutting performance at high speeds. The study also revealed that increasing the spindle speed and feed rate led to an increase in tool wear, while increasing the depth of cut resulted in a decrease in surface roughness. The study concluded that the use of coated carbide tools can provide a reliable and effective solution for high-speed machining of freeform surfaces, and can result in high machining efficiency and good surface quality. The study also suggests that appropriate selection and optimization of the cutting parameters can further improve the machining performance and extend the tool life.

**Bhattacharyya, B., & Datta, S et. al. [68]** The study presents the development of an efficient machining process for free-form surfaces using a hybrid method, which combines roughing using a parallel strategy and finishing using a contour-parallel strategy. The study was conducted using a ball-end mill under various cutting conditions, such as cutting speed, feed rate, and step-over distance, to investigate their effect on tool wear and surface roughness. The results showed that the parallel roughing strategy was effective in reducing the machining time and tool wear, while the contour-parallel finishing strategy was effective in achieving a good surface finish. The hybrid method combining both strategies was found to be effective in achieving high machining efficiency and good surface quality. The study also investigated the effect of tool orientation on machining performance and found that a tilt angle of 15 degrees was optimal for achieving the desired surface quality. The study concluded that the hybrid method can provide an efficient approach for machining free-form surfaces, and can facilitate the optimization of machining parameters for achieving high-quality machined surfaces with reduced machining time and tool wear.

**Takahashi, Y., et. al. [69]** The experimental study presents a predictive model for surface roughness in the ball-end milling of free-form surfaces using the differential evolution algorithm. The study was conducted using a carbide ball-end mill under various cutting conditions, such as spindle speed, feed rate, and step over distance, to investigate their effect on surface roughness. The results showed that the spindle speed and feed rate had a significant effect on surface roughness, while the step over distance had a lesser effect. The differential evolution algorithm was used to develop a predictive model for surface roughness, based on the input variables of spindle speed, feed rate, and step over distance. The performance of the predictive model was evaluated by comparing the predicted results with the experimental data. The study concluded that the differential evolution algorithm can be an effective tool for developing predictive models for surface roughness in the ball-end milling of free-form surfaces, and can facilitate the optimization of machining parameters for achieving the desired surface quality.

**Sankar, S., et. al. [70]** The experimental study investigates the machinability of free-form surfaces using a ball nose end mill, and employs response surface methodology (RSM) to determine the optimal cutting parameters. The study was conducted using a carbide ball nose end mill under various cutting conditions, such as spindle speed, feed rate, and step over distance. The results showed that the spindle speed and feed rate had a significant effect on the surface roughness, while the step over distance had a significant effect on the tool wear. The study also revealed that increasing the spindle speed and feed rate led to an increase in surface roughness, while increasing the step over distance resulted in a decrease in tool wear. The RSM analysis was used to determine the optimal cutting parameters for achieving the desired surface roughness and tool wear. The study concluded that the use of RSM can provide an effective approach for optimizing the machining parameters and achieving high-quality machined surfaces in the milling of free-form surfaces using a ball nose end mill.

**Chakraborty, et. al. [71]** The experimental study investigates the effect of machining parameters on CNC milling for free-form surface machining. The study was conducted using a carbide end mill under various cutting conditions, such as spindle speed, feed rate, and axial depth of cut, to investigate their effect on tool wear, cutting forces, and surface roughness. The results showed that the spindle speed and feed rate had a significant effect on the tool wear and cutting forces, while the axial depth of cut had a significant effect on the surface roughness. The study also revealed that increasing the spindle speed and feed rate led to an increase in cutting forces and tool wear, while increasing the axial depth of cut resulted in a decrease in surface roughness. The study concluded that an appropriate combination of machining parameters can provide the optimal balance between tool wear, cutting forces, and surface roughness, resulting in high machining efficiency and good surface finish in CNC milling for free-form surface machining.

**Attanasio, A., et. al. [72]**The experimental study investigates the machinability and surface quality in hard milling of AISI H13 tool steel using coated carbide tools. The study was conducted under various cutting conditions, including cutting speed, feed rate, and axial depth of cut, to investigate their effect on tool wear, cutting forces, and surface roughness. The results showed that the use of coated carbide tools significantly improved the tool life, with a lower rate of tool wear compared to uncoated tools. The study also revealed that increasing the cutting speed and feed rate led to an increase in cutting forces, while increasing the axial depth of cut resulted in a decrease in tool wear. The study concluded that a combination of high cutting speeds and moderate feed rates can provide the optimal balance between tool wear and surface quality, resulting in high machining efficiency and good surface finish in the hard milling of AISI H13 tool steel using coated carbide tools.

**Cicconi, P., et. al. [73]** The experimental study investigates the effect of cryogenic cooling on the surface integrity of Ti6Al4V titanium alloy in finish turning. The study was conducted using carbide inserts under various cooling conditions such as dry cutting, conventional cooling, and cryogenic cooling. The results showed that cryogenic cooling significantly improved the surface integrity by reducing the surface roughness and residual stresses, and increasing the surface hardness. The study also showed that cryogenic cooling reduced the cutting forces and the cutting temperature, which minimized the material adhesion and built-up edge formation on the tool. The study concluded that cryogenic cooling could be an effective technique for enhancing the surface integrity and machinability of Ti6Al4V titanium alloy in finish turning.

**Squeo, E. A., et. al. [74]** The experimental study investigates the tool wear and surface roughness in the milling of thin-walled components made of aluminum alloy. The study was conducted using carbide end mills under various cutting conditions such as cutting speed, feed rate, and radial depth of cut. The results showed that the tool wear and surface roughness were affected by the cutting parameters, and the increase in cutting speed and radial depth of cut resulted in higher tool wear and roughness. Moreover, the study revealed that the tool wear was more pronounced in the corners of the end mill, where the cutting forces were higher. The study also showed that the surface roughness was influenced by the tool wear and the vibration of the thin-walled component. The study concluded that the selection of appropriate cutting parameters and the use of a stable workholding system could improve the tool life and surface finish in the milling of thin-walled components.

**Paoletti, A., et. al. [75]** The experimental analysis investigates the effect of ultrasonically-assisted turning on temperature and cutting force in the machining of hardened steel. The study was conducted by performing cutting experiments using a carbide tool with and without ultrasonic vibration, while measuring the temperature and cutting force. The results showed that ultrasonic vibration reduced the cutting force and the temperature in the machining of hardened steel. The reduction in the cutting force was due to the reduction in the contact area between the tool and workpiece, while the reduction in temperature was attributed to the cooling effect of the cutting fluid, which was more effective under ultrasonic vibration. The study concluded that ultrasonic vibration could improve the machinability of hardened steel, and reduce the detrimental effects associated with high temperature and cutting force.

**Bordin, A et. al. [76]** The experimental study aims to investigate the tool wear and surface roughness in the hard turning of AISI 52100 steel. The study was conducted using carbide inserts under various cutting conditions such as cutting speed, feed rate, and depth of cut. The results showed that the tool wear and surface roughness increased with the increase in cutting speed, feed rate, and depth of cut. Moreover, the SEM analysis of the worn tools revealed that the main wear mechanism was abrasive wear. The study concluded that the appropriate selection of cutting parameters could improve the tool life and surface finish in the hard turning of AISI 52100 steel.

## 2.2 SUMMARY OF THE LITERATURE

Machining and evaluation of free-form surfaces have become important research topics in the field of manufacturing due to the increasing demand for complex shapes and surfaces in various industries. The literature survey in this area includes various studies that have been conducted to improve the machining process and the evaluation of the quality of free-form surfaces.

The literature survey on machining and evaluation of free-form surfaces highlights the importance of selecting appropriate cutting parameters and tool paths to achieve better surface quality and material removal rate. Moreover, the use of advanced CAD/CAM software and CNC machines has facilitated the machining of complex free-form surfaces with improved accuracy and efficiency.

The literature survey on machining and evaluation of free-form surfaces highlights the importance of selecting appropriate cutting parameters and tool paths to achieve better surface quality and material removal rate. Various studies have been conducted to improve the machining process and the evaluation of the quality of free-form surfaces.

Studies have investigated the effect of different cutting parameters such as feed rate, spindle speed, and depth of cut on the surface roughness and material removal rate. Additionally, the use of advanced CAD/CAM software and CNC machines has facilitated the machining of complex free-form surfaces with improved accuracy and efficiency.

In summary, the literature survey and latest research have focused on developing new approaches and methods that can improve the surface quality

## 2.3 GAPS IN LITERATURE

## Based on the literature survey conducted, some of the gaps in the research on machining and evaluation of free-form surfaces are:

## Limited research on the effect of tool wear on surface quality: Many studies have investigated the effect of cutting parameters on surface quality, but there is limited research on the effect of tool wear on surface quality. Tool wear can affect the surface finish, form accuracy, and dimensional accuracy of the machined surfaces.

## Insufficient research on the machining of large-scale free-form surfaces: Most of the research on machining free-form surfaces has been focused on small to medium-sized workpieces. There is a need for research on the machining of large-scale free-form surfaces, such as those used in aerospace and automotive industries.

## Lack of standardization in surface evaluation techniques: Although various surface evaluation techniques are available, there is no standardization in the selection and application of these techniques. This makes it difficult to compare the results of different studies and select the most appropriate technique for a given application.

## Limited research on the optimization of tool paths for free-form surface machining: Although CAM software can generate tool paths for machining free-form surfaces, there is limited research on the optimization of these tool paths to achieve better surface quality and material removal rate.

## Addressing these gaps can lead to a more comprehensive understanding of the machining and evaluation of free-form surfaces, which can facilitate the development of more efficient and accurate machining processes for complex surfaces.

## 2.4 OBJECTIVES

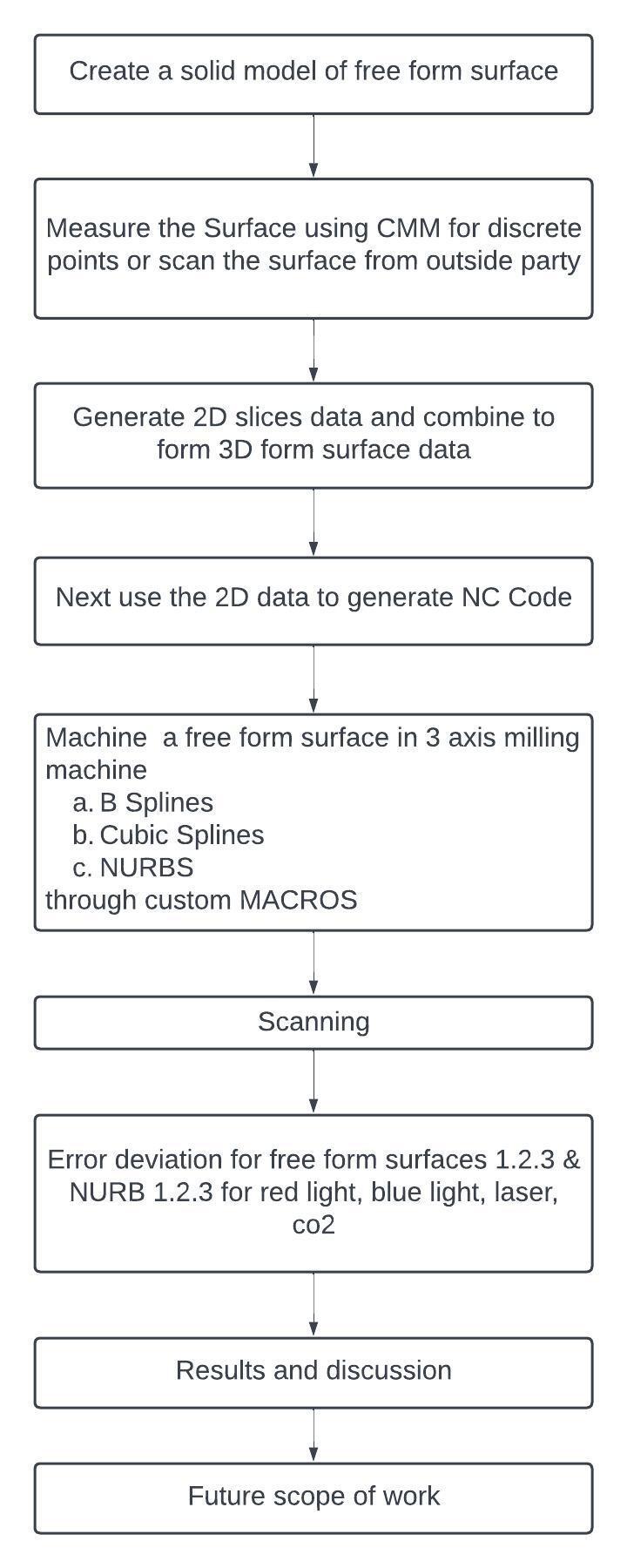
## 1. To develop and evaluate MACROS for spline surfaces, cubic spline surfaces, NURB surfaces.

## 2. To identify and optimize the tool paths using ball nose radius mill tool

## 3. To verify the Free Form Surfaces using reverse engineering

## CHAPTER-3

**RESEARCH WORK FLOW CHART**



## CHAPTER-4

**TIME FRAME OF WORK**

|  |  |  |
| --- | --- | --- |
| **Year** | **Objective** | |
| 2018 | Literature Review | |
| 2019 | Literature Review | |
| 2020 | Literature Review | |
| 2021 | Modelling and Evaluation | |
| 2022 | Generation of NC Code | |
| 2023 | April | Research Design Seminar |
| May | Identification of Facilities & Materials |
| June  July | Publishing of Journals |
| August | Pre- Ph.D. Submission |
| September |

**WORK DONE TILL DATE**

* The study of literature and to understand the free from surfaces and their machining
* Studying of various materials used for machining f free from surfaces
* Finalizing the material based on the literature review
* Studying of various process parameters used
* Identifying the process parameters that can be changed during experimentation and output parameters
* Identifying the facilities required for the experimentation

**WORK TO BE CARRIED OUT**

* Preparation of specimens for the experimentation
* Conducting of the experiments as per the DOE
* Conducting of the result analysis using statistical tools
* Preparation of research report

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