Measurement Strategies for Evaluation of Freeform Surfaces using Coordinate Measuring Machine: A Comprehensive Review

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Abstract. This paper reviews the different methodologies used to optimize the probe path for measuring the free-form profiles using Coordinate Measuring Machines (CMM). A CMM is mostly used in manufacturing industries for inspecting the part with simple and complex geometries. The parts with simple geometries can be effectively measured using CMM, however, the optimization techniques are used to select the sampling points during measurement of freeform profiles. The study explores the utilization of computing techniques such as Genetic Algorithms (GA), Ant Colony Optimization (ACO) algorithms, Particle Swarm Optimization (PSO) algorithms and B-spline curves for optimizing the sampling points while measuring the freeform profiles. The literature review also discusses the use of optimization techniques for dimensional control and inspection planning. This study provides valuable insights into the optimization of probe path and sampling points in CMM measurements, contributing to the advancement of dimensional control and inspection planning for parts with free-form profiles.

Keywords: Genetic Algorithm, Particle Swarm Optimization algorithms, Ant Colony Optimization, probe path planning, Sampling points, Free-form Surfaces, Coordinate Measuring Machines.

1. Introduction

The part with freeform surfaces finds applications in many engineering fields such as automotive, marine, aerospace industries and biomedical application. CMMs have emerged as essential instruments in the field of precision measurement and dimensional analysis, facilitating the precise evaluation of manufactured components across a wide range of industries. Their importance in contemporary manufacturing cannot be overstressed, given

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their crucial role in guaranteeing product quality and precision across various sectors including aerospace, automotive, and medical devices. With the increasing demand for stricter tolerances and higher product quality, there is a growing emphasis on optimizing the efficiency and accuracy of CMMs. This review paper is centred around the optimization of probe paths for measuring free-form surfaces using Coordinate Measuring Machines (CMMs). The primary goal of this review is to investigate a variety of studies and research papers that have explored different algorithms and methodologies aimed at enhancing the accuracy and efficiency of CMM measurements. This literature review embarks on a journey spanning two decades, delving into numerous studies that collectively contribute to the ongoing pursuit of enhancing CMM operations. These studies all share a common objective: to elevate the precision and efficiency of CMM measurements in order to meet the rigorous quality standards of modern industries.

2. Freeform Profiles Measurement Strategies

The deviation of freeform profiles is evaluated using the coordinate points. A CMM is mostly used in the manufacturing industries to acquire the coordinate points. The accuracy of the measurement is based on the number of sampling points and density of the points captured on the freeform surfaces. Many computing techniques are used to optimize the sampling points of the freeform surfaces and these techniques are presented in this section.

Many researchers have applied Genetic algorithm technique to optimize the sampling points. Rossi et al. [1] have studied the utilization of a genetic algorithm (GA) to optimize the sampling points for roundness errors analysis using CMM. The roundness error assessment based on the minimum zone tolerance (MZT) criterion was developed using genetic algorithm and large sample datasets were utilized for parameter optimization. G. Mansour et al. [3] applied genetic algorithm to determine the minimum number of points required for the dimensional control of blades within a CMM. This algorithm leverages the power of 3rd-degree polynomial curves to establish a precise representation of the blades. Significant test time reduction is Max deviations 10-20µm.

The authors have employed various optimization techniques to assess the accuracy of freeform surfaces using Coordinate Measuring Machines (CMM). Adrian et al. [5] and Chen et al. [15] explored the utilization of Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) techniques in this regard. Their investigation revealed that the ant colony algorithm exhibited superior performance in optimizing the path for freeform surfaces.

Yu et al. [2] has studied about Comparative analysis against traditional methods, equi-parametric and patch mean Gaussian curvature-based in Zeiss CMM with the type of CS100-2828-18 and demonstrates the effectiveness and robustness of this adaptive approach, with both simulated and experimental results confirming its advantages in inspection planning.

A Particle Swarm Optimization (PSO) technique is applied by many researchers to evaluate the profile error of freeform surfaces. The PSO techniques provides shorter probe path for freeform surface measurement. [4, 8, 16]. Stojadinovic et al. [6], Li et al.[13] and Chen et al. [18] investigated the use of improved ant colony optimisation algorithm for CMM probe path planning. The results show that the improved ACO algorithm is more effective and the fastest algorithm compared to GA and PSO algorithm.

Sampling techniques such as Uniform block random sampling and Latin hypercube random sampling have demonstrated greater effectiveness in optimizing the number of sampling points on freeform surfaces [17]. Figure 1 illustrates the freeform surface utilized for evaluating these sampling techniques, while Figure 2 depicts the optimized sampling points. variety of optimization techniques are reported in the literature for selection the number of sampling point and distributing these sampling points on the freeform surfaces. The characteristics, advantages and limitations of these techniques are described in Table 1.

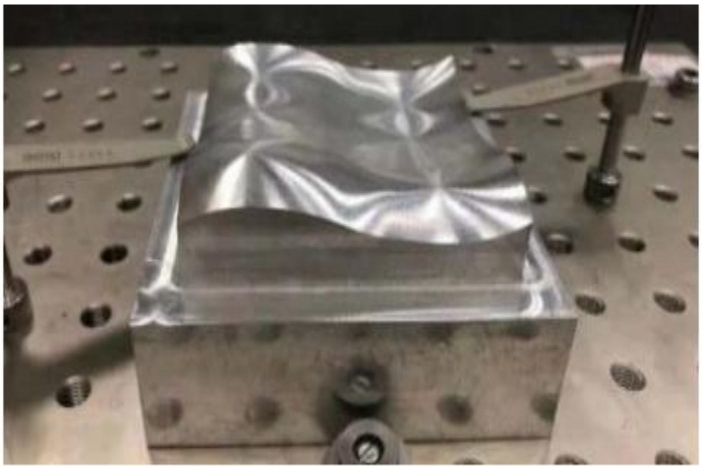

Fig. 1. Freeform surface [17]

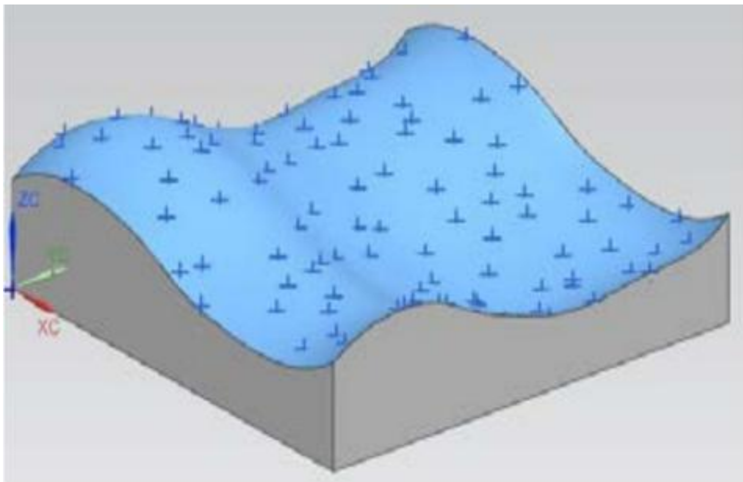

Fig. 2. Optimized sampling points

Table 1. Literature summary

Author	Algorithms used	Part Geometry	Inference
A. Rossi et al. [1]	1. Genetic algorithm	Roundness profile with seven different parameters were used	The results from the computational experiments highlight important trends. Larger datasets require larger population sizes, confirming expectations. Crossover probabilities remain consistent across dataset sizes, while mutation probabilities decrease with larger datasets, attributed to increased available information. To ensure stability, a speed condition and stopping criterion have been set, offering insights into the impact of dataset size and genetic operator probabilities on algorithm performance.
M. Yu et al. [2]	1. Modified algorithms 2. Iterative closest points algorithms	Sculptured surface of a piston	The method incorporates a form error model, which enhances the precision of the sampling strategy by introducing controlled form errors to nominal data, simulating the actual manufactured surface. This approach employs scattered points as input data to intelligently identify sampling points. Experimental findings indicate that this method enhances both the efficiency and accuracy of free-form surface inspection when employing Coordinate Measuring Machines (CMM).
G. Mansour et al. [3]	1. Genetic algorithm	3D model of blade	This paper focuses on the development and application of a MATLAB-based algorithm for dimensionally controlling blades on a CMM machine using polynomial approximations and 3rd-degree curves. The algorithm's key feature is its ability to identify and select the minimum number of data points that closely align with the blade's individual cross-sectional curves along the Z-axis, thereby enhancing the efficiency and cost-effectiveness of the inspection process.
C. L. Du et al. [4]	1. Standard PSO Algorithm	Circular shaft component	This paper introduces the standard Particle Swarm Optimization (PSO) algorithm, emphasizing a theoretical analysis of parameter choices (inertia weight x, learning factors c1, and c2) on algorithm performance. Optimal parameters are found as c1 and c2 both set to 2 and x ranging from 1/3 to 1/2. Gradually decreasing x from 0.9 to 0.4 enhances stability and accuracy, outperforming other x values (1, 0.5, or 0) over 20 iterations. This research offers valuable insights for optimizing PSO in diverse tasks.
A. M. Adrian et al. [5]	1. Ant colony algorithm 2. Genetic algorithm 3. Particleswarm optimization algorithm	Datasets in the literature survey are used for evaluating algorithms	i) The three algorithms performed equally well in terms of effectiveness. ii) ACO was the fastest, followed by GA and then PSO in terms of efficiency. iii) All methods proved to be consistent in solving the construction site layout problem.
S.M. Stojadinovic et al. [6]	1. Ant colony algorithm (ACO)	Prismatic part with Circle, Hemisphere Cylinder, Cone, Truncated cone and Truncated Hemisphere	When comparing the optimal path acquired through Ant Colony Optimization (ACO) with the online programmed path, a reduction in the measuring path length of over 20% is observed. Furthermore, the path derived from ACO is more than 10% shorter compared to the path obtained with Pro/ENGINEER, utilizing identical parameter settings for both methodologies.

Z. Han et al. [7]	1. Improved ant colony algorithm	Inline- 4 cylinder Engine Block	A 3D ant map is established for CMMs to represent the measuring environment.An improved ACO algorithm is proposed to optimize the measuring path for CMMs. It utilizes artificial potential field force direction to update local pheromones and optimizes the ant's route in each iteration.A path re-optimization algorithm, RE-OP, is introduced to enhance the efficiency and intelligence of CMMs based on the new 3D collision detection algorithm.
V. K. Pathak et al. [8]	1. Particle swarm optimization (PSO) 2. Genetic algorithm (GA) 3. Modified particle swarm optimization algorithm (MPSO).	Two coaxial cylinders	The MPSO algorithm emerges as a robust and potent tool for assessing form errors. Its superiority lies in its heightened accuracy and efficiency compared to conventional heuristic optimization algorithms. Moreover, it is particularly well-suited for evaluating form errors using data obtained from Coordinate Measuring Machines (CMM).
J. Li et al. [9]	1. Ant colony optimization algorithm	Datasets in the literature survey are used for evaluating algorithms	The improved algorithm proposed in this paper demonstrates superior performance in solving TSP compared to the negative feedback ant colony algorithm. The algorithm exhibits higher convergence accuracy and effectively avoids local optima, as evidenced by simulation results on various datasets from the TSPLIB standard library.
D. Zhao et al. [10]	1. Samplingmethod algorithm (B-spline)	Case1: Free form surface Case2: Dolphin curve Case3: Compressor blade Case4: Complex Compressor blade	The suggested measurement point sampling method for inspecting parts featuring free-form surfaces presents a promising avenue for enhancing both the efficiency and accuracy of the inspection process. This method has demonstrated a notable reduction in the necessary measurement points without compromising the precision of surface modeling. Additionally, it exhibits accuracy and robustness even in the presence of noise within the measurement data.
G. He et al.[11]	1. Equi parametric algorithm	Three dimensional “S” shape test piece	This paper proposes an innovative approach for enhancing freeform surface inspections on Coordinate Measuring Machines (CMM). It integrates the Hammersley sequence to reduce aliasing and a Machining Error Model (MEM) for assessing deviations probability. An adaptive sampling technique aligns the Hammersley sequence with the surface according to MEM, enhancing inspection accuracy and efficiency.
Z. Q. Zhu et al. [12]	1. Iterative closest point algorithm 2.Genetic algorithm	Aero engine blade	The proposed strategy offers a methodical approach for assessing geometric errors in aero-engine blades, thereby mitigating the risk of erroneous feedback during manufacturing operations. It encompasses precise localization, enhanced measurement techniques, and efficient evaluation processes, complemented by a practical evaluation criterion.
J. Li et al. [13]	1. Ant colony algorithm	Datasets available in the literature survey are used for evaluating algorithms	The PACON algorithm improves convergence speed and accuracy in the Ant Colony Algorithm by introducing the pheromone transfer rule, an adjustment is made to the angle, enabling the concurrent updating of pheromone concentrations on both the worst and optimal paths, there is a reinforcement of the weights assigned to the pheromone concentration along the optimal path.
B. Abhishek et al. [14]	1. Hybrid algorithm particle swarm optimization (PSO) with harmony search	Datasets available in the literature survey are used for evaluating algorithms	The paper introduces two innovative hybrid meta-heuristic algorithms, each integrating Particle Swarm Optimization (PSO) with either Harmony Search Algorithm (HSA) or Genetic Algorithm (GA). These hybrids are specifically developed to enhance path planning for Unmanned Aerial Vehicles (UAVs) navigating through intricate environments crowded with obstacles. These

	algorithm 2.PSO with genetic algorithm. 3.Particle swarm optimization (PSO) 4. Simulated annealing (SA)		algorithms lead to more efficient and safer paths, reducing traversal time and fuel consumption, with up to 40% improvement over traditional methods, such as IWO, and the application of B-spline curve smoothing to meet turning constraints.
Y. Chen et al.[15]	1. Genetic algorithm 2. ACO algorithm 3. PSO algorithm	Free form surface	Theoretical paths and inspection times were similar for ACO and genetic algorithms, both outperforming PSO. However, ACO was notably faster in MATLAB, saving nearly a minute for 50 sampling points in path optimization. The time savings depended on sampling points and CMM speed, with the ant colony algorithm showing superiority over genetic and particle swarm algorithms.
B. A. S. Emambocus et al. [16]	1. Swap Sequence based PSO (SSPSO) 2. Enhanced Swap Sequence based PSO (Enhanced SSPSO) algorithm	Datasets available in the literature survey are used for evaluating algorithms.	The paper proposes an improved swap sequence based PSO algorithm integrating strategies from XPSO, outperforming the original PSO in solution quality but lagging in convergence speed.
Y. Zhang et al. [17]	1.Uniform block random sampling. 2.Latin hypercube random sampling	Free form surface	The study examines the influence of different sampling grid sizes and ball diameters on surface normal deviation. It compares Latin Hypercube Random Sampling and Uniform Area Block Random Sampling against the Uniform Measuring Point method. Higher sampling accuracy, where points closely align with the true surface, enhances curved surface trough detection, ultimately improving measurement accuracy with an equivalent number of measuring points.
Y. Chen et al. [18]	1.Improved ant colony optimisation algorithm 2. Simulated annealing	Blade model	This paper enhances the traditional ACO algorithm with a negative feedback mechanism in pheromone updates, resulting in improved performance and reduced inspection path length for free-form surface inspections. Experimental comparisons on MATLAB and CMM confirm that the ACO-N algorithm outperforms the SA and ACO algorithms, delivering shorter inspection paths, faster execution, and more efficient inspections across various measurement point scales.
B. Yi et al. [19]	1. Cluster algorithm	Impeller blade	The proposed approach limits probe posture variations to just 2, contrasting with the continuous changes in posture seen in the ACB method. This results in a notable reduction in measuring time by 39.2% and 38.2% during estimation and actual experimentation respectively. The method is particularly well-suited for measuring workpieces with intricate geometries.
Chen et al. [20]	1. Improved cuckoo search algorithm 2. Genetic algorithm 3. Simulated annealing algorithm 4. Ant colony optimisation algorithm.	Impeller	This paper introduces the ADNHCS algorithm, an improved version of the cuckoo search algorithm, for optimizing free-form surface inspection paths. By enhancing global search capabilities and incorporating forbidden search, it reduces path length and inspection time. Comparative experiments demonstrate significant efficiency improvements over traditional algorithms, offering cost savings in manufacturing.

3. Results and Discussion

This study undertakes a comparative analysis of the effectiveness of three optimization algorithms—genetic algorithm, ant colony optimization algorithm, and particle swarm optimization algorithm—in path planning for coordinate measuring machines. The ACO algorithm closely approximates the theoretical path of the genetic algorithm, yielding similar inspection times, outperforming the PSO algorithm. Despite this, notable discrepancies exist in their computational efficiencies, with the ACO algorithm demonstrating faster speeds on MATLAB. The study elucidates the optimization of probe paths utilizing these algorithms, successfully demonstrating their efficacy post-parameter adjustments. Fieldwork experiments further validate the feasibility of these algorithms, showcasing significant time savings of nearly one minute for 50 sampling points[15]. The extent of time saved varies with the quantity of sampling points and the movement speed of the CMM. Notably, the ant colony algorithm outperforms both the genetic algorithm and the particle swarm algorithm in this context. Employing these algorithms offers substantial reductions in inspection time compared to non-optimized approaches, albeit with marginal differences observed among the algorithms. The primary benefit of path optimization lies in enhancing inspection efficiency, enhancing safety, and mitigating collision risks, particularly in assessments involving free-form surfaces or intricate components. Genetic Algorithm (GA) are effective in path optimization and handling complex structures. However, it takes longer computation times may be a drawback. Ant Colony Optimization (ACO) Provides a path similar to GA with faster computation times, proving efficient for path optimization. But sensitivity to parameter settings may be a limitation. Particle Swarm Optimization (PSO) has fast convergence to solutions. Although, it performs less effectively than GA and ACO for path planning, especially on complex surfaces.

4. Conclusions

This paper presents the various optimization techniques such as Genetic algorithm, Ant Colony Optimization and Modified Particle Swarm Optimization used for evaluating the profile error of freeform profiles using CMM. It highlights that while the ACO algorithm closely matches the genetic algorithm in path approximation and inspection times, it outperforms the PSO algorithm and exhibits faster computational speeds in MATLAB. The study demonstrates the effectiveness of these algorithms in optimizing probe paths, leading to significant time savings during inspection. Additionally, it emphasizes the advantages of path optimization in enhancing inspection efficiency, safety, and collision avoidance, particularly in scenarios involving complex surfaces or components. This review highlights the highlight advancements made in path-planning algorithms and methodologies used for freeform profile measurements. These findings contribute to the continuous improvement of manufacturing processes and quality assurance in the field of coordinate measuring machines.

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