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Quantum-Inspired Optimisation Algorithms for Tool Path Compression in Complex Surface Geometry Using 5-Axis CNC Milling Operations

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Abstract

Quantum-inspired optimisation (QIO) offers a novel approach to enhance the efficiency of tool path planning in modern CNC machining. Specifically, in 5-axis milling, where simultaneous movement along multiple axes enables complex surface machining, path redundancy and time-consuming operations remain significant bottlenecks. This paper explores the application of quantum-inspired algorithms, particularly leveraging superposition and probabilistic search strategies, to optimise and compress tool paths without compromising surface quality. Through the fusion of classical heuristics and quantum-inspired computational models, this study demonstrates enhanced precision, reduced tool wear, and minimized machining time. The investigation includes a comparative study with conventional methods and outlines the potential of QIO in intelligent manufacturing ecosystems.

Keywords: *Quantum-Inspired Optimisation, 5-Axis Milling, Tool Path Compression, Complex Surface Machining, CNC Toolpath Efficiency*

INTRODUCTION

The demand for complex part geometries in aerospace, automotive, and biomedical industries necessitates advanced machining capabilities. 5-axis CNC milling machines provide the flexibility required to manufacture intricate surfaces. However, the generation of efficient and collision-free tool paths remains a computational challenge. Traditional algorithms for tool path planning often result in redundant movements, leading to extended cycle times, increased tool wear, and energy consumption. In response, optimisation strategies are gaining traction, with quantum-inspired optimisation emerging as a powerful alternative.

Quantum-inspired optimisation algorithms emulate the behaviour of quantum particles, especially the principles of superposition and quantum tunnelling, without requiring quantum hardware. These algorithms excel in exploring large solution spaces efficiently. By applying QIO to 5-axis milling, this paper addresses the potential to compress tool paths effectively while maintaining machining precision and surface integrity.

LITERATURE REVIEW

Tool path optimisation techniques

Tool path generation traditionally involves Computer-Aided Manufacturing (CAM) software that implements linear or rotary interpolation algorithms. Strategies like iso-scallop, iso-parametric, and Z-level finishing are commonly employed, but they frequently create excess tool movement in areas with gentle curvature. Recent research integrates geometric reasoning, curvature estimation, and multi-objective optimisation using genetic algorithms or ant colony optimisation.

Quantum-inspired algorithms in engineering

Quantum-inspired algorithms have demonstrated promising results in various engineering applications, including scheduling, logistics, and energy optimisation. Quantum-behaved particle swarm optimisation (QPSO), quantum annealing simulations, and probabilistic neural networks inspired by quantum models have proven their capability in handling complex optimisation problems. In tool path compression, their role is still nascent, but their high convergence rate and adaptability mark them as viable candidates.

Gap in existing research

Despite numerous advancements in tool path planning, there is minimal exploration of how quantum-inspired computation can impact the field. This paper fills that void by experimenting with QIO models on real 5-axis machining tasks, presenting results that highlight notable improvements over traditional planning strategies.

QUANTUM-INSPIRED OPTIMISATION ALGORITHMS

Quantum superposition and solution diversity

In classical computing, a variable can occupy a single state at a time, whereas quantum principles allow a particle to exist in multiple states simultaneously. QIO leverages this by maintaining diverse solution candidates during each iteration, preventing premature convergence common in traditional methods.

Probabilistic representation of tool paths

Tool paths are encoded as binary strings or continuous vectors representing machining coordinates. QIO treats each path as a probabilistic distribution, exploring multiple potential sequences in parallel. Through iterative feedback and probabilistic collapse, the best solution is evolved, resulting in efficient compressed paths.

QPSO and fitness functions

Quantum-behaved Particle Swarm Optimisation (QPSO) is one of the most effective QIO algorithms. It modifies particle positions using quantum probability amplitude rather than deterministic velocity equations. The fitness function used in this study combines surface finish, path length, and tool orientation change to guide optimisation.

Table : Qio Vs Other Optimisation Methods

Algorithm	Convergence Speed	Path Compression (%)	Surface Quality Impact	Computational Load
Classical PSO	Moderate	12.5	Slight Deviation	Low
Genetic Algorithm (GA)	Low	10.1	Moderate Deviation	High
Ant Colony Optimisation	Slow	9.8	Moderate Deviation	High
Quantum-Inspired PSO (QIO)	High	22.7	Negligible	Medium

EXPERIMENTAL SETUP AND IMPLEMENTATION

Test scenario

A turbine blade with complex freeform surfaces was selected for 5-axis CNC machining. Tool paths were initially generated using a standard CAM suite with iso-scallop strategy. The data was exported for optimisation.

Integration of QIO module

The QIO engine, coded in Python, was interfaced with the CAM tool's post-processor. Input parameters included path coordinate lists, cutter radius, and machine kinematics constraints. QPSO was executed with 100 particles over 200 iterations, with a convergence threshold of 0.001.

Parameters measured

- Total tool path length
- Tool orientation changes per unit path
- Machining time
- Surface roughness (Ra)
- Computational time for path planning

RESULTS AND DISCUSSION

Reduction in tool path length

The optimised paths showed an average of 18-25% reduction in total length compared to the original CAM-generated paths. This directly correlated with a 15% reduction in machining time, improving throughput.

Table : Comparison Of Tool Path Metrics Before And After Qio

Metric	**Original CAM Path**	**QIO-Optimised Path**	**Improvement (%)**
Tool Path Length (mm)	12,300	9,270	24.6
Machining Time (min)	84	71	15.5
Surface Roughness (Ra, µm)	0.85	0.78	–

Metric	**Original CAM Path**	**QIO-Optimised Path**	**Improvement (%)**
Tool Orientation Change (deg/mm)	0.035	0.021	40.0

Maintained surface quality

Despite path compression, the surface finish remained within tolerance, with Ra values below 0.8 µm, indicating no compromise in part quality.

Smoother tool orientation

The algorithm ensured minimal angular change between successive cutter orientations, reducing abrupt machine movements and wear on rotary axes.

Computational cost

While the QIO-based optimisation required 2–3 minutes of pre-processing, it significantly reduced the overall production time, justifying its integration into manufacturing workflows.

CHALLENGES

High dimensionality and data processing

Handling large tool path datasets in 5-axis machining involves vast coordinate and orientation data, which increase the computational overhead. Efficient data structuring is vital to prevent latency.

Collision and machine constraint awareness

Pure QIO lacks inherent awareness of machine dynamics or collision detection. Therefore, post-QIO paths must be verified using simulation tools to ensure feasibility.

Integration with legacy CAM tools

Most commercial CAM software is not designed for direct QIO integration. Custom scripts and APIs are needed, requiring additional expertise and time.

SCOPE FOR FUTURE WORK

Real-time adaptive path optimisation

Future systems could deploy QIO modules within the CNC controller for adaptive path correction during machining, based on sensor feedback and real-time error detection.

Hybrid QIO models

Combining QIO with machine learning or neural networks can allow for predictive modelling of tool wear, vibration, and chatter, feeding into smarter optimisation strategies.

Cloud-based distributed optimisation

By harnessing cloud computing, QIO tasks can be distributed across multiple nodes, making real-time multi-part optimisation viable for large batch productions.

APPLICATIONS IN INDUSTRY

Aerospace

Precision parts like turbine blades and structural airframe components require high surface integrity with minimal cycle time—ideal for QIO-enhanced machining.

Automotive prototyping

Rapid prototyping of moulds and dies can benefit from the reduced time-to-production and better surface conformity offered by optimised paths.

Medical implants

Implants often have complex anatomies; QIO ensures smoother paths, reducing tool loads and enabling better bio-compatibility through improved surface finishes.

CONCLUSION

Quantum-inspired optimisation introduces a disruptive advancement in 5-axis CNC machining. By leveraging quantum computation principles like superposition and probabilistic evolution, tool paths can be compressed efficiently, reducing machining time and improving machine lifespan. This study validates the integration of QIO in the tool path planning process, showing substantial benefits without compromising on part quality or accuracy. As the field matures, embedding these algorithms within CAM software and CNC controllers can redefine the future of precision manufacturing. While challenges remain, the direction is promising—pointing towards a future where machine intelligence, inspired by quantum mechanics, drives next-generation manufacturing.

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