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Intelligent System for Automated G-Code Generation: Development and Validation of STEP File Integration in CNC Machining

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Abstract

Integrating Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) remains critical for automating tool path generation in CNC machining. However, interoperability issues and reliance on proprietary CAM systems hinder efficiency, particularly for small-scale manufacturers. This study presents an Integrated Interface System (IIS) that directly converts STEP file geometric data into G-code, bypassing intermediary CAM software. Developed using PHP, IIS extracts and processes geometric entities such as EDGE_LOOP, ORIENTED_EDGE, and CARTESIAN_POINT to generate precise machining tool paths. Validation was performed by comparing IIS-generated G-code with SolidCAM output using CNC Simulator software, demonstrating equivalent tool path accuracy with less than 0.002% deviation. A case study on a 3-axis CNC milling machine confirmed IIS's capability to generate both linear and circular tool paths with a 10 mm depth of cut, ensuring high-precision machining. The proposed system streamlines tool path generation, offering SMEs a cost-effective and scalable solution.

1. Introduction

The integration of Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM) systems has significantly transformed modern manufacturing by enabling automation and enhancing machining precision. However, challenges persist in the seamless adoption of these technologies, particularly for small-to-medium-scale manufacturers, due to high costs and the complexity of proprietary CAM software [1,2]. Furthermore, interoperability issues between CAD and CAM systems exacerbate inefficiencies, leading to data redundancy and errors in tool path generation, ultimately impacting production efficiency and accuracy [3,4]. Addressing these challenges is imperative to improving manufacturing productivity and reducing operational costs [5,6].

The Standard for the Exchange of Product Model Data (STEP), as defined by ISO 10303, provides a standardized format for representing product data, facilitating interoperability between CAD and CAM systems [7,8]. STEP files contain Boundary Representation (B-rep) geometric data, which can be leveraged to generate Cutter Location (CL) data and subsequently convert it into G-code [9,10]. While traditional CAM software automates tool path generation, reliance on such software introduces substantial costs and complexities [11,12]. Manual G-code generation, although an alternative, is labor-intensive, error-prone, and heavily reliant on skilled operators [13,14]. Consequently, there is a growing demand for systems capable of directly interpreting STEP file data to generate machining instructions without proprietary CAM software [15,16].

Recent research has explored methodologies for utilizing STEP files in Computer Numerical Control (CNC) machining, particularly in automating G-code generation [17,18]. These studies highlight the challenges associated with extracting and interpreting geometric data from STEP files, necessitating precise selection and transformation of data entities such as EDGE_LOOP, ORIENTED_EDGE, and CARTESIAN_POINT [19,20]. Although various approaches to STEP-based tool path generation have been proposed, existing solutions largely remain constrained by their focus on specific machining features, such as linear and circular geometries, while lacking scalability and user-friendliness for practical applications in small-scale manufacturing [21,22].

To address these gaps, this study presents the development of an Integrated Interface System (IIS) designed to directly convert STEP file data into G-code, thereby eliminating reliance on proprietary CAM software [23,24]. The IIS employs a modular architecture to extract, process, and transform geometric data into accurate tool paths [25,26]. The system's effectiveness has been validated through comparative analysis with tool paths generated by SolidCAM, demonstrating its precision and reliability [27,28]. By streamlining tool path generation and enhancing accessibility for small-scale manufacturers, this research contributes to advancing CAD/CAM integration and promoting cost-effective automation in CNC machining [29,30].

The remainder of this research details the methodology employed in developing the IIS, the results of validation studies, and a discussion of the system's practical applications and limitations [31,32]. Future enhancements will focus on expanding the IIS capabilities to support multi-axis CNC machining and improving its algorithms for feature recognition, ensuring adaptability to evolving manufacturing requirements [33,34]. By addressing these challenges, the proposed system has the potential to become a cornerstone for advanced, interoperable manufacturing solutions, aligning with industry trends toward greater automation and efficiency [35,36]. The research also emphasizes the importance of further integrating adaptive machining strategies, machine learning algorithms, and real-time feedback mechanisms to optimize CNC machining processes [37,38]. Future developments will explore scalability improvements and enhanced feature recognition techniques to improve precision and operational flexibility [39,40].

2. Methodology

Fig. 1 depicts the integrated interface system developed to automate the process of tool path generation by directly converting STEP file geometric data into G-code, eliminating the need for proprietary CAM software. The system follows modular architecture, ensuring that data extraction, processing, tool path generation, and validation are organized and efficient. Each module uniquely transforms STEP file geometric data into CNC-compatible G-code, ensuring high precision and automation. The data extraction module retrieves geometric and topological data from STEP files, identifying key machining features such as EDGE_LOOP, ORIENTED_EDGE, and CARTESIAN_POINT. A structured parsing algorithm is employed to analyze the hierarchical structure of the STEP file, ensuring that only machining-relevant entities are retained. At the same time, redundant or non-essential data is filtered out. This automated feature extraction reduces human intervention and minimizes potential errors in tool path generation.

Once the geometric data is extracted, it is processed by the data processing module, which determines critical machining parameters such as tool path coordinates (X, Y, Z), depth of cut, feed rate, and spindle speed. The system applies geometric transformation algorithms to convert the extracted data into machine-compatible movement instructions. Additionally, collision avoidance mechanisms and path optimization algorithms ensure that tool paths are generated efficiently without unnecessary tool retractions or repositioning. These steps enhance machining accuracy and reduce material waste. The tool path generation module translates the processed data into CNC-executable G-code. The system employs linear (G01) and circular (G02/G03) interpolation algorithms to ensure precise tool motion along straight and curved trajectories. The IIS intelligently sequences the tool paths based on an optimized tool movement strategy, reducing unnecessary repositioning and enhancing machining efficiency.

Furthermore, IIS adheres to ISO 6983 G-code standards, making the generated tool paths compatible with a wide range of CNC controllers. To ensure the accuracy and reliability of the generated G-code, the validation and optimization module performs CNC simulation. It compares the results against benchmark CAM-generated tool paths (e.g., from SolidCAM). This module evaluates tool path accuracy and machining efficiency deviations, making necessary adjustments such as feed rate modulation and tool offset compensation to optimize performance. The validated G-code is then ready for execution on CNC machines, ensuring a reliable and cost-effective machining workflow. The IIS system demonstrates intelligence through its ability to autonomously extract, interpret, and convert geometric data into CNC machining instructions without manual intervention. The system identifies machining features directly from STEP file data by employing automated feature recognition algorithms, eliminating human error and dependency on CAM software. Unlike conventional CAM-based solutions requiring multiple software conversions, IIS streamlines the CAD-to-CNC workflow, reducing processing time while maintaining accuracy. One of the key intelligent capabilities of IIS is adaptive tool path optimization. The system dynamically adjusts machining parameters based on workpiece geometry, cutting tool limitations, and surface finishing requirements. IIS selects the most efficient tool movement strategy by applying rule-based decision-making, minimizing tool wear, and improving cutting efficiency.

Additionally, real-time feed rate adjustments and automatic tool offset compensation enhance the system's ability to optimize machining operations. The IIS system is also designed for seamless integration with CNC workflows. By generating standardized ISO 6983 G-code, the system ensures compatibility with a wide range of CNC controllers. Unlike traditional CAD-to-CNC workflows, which require intermediate CAM software, IIS eliminates the need for software conversions, reducing compatibility issues and improving overall machining efficiency. This approach enhances interoperability, making IIS a scalable and adaptable solution for manufacturers. The modular design of IIS ensures future scalability and enhancements. Potential upgrades include multi-axis machining support, AI-assisted machining feature recognition, and real-time tool path adjustments based on sensor feedback.

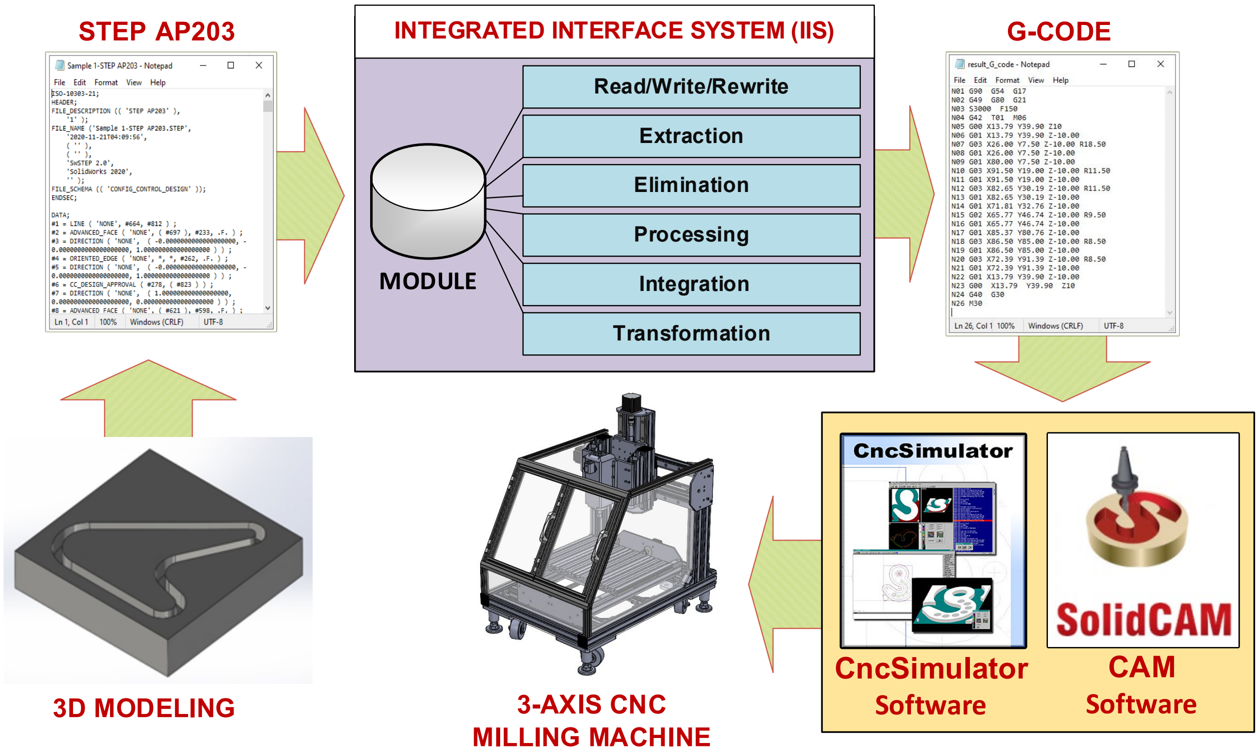


Fig. 1 *An alternative method for CNC milling operations*

2.1 Module Framework

Developing the Integrated Interface System for CNC tool path generation utilizes a structured and modular framework to ensure accurate data extraction, interpretation, and transformation from STEP files into G-code. The framework comprises two primary components: workflow construction and results generation. This modular approach enhances the system's scalability and facilitates the integration of user-defined machining parameters. The workflow construction component divides the geometric data extracted from STEP files into distinct categories based on machining features. These categories include workpiece dimensions, profile features, minimum x and y values, depth of cut, EDGE_LOOP path, profiling path, circular path, and linear path. The extracted data is analyzed through an interpretation cluster, which applies algorithms to identify and organize geometric entities such as ORIENTED_EDGE, EDGE_CURVE, VERTEX_POINT, and CARTESIAN_POINT. This hierarchical data structure allows for precisely determining critical machining parameters and tool paths. The workflow algorithm incorporates iterative processes to refine the interpretation and recognition of geometric data.

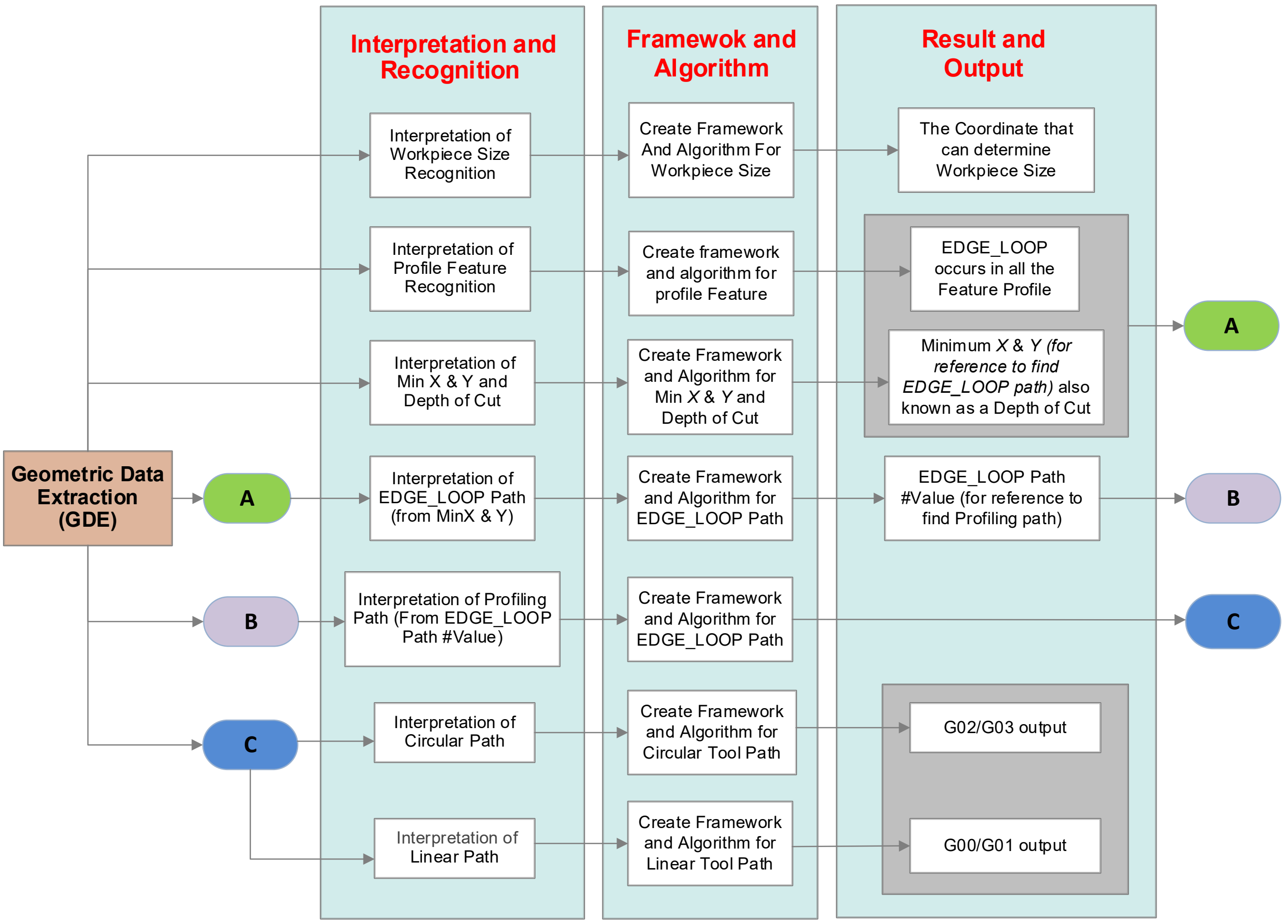


Fig. 2 *The Integrated Interface System (IIS) module framework*

For instance, the EDGE_LOOP entity, which serves as a reference for machining profiles, is linked to its sub-entities to define accurate cutting paths. The system also calculates minimum x and y coordinates, establishing the starting points for tool path generation. These algorithms are designed to handle the semi-structured and complex nature of STEP files, ensuring reliability in data extraction. The results generation component processes the interpreted data to produce G-code outputs tailored to CNC machining requirements. This component employs sequential logic to generate outputs such as circular (G02/G03) and linear (G01) tool path movements. For example, the interpretation of EDGE_LOOP entities yields data that informs profiling and depth of cut, which are subsequently used to generate smooth and continuous tool paths. The IIS framework integrates user-defined inputs, including feed rate, spindle speed, and cutting tool specifications, to customize the generated G-code. This flexibility ensures that the tool paths are optimized for specific machining scenarios. The final output provides Cartesian coordinate data for the x, y, and z axes, enabling precise machining operations.

The module framework was validated through a case study focusing on EDGE_LOOP entities within a STEP file. The system's ability to accurately interpret and process these entities was demonstrated by generating tool paths that matched the intended machining profiles. The validation process also confirmed that the IIS framework's outputs align with the results produced by commercial CAM software, such as SolidCAM. Additionally, the generated G-code was verified through CNC simulation and physical machining tests, showcasing its effectiveness in delivering high-quality workpieces. The IIS framework balances complexity and usability by organizing the workflow into modular components. Future enhancements will focus on expanding its capabilities to accommodate advanced CNC configurations, such as multiple-axis machining, and refining its algorithms for handling complex geometric data. This modular framework represents a significant advancement in STEP-based CNC tool path generation, providing a robust and scalable solution for modern manufacturing applications.

2.2 Framework Interpretation and Recognition

Through the framework presented in Fig. 2, the interpretation and recognition components of the IIS play a pivotal role in extracting, analyzing, and utilizing geometric data from STEP files to generate precise CNC tool paths. These processes ensure the accurate identification of critical machining features and the systematic translation of data into actionable outputs for CNC machining operations. The IIS interprets geometric entities within the STEP file by subdividing them into seven distinct subcategories: workpiece size, profile features, minimum x, and y values, depth of cut, EDGE_LOOP path, profiling path, and linear and circular paths. Each of these subcategories is processed to establish their hierarchical relationships and interdependencies. The EDGE_LOOP entity, for example, is identified and linked to its associated sub-entities, such as ORIENTED_EDGE, EDGE_CURVE, VERTEX_POINT, and CARTESIAN_POINT. This structured approach enables the system to define the machining features required for tool path generation accurately. In-depth recognition algorithms analyze the data to locate and classify the EDGE_LOOP entities. These entities are fundamental to determining tool path motion, including offset direction and cutting tool positioning (e.g., left or right cutter compensation).

Furthermore, the minimum x and y values are identified to establish reference points for machining profiles. The system also calculates the depth of cut values for each identified feature, which are critical for precise machining operations. The interpretation workflow systematically maps geometric data to corresponding machining operations. For example, EDGE_LOOP entities are analyzed to determine the sequence of Cartesian points that form the tool path. These points are arranged into linear (G01) and circular (G02/G03) movements, ensuring smooth transitions and continuous machining processes. The mapping of these entities is guided by algorithms designed to interpret semi-structured data within the STEP file, resolving ambiguities and redundancies commonly encountered in complex geometric models. The module framework's interpretation capabilities were validated through a case study involving identifying and processing EDGE_LOOP entities.

The system recognized the required entities and generated accurate tool paths with specified offsets and cutting depths. Comparative analysis with commercially generated tool paths demonstrated that the IIS framework produces equivalent or superior results, confirming its reliability and precision. The framework's ability to interpret and recognize geometric data extends beyond EDGE_LOOP entities, enabling the identification of complex machining features. For example, sub-entities such as ORIENTED_EDGE and EDGE_CURVE are processed to determine their positional and relational attributes within the machining profile. This comprehensive data processing ensures that all relevant geometric information is incorporated into the tool path generation process. Enhancing the interpretation and recognition module will focus on improving the accuracy of feature detection algorithms and expanding its capabilities to handle more complex geometries and multi-axis CNC configurations. By refining these processes, the IIS aims to provide a robust and versatile solution for CNC machining, addressing the evolving needs of modern manufacturing systems.

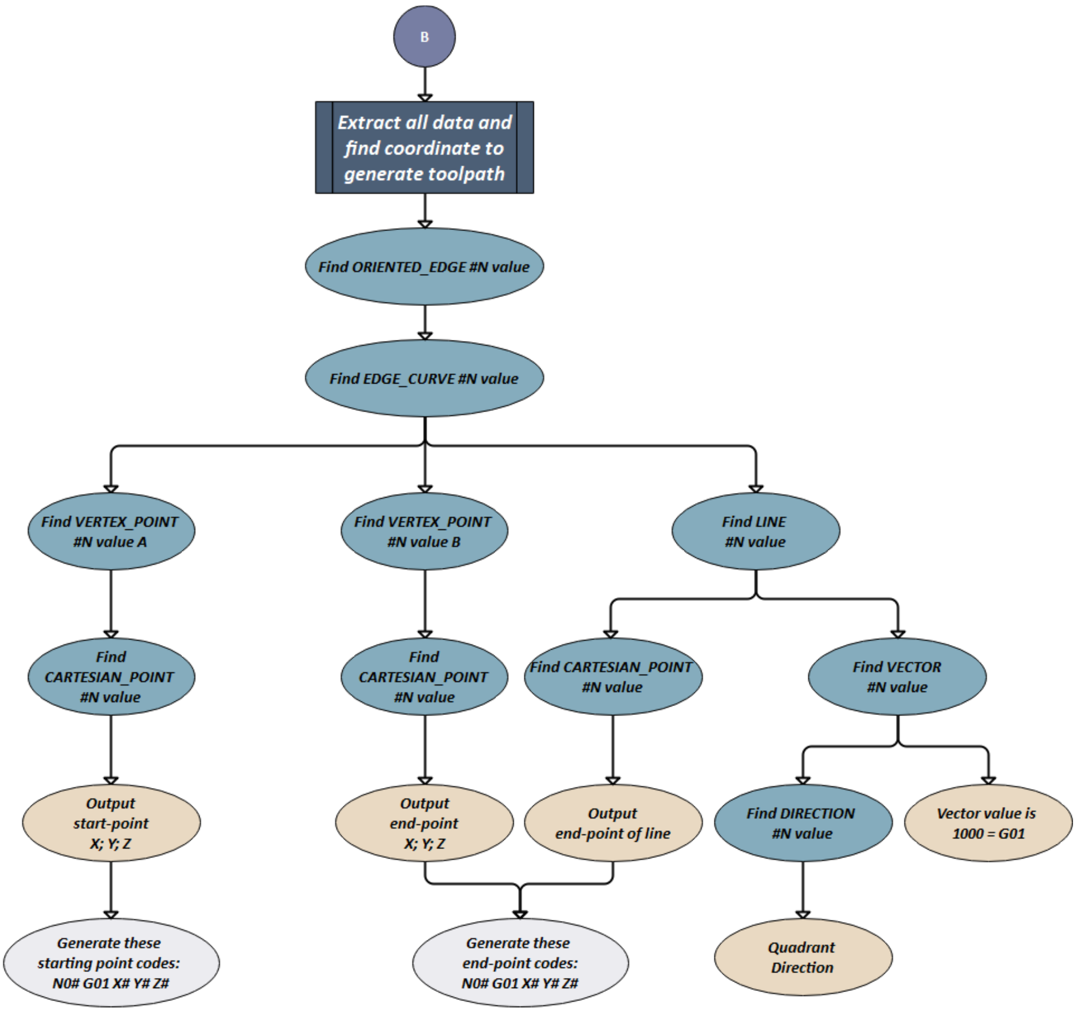
2.3 IIS Geometric Processing for Tool Path Generation

As illustrated in Fig. 3, the IIS plays a pivotal role in transforming geometric entities from CAD models into executable G-code for CNC machining. This transformation follows a structured process, ensuring the precise conversion of design data into machine instructions. This section provides a detailed algorithmic breakdown of two fundamental workflows: linear route tool path generation and circular route tool path generation. Each workflow governs how the system interprets EDGE_LOOP entities and maps them to appropriate motion commands in G-code. As depicted in Fig. 4(a), the workflow for linear route tool path generation begins with the IIS identifying the EDGE_LOOP entity within the geometric representation of a component. This entity comprises a series of interconnected linear edges that define the boundary or contour of a feature. The system extracts the coordinates of each edge segment and determines whether they form a continuous straight-line trajectory.

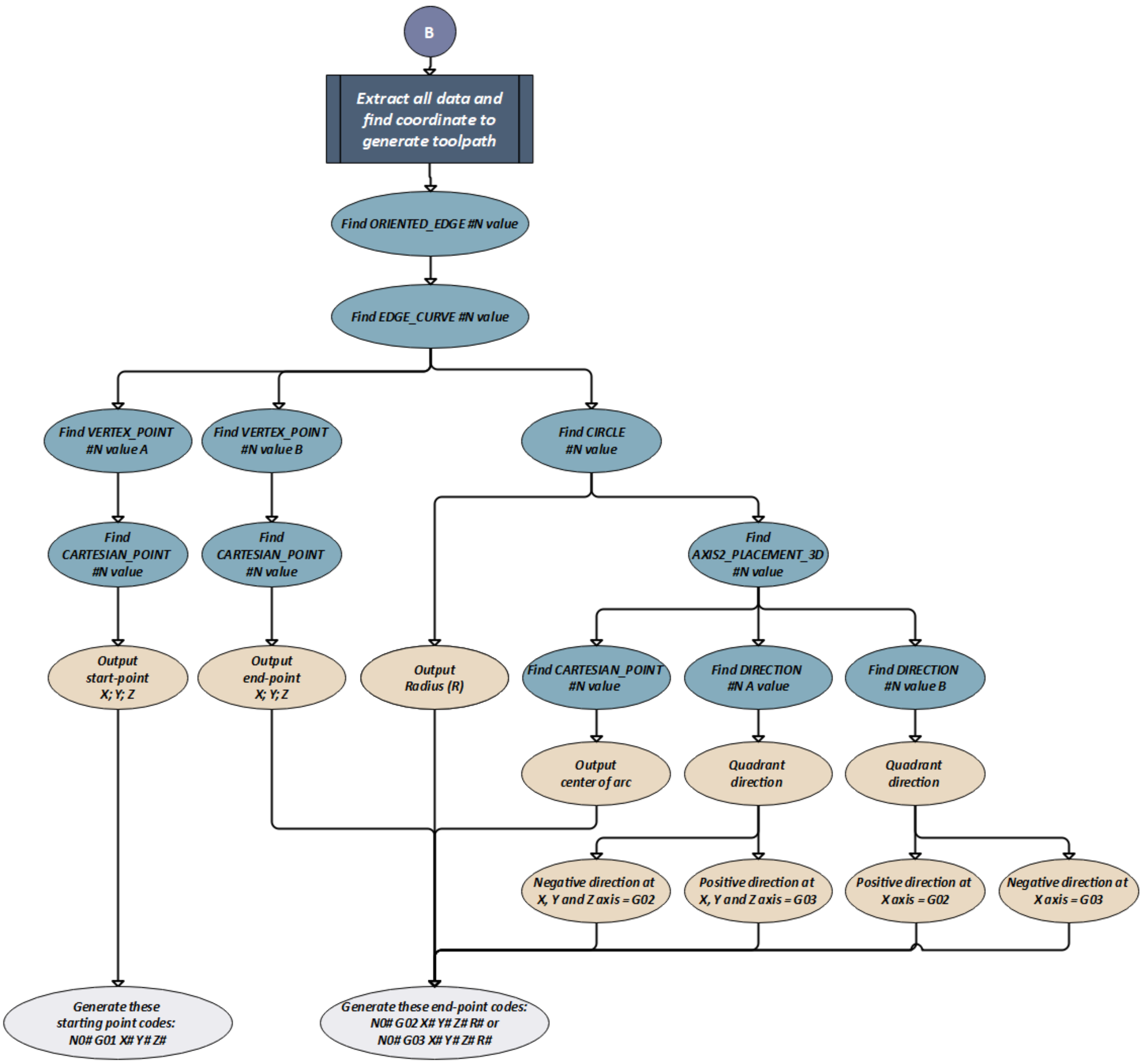
Once the linear edges are identified, the algorithm proceeds with segment mapping and path planning. At this stage, the extracted edges are translated into G01 commands, which define linear interpolation movements in G-code. The edges are ordered sequentially to ensure smooth transitions between consecutive segments and prevent abrupt changes in tool movement. This step is critical for maintaining machining efficiency and ensuring a consistent material removal process. The system then performs coordinate transformation, converting the extracted geometric coordinates into machine-specific reference points. The Cartesian coordinates (X, Y, Z) are recalculated based on the CNC machine's work coordinate system (WCS). If necessary, offsets are applied for tool compensation or fixture placements, ensuring precise alignment between the generated tool path and the intended design. The next phase involves assigning appropriate feed rate (F) and spindle speed (S) based on machining parameters, including material properties, tool type, and surface finish requirements. These values are crucial for optimizing cutting efficiency and minimizing tool wear. The system dynamically adjusts these parameters to maintain a stable and efficient cutting environment.

Finally, the IIS generates the G-code sequence, where each linear segment is represented as a G01 command with corresponding coordinate values. A typical G-code instruction for linear motion follows the format (G01 X_ Y_ Z_ F_). This command directs the CNC machine to move the tool linearly to a specific position at the designated feed rate. Before execution, a simulation and optimization phase is conducted to verify the accuracy of the generated tool path. This step ensures that potential issues, such as collisions, tool over-travel, or inefficiencies in motion planning, are identified and rectified before final deployment. If necessary, corrective adjustments are applied to optimize machining performance.

Fig. 3 *The Integrated Interface System (IIS) module framework (10)*



(a)



(b)

Fig. 4 *The Workflow of tool path generation (a) Linear route; (b) Circular route*

In contrast to the linear path, the circular route tool path generation involves a more complex interpolation process. The IIS first identifies circular geometries within the EDGE_LOOP entity. This entails detecting edges that form arcs or full circles and extracting key parameters such as the center point, radius, and start/end angles. Recognizing these properties is essential for accurate conversion into CNC motion instructions. As shown in Fig. 4(b), the system proceeds with arc segmentation and path planning once the circular features are classified. Instead of straight-line interpolation, the IIS employs arc interpolation through the G02 (clockwise arc) and G03 (counterclockwise arc) commands. These commands enable smooth curved motion without approximating the arc as a series of short linear segments, improving machining accuracy and surface finish. The next phase involves coordinate system transformation, where the system calculates the arc's center point relative to the starting position. This transformation is crucial for defining the R parameters, which specify the relative distance from the start point to the arc center in the X, Y, and Z directions. The CNC controller relies on these values to generate continuous, smooth circular motion. As with the linear route, the IIS assigns optimal feed rate and spindle speed.

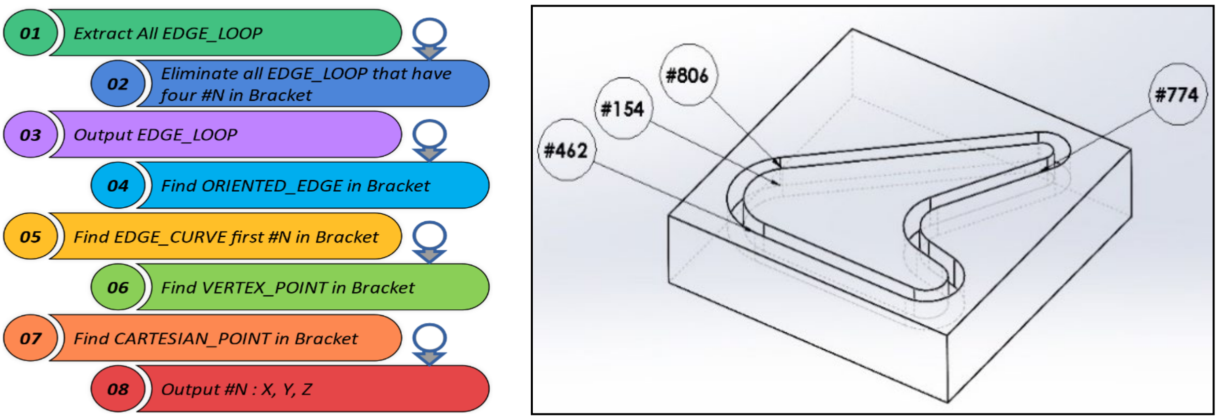
However, in circular tool paths, feed rate adjustments are more dynamic to account for varying cutting forces along the arc. This adaptive speed control minimizes tool deflection and ensures uniform material removal. The final stage involves G-code generation, where the system produces commands such as (G02 X_ Y_ Z_ R_ or G03 X_ Y_ Z_ R_). These commands specify the arc's endpoint and center offset, allowing the CNC machine to execute precise circular movements. Before execution, the system conducts a simulation and verification process, ensuring the generated tool path conforms to the desired geometric profile. Any deviations or potential machining errors are corrected before actual cutting operations commence. The key differences between linear and circular tool path processing lie in the interpolation method, coordinate transformations and tool movement strategies. Linear paths use G01 commands to define straight-line movements, while circular paths utilize G02/G03 commands for arc interpolation. Additionally, linear tool paths require simple X, Y, and Z coordinate transformations, whereas circular paths necessitate R parameter calculations to define the arc's center.

Furthermore, motion planning in circular routes is inherently more intricate due to the continuous curvature of the tool path. Unlike linear paths, which typically operate at a constant feed rate, this requires dynamic feed rate adjustments to maintain cutting stability. Despite these complexities, circular interpolation offers superior machining accuracy and surface finish, making it ideal for contour machining and rounded edges. The IIS algorithm processes linear and circular geometric entities efficiently, ensuring precise tool path generation while optimizing machining performance. By leveraging advanced coordinate transformations and interpolation techniques, the system enables seamless conversion of CAD models into CNC-executable G-code, facilitating high-precision manufacturing processes.

2.4 Results and Discussion

This study evaluates the effectiveness of the IIS in extracting and processing STEP file data for CNC tool path generation. The performance of IIS was assessed based on its ability to generate precise tool paths, ensure compatibility with CNC machine controllers, and match machining profiles produced by commercial CAM software. Validation was conducted through CNC simulations, physical machining experiments, and comparative analysis with SolidCAM-generated tool paths. The IIS successfully generated G-code for a three-axis CNC milling machine by accurately extracting and interpreting geometric data from STEP files. Key extracted entities, including EDGE_LOOP, ORIENTED_EDGE, and CARTESIAN_POINT, were processed to define machining features and generate corresponding tool paths. CNC simulation results demonstrated that the generated tool paths were smooth and continuous, aligning well with machining parameters such as feed rate and spindle speed. A case study involving a 10 mm depth of cut confirmed that the IIS accurately replicated the intended machining profiles, underscoring its precision. Fig. 5(a) illustrates the workflow of profile feature recognition within IIS, detailing the identification and linkage of geometric entities to define machining features.

Meanwhile, Fig. 5(b) highlights the significance of EDGE_LOOP entities, which are crucial in determining tool offset directions and cutting depths. These figures comprehensively visualize the system's structured approach to data interpretation and workflow organization. Fig. 6 presents the generated tool path motion and cutter position, showcasing the smooth transitions and continuous machining processes achieved by IIS. The edge loop entity #154 analysis revealed multiple values, including (595, #649, #379, #904, #82, #590, #363, #654, #375, and #851). These values were arranged in original order and translated into a graphic illustration. Fig. 6 represents the cutting tool's motion from the starting point (#595) to the endpoint (851). Meanwhile, Fig. 7 focuses on the geometric data extraction process for an EDGE_LOOP entity (154). The diagram demonstrates how the IIS interprets and processes sub-components such as ORIENTED_EDGE and CARTESIAN_POINT to generate precise tool path coordinates. The systematic analysis ensures that all necessary data is accurately translated into G-code. The output G-code was generated to determine curved paths (Fig. 7a) and linear paths (Fig. 7b).



(a) **(b)**

Fig. 5 *Profile feature recognition (a) The workflow; (b) EDGE_LOOP entity*

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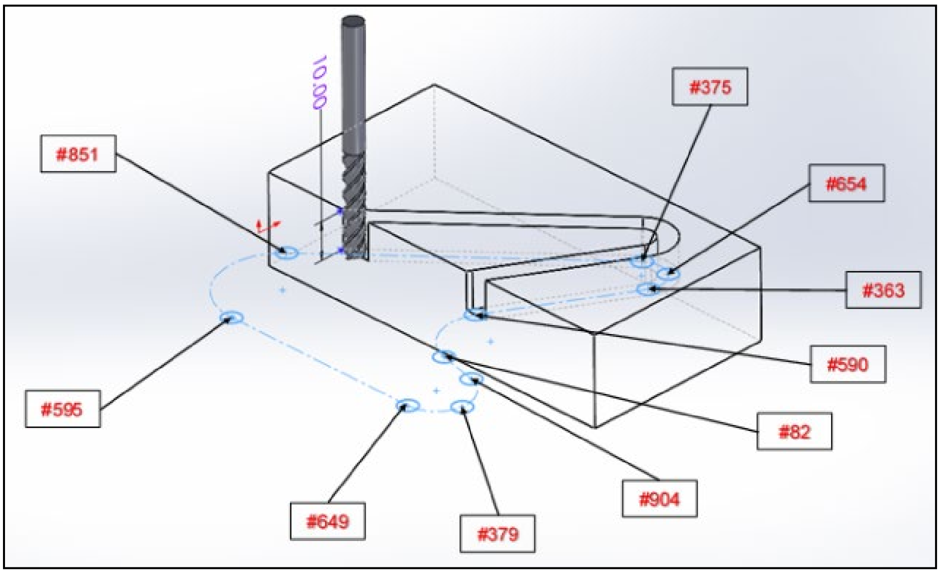
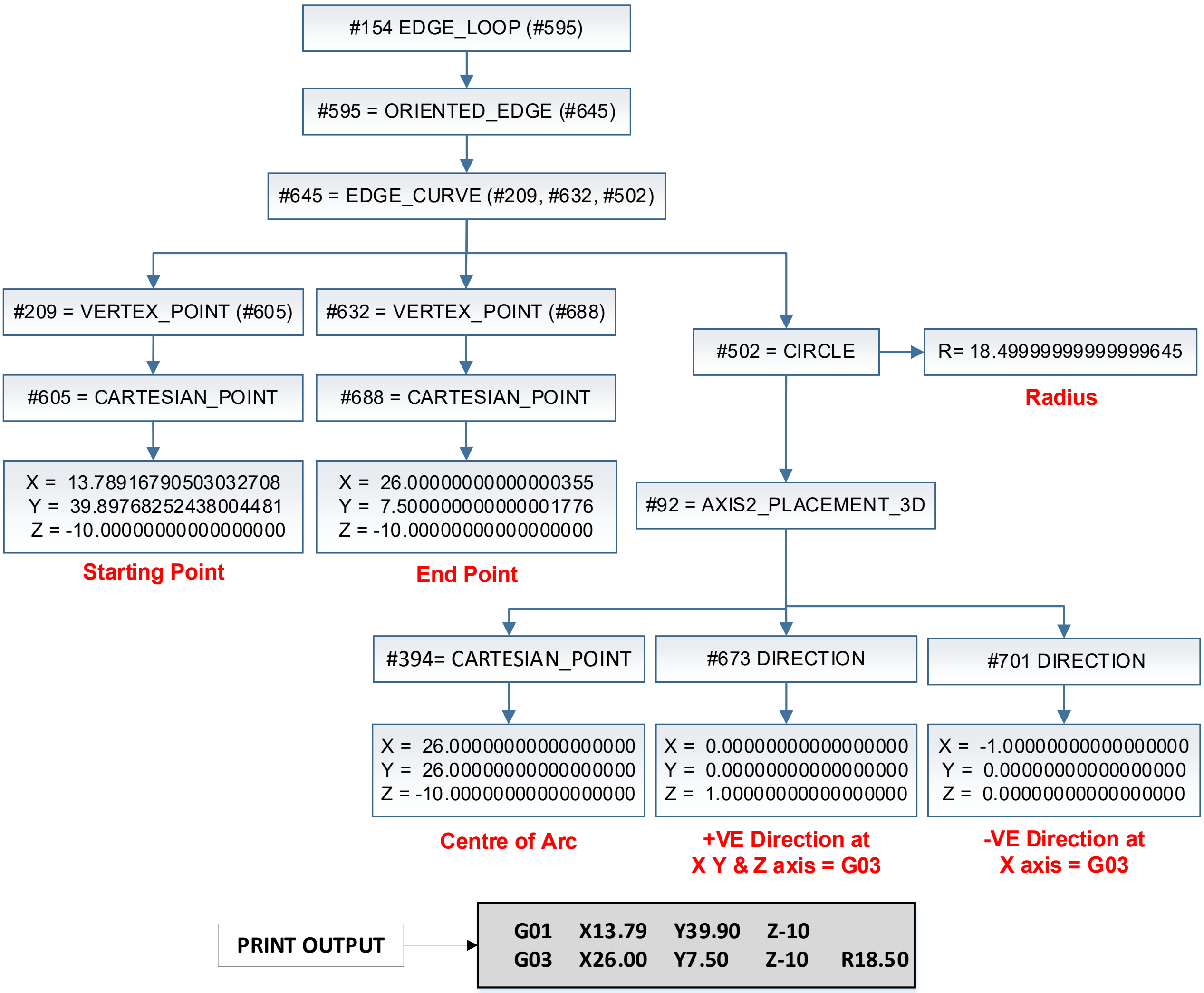
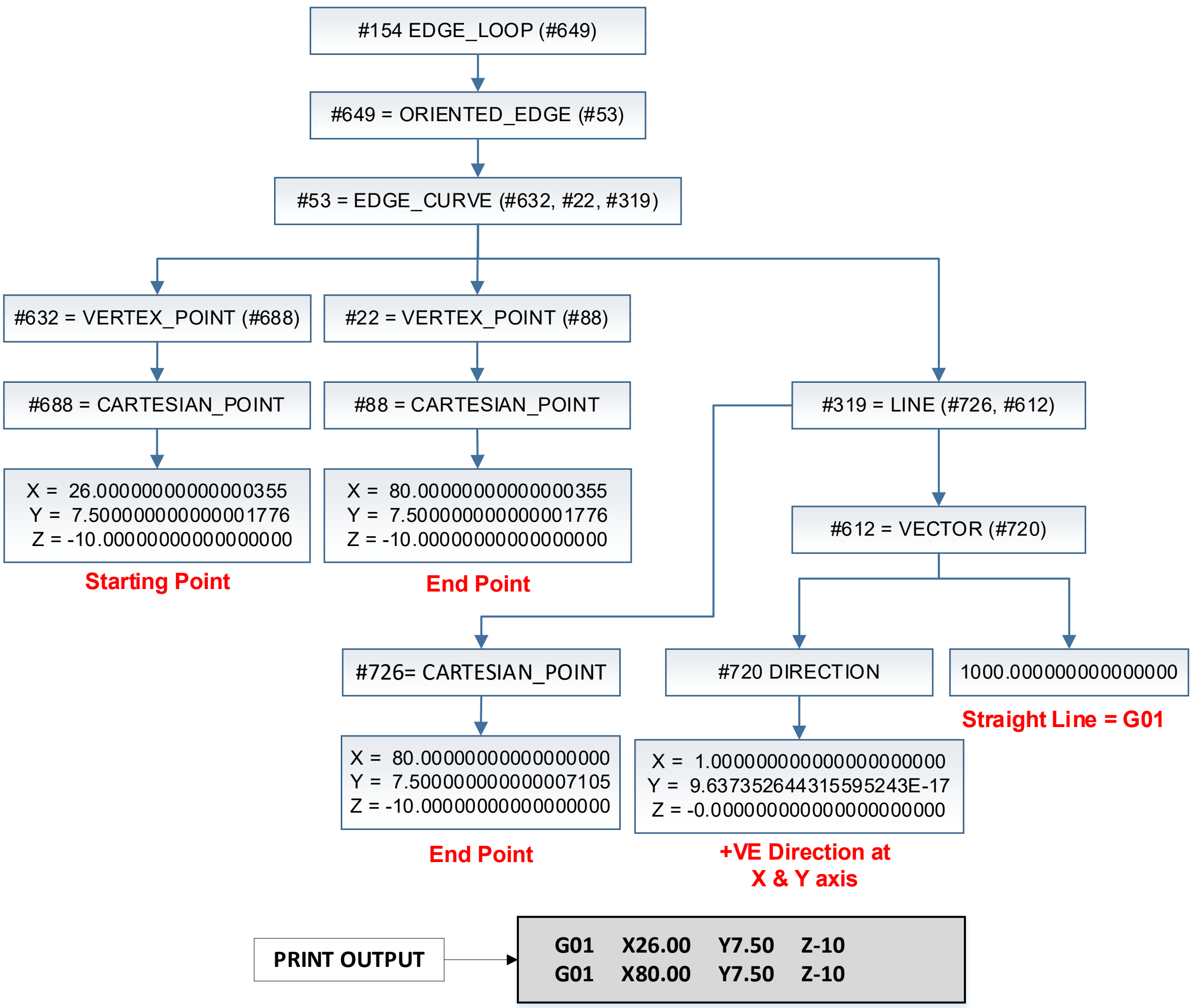


Fig. 6 *The toolpath motion and cutter position*



(a)



(b)

Fig. 7 *The toolpaths for determining (a) Starting point for curved paths; (b) Second point for linear paths*

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N01 G90 G54 G17
N02 G49 G80 G21
N03 S1000 F250
N04 G41 T01 M06
N05 G00 X13.79 Y39.90 Z10
N06 G01 X13.79 Y39.90 Z-10.00
N07 G03 X26.00 Y7.50 Z-10.00 R18.50
N08 G01 X26.00 Y7.50 Z-10.00
N09 G01 X80.00 Y7.50 Z-10.00
N10 G03 X91.50 Y19.00 Z-10.00 R11.50
N11 G01 X91.50 Y19.00 Z-10.00
N12 G03 X82.65 Y30.19 Z-10.00 R11.50
N13 G01 X82.65 Y30.19 Z-10.00
N14 G01 X71.81 Y32.76 Z-10.00
N15 G02 X65.77 Y46.74 Z-10.00 R9.50
N16 G01 X65.77 Y46.74 Z-10.00
N17 G01 X85.37 Y80.76 Z-10.00
N18 G03 X86.50 Y85.00 Z-10.00 R8.50
N19 G01 X86.50 Y85.00 Z-10.00
N20 G03 X72.39 Y91.39 Z-10.00 R8.50
N21 G01 X72.39 Y91.39 Z-10.00
N22 G01 X13.79 Y39.90 Z-10.00
N23 G00 X13.79 Y39.90 Z10
N24 G40 G30
N26 M30
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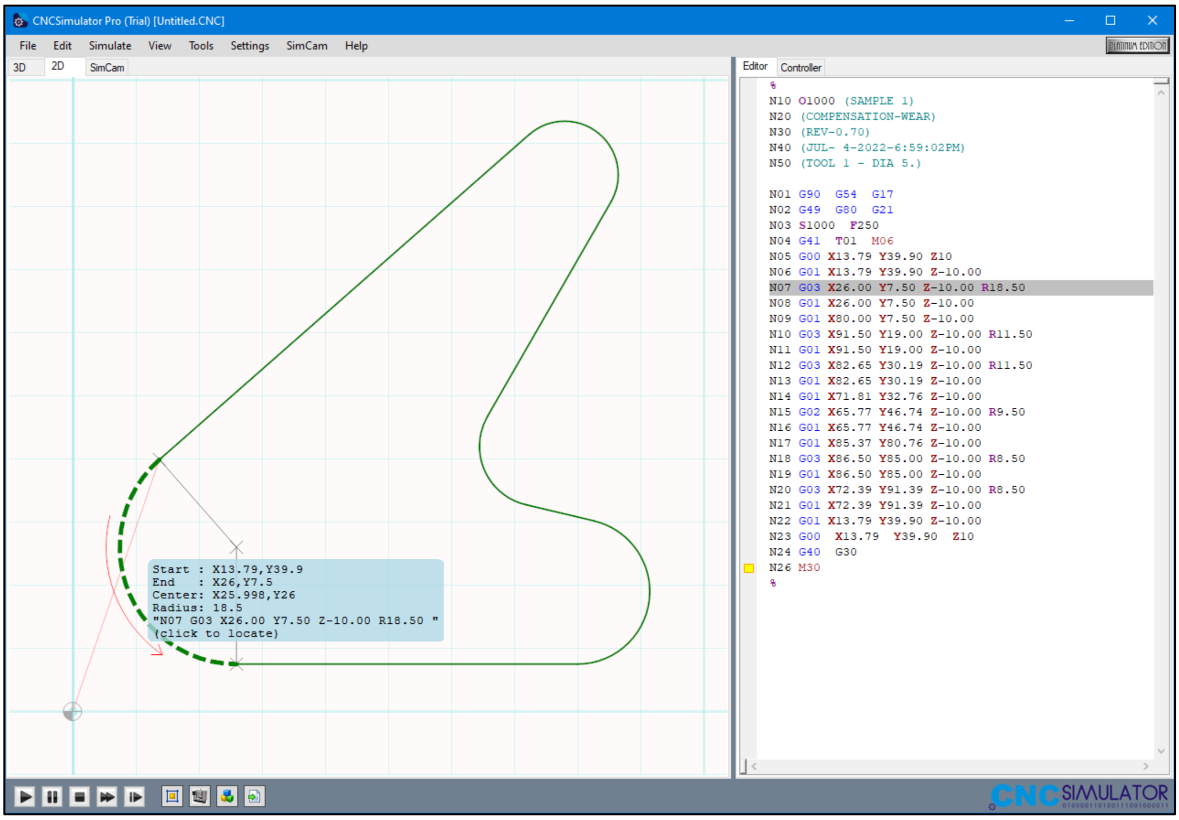
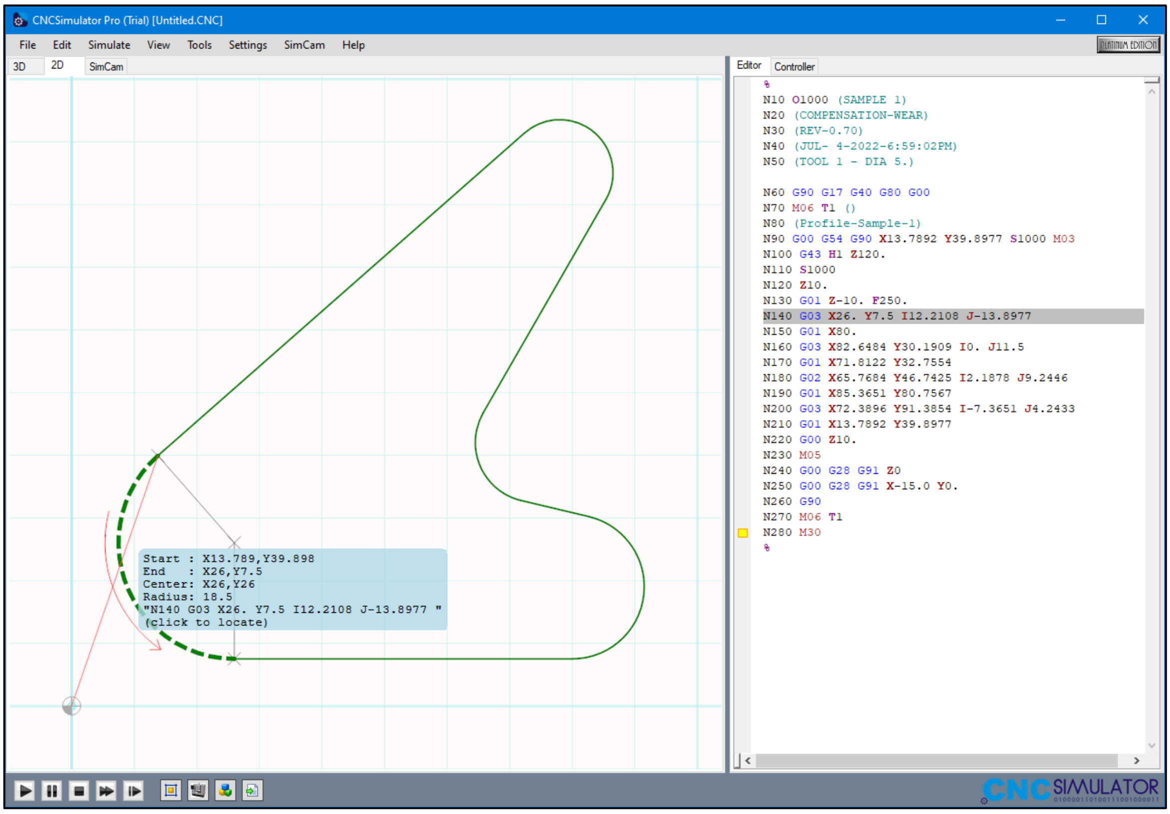
(a)

(b)

Fig. 8 *Output (a) CNC programming; (b) Finishing product*

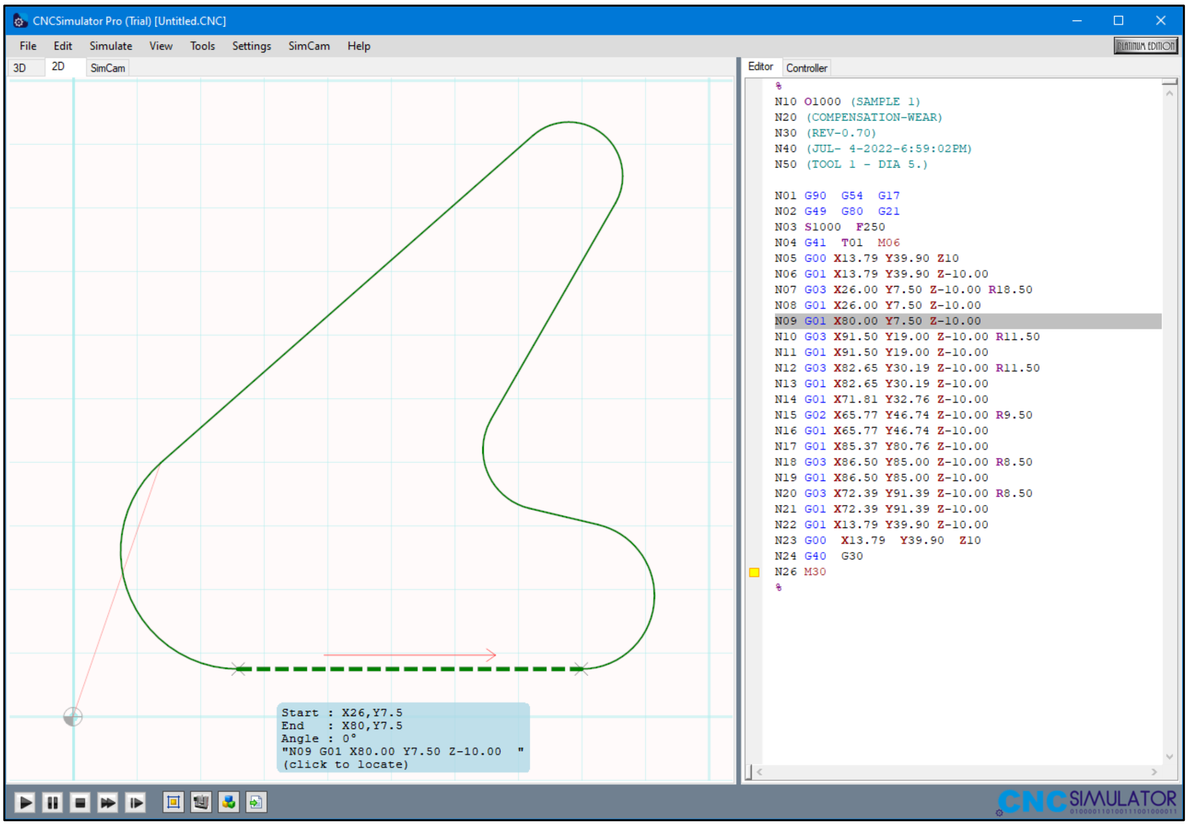


(a)

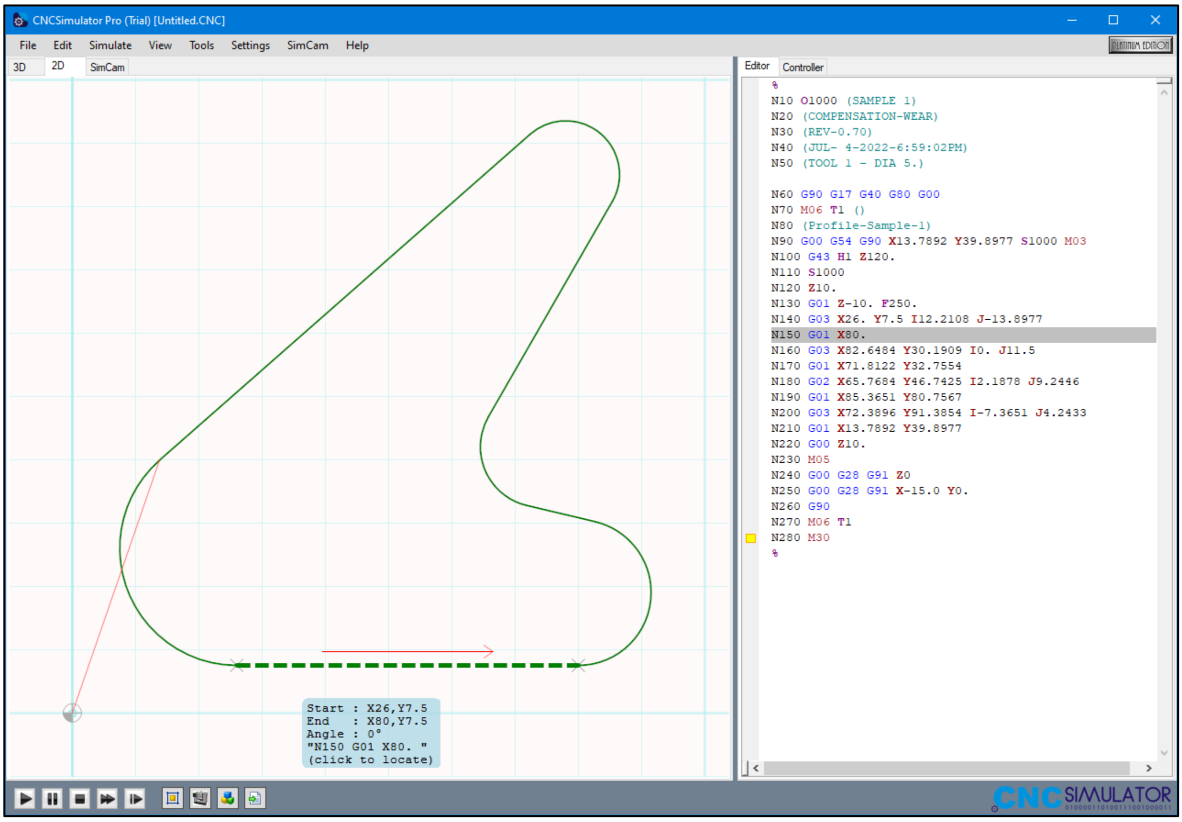


(b)

Fig. 9 *The NC viewer starting point (a) IIS; (b) SolidCAM*



(a)



(b)

Fig. 10 *The NC viewer second point (a) IIS; (b) SolidCAM*

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To further validate the performance of IIS, physical machining tests were conducted using the G-code generated by the system to fabricate a UHMWPE workpiece. The resulting machined product was compared to the original 3D CAD model and the SolidCAM-generated profile. The comparison revealed high accuracy between the machined output and the intended design, demonstrating the system's capability to translate CAD data into precise physical components. Key machining parameters, including a spindle speed of 1000 rpm and a feed rate of 250 mm/min, were maintained throughout the process to ensure consistency. Fig. 8(a) presents the CNC programming output, displaying the G-code generated by IIS for a circular feature. The results indicate that IIS integrates machining parameters and geometric data into a cohesive tool path program. Fig. 8(b) showcases the finished product, highlighting the high fidelity between the machined workpiece and the intended CAD design.

Furthermore, the validation results presented in Fig. 9 and Fig. 10 compare the tool paths IIS and SolidCAM generated, confirming the proposed system's accuracy and reliability. The findings also underscore the IIS's capability to handle diverse machining profiles, including complex linear and circular paths. By incorporating user-defined inputs such as tool specifications and cutting parameters, the system optimizes tool path generation for various machining scenarios. These results highlight the flexibility and scalability of IIS, making it a viable solution for small- to medium-scale manufacturing applications. Compared to traditional CAM software, IIS offers significant advantages, including reduced reliance on proprietary solutions, lower operational costs, and improved accessibility for users with limited resources.

Moreover, the modular architecture of IIS facilitates efficient geometric data processing and seamless integration with CNC workflows. Using STEP files further enhances interoperability, allowing the system to function effectively in diverse manufacturing environments. The results demonstrate that IIS is a robust and efficient tool path generation system, capable of producing accurate machining output while improving accessibility and reducing dependency on commercial CAM solutions. The proposed approach holds promise for further development and integration into broader manufacturing applications, particularly in automated and smart manufacturing systems.

2.5 Comparison and Validation

The coding methodology was validated by comparing the results generated by commercial CAM software with those produced by the Integrated Interface System (IIS). The primary objective was to ensure that the G-code generated by IIS was precise, accurate, fully functional, and practical for CNC machining. SolidCAM software served as a benchmark, employing specific technical parameter settings. CNC Simulator software was also used to verify the tool path movements and simulate the machining process for both G-code outputs. Key metrics for verification included positional accuracy (start and end points), reference points (origin), cartesian coordinates (X, Y, and Z), tool path direction (CW/CCW), geometry features (circular/linear), and cutter compensation (right/left).

Table 1 *Comparison of circular feature outcomes*

Metric	NC viewer (IIS)	NC viewer (SolidCAM)	Outcome
Direction	Counter-clockwise	Counter-clockwise	Same
Start Point	X13.79, Y39.9	X13.789, Y39.898	Same
End Point	X26, Y7.5	X26, Y7.5	Same
Center Point	X25.998, Y26	X26, Y26	Same
Radius	18.5	18.5	Same
NC Block Program	G03 X26.00 Y7.5 Z-10.00 R18.5	G03 X26., Y7.5, I12.2108, J-13.8977	Same G03, different format

Table 2 *Comparison of linear feature outcomes*

Metric	NC viewer (IIS)	NC viewer (SolidCAM)	Outcome
Direction	Counter-clockwise	Counter-clockwise	Same
Start Point	X26, Y7.5	X26, Y7.5	Same
End Point	X80, Y7.5	X80, Y7.5	Same
Angle	0	0	Same
NC Block Program	G01 X80.00 Y7.5 Z-10.00	G01 X80.	Same G01, different format

A combination of circular and linear geometries was selected to validate the system comprehensively. This combination ensures a complete representation of the machining profile and facilitates an accurate evaluation of the results. The IIS and SolidCAM generated G-code automatically based on identical input parameters, including machining parameters, clearance, spindle speed (S), feed rate (F), cutting tool specifications, cutter compensation, cutter rotation, and tool path movements. Additional parameter variations were explored to assess the flexibility and reliability of the IIS under different machining scenarios.

In the final validation phase, physical machining tests were conducted to compare the CNC simulation results with the actual machining outcomes on a physical workpiece. Fig. 10 illustrates the NC Viewer outputs for circular features generated by IIS and SolidCAM, while Fig. 11 presents similar outputs for linear features. These visualizations highlight the development of machining profiles, including starting and ending points, curve radii, circle centers, and the complete NC block program. The validation results, summarized in Tables 1 and 2, confirm that the G-codes generated by IIS and SolidCAM for circular and linear features were identical regarding tool path motion, shape, and positional accuracy. The functional outputs remained consistent despite differences in the NC block program's formatting with IIS using radius (R) for circular features and SolidCAM employing I, J, and K notations.

2.6 Percentage Deviation

The IIS-generated G-code was validated against SolidCAM output by analyzing the data in Table 1 and Table 2 of the journal. The comparison focused on key machining parameters, including the start and end coordinates, center points, and tool path directions for circular and linear features. The results indicated a minimal deviation between the two G-code outputs, confirming the accuracy of the IIS in replicating SolidCAM-generated tool paths. The deviation was calculated for circular features by comparing the tool path's start, end, and center point coordinates. The absolute difference between the IIS and SolidCAM outputs for these points was 0.0022 mm for the start point and 0.002 mm for the center point, while the endpoint remained identical. Given that the total circumference of the circular path was 116.18 mm, the percentage deviation was determined using the formula.

$$\text{Percentage Deviation} = \left(\frac{\text{Average Deviation}}{\text{Nominal Tool Path Length}}\right) \text{ x } 100 \tag{1}$$

With an average deviation of 0.0021 mm, the final percentage deviation for circular features was calculated to be 0.0018%, which is extremely low. This confirms that the IIS-generated tool paths maintain high precision compared to industry-standard CAM software like SolidCAM. Similarly, for linear features, the start and end points remained exactly the same in both IIS and SolidCAM-generated G-code. The linear tool path covered a total distance of 54 mm, and no deviation was observed in the coordinate values. Consequently, the percentage deviation for linear features was calculated as 0%, confirming that the IIS accurately reproduced straight-line machining movements without any measurable error. Overall, the results demonstrate that the IIS-generated G-code is nearly identical to SolidCAM output, with an overall deviation of less than 0.002%. This confirms that the IIS is a reliable and cost-effective alternative for tool path generation, providing accuracy comparable to commercial CAM solutions while eliminating the need for proprietary software. The negligible deviation further validates the feasibility of using IIS for automated CNC programming, ensuring precise and efficient machining operations.

2.7 Physical Machining Validation

Following the simulation phase, physical CNC machining was performed to validate the IIS-generated G-code further. The machining tests used a UHMWPE workpiece and were carried out on a benchtop 3-axis CNC milling machine. Cutting parameters were set to a spindle speed of 1000 rpm and a 250 mm/min feed rate. The G41 function was employed to compensate for the left cutter, resulting in counter-clockwise machining along the outer profiling tool path with an offset to the left of the tool path. Fig. 8(b) shows the physical machining results demonstrated excellent agreement with the initial 3D CAD designs and simulation outputs. The simulated and physical end products matched in profile shape, size, and accuracy. This validation underscores the IIS's capability to generate reliable and accurate tool paths for CNC machining, providing a cost-effective and efficient alternative to commercial CAM software.

2.8 Comparison with Other Approaches

The integration of CAD and CAM has been extensively explored through various methodologies, including the application of Artificial Intelligence (AI) for tool path optimization and direct G-code scripting. AI-based approaches leverage machine learning algorithms to analyze CAD models and generate optimized tool paths based on material properties, tool wear, and machining efficiency. These methods enhance precision and reduce machining time; however, they require large training datasets and high computational power, limiting their accessibility to small and medium-sized enterprises due to cost and complexity. Another prevalent method involves direct G-code scripting, where tool paths are manually programmed using parametric G-code or scripting languages such as Python. While this approach offers high customization and flexibility, it demands significant expertise in CNC programming and an in-depth understanding of machining parameters, increasing the potential for human error and inefficiencies in tool path generation.

In contrast, commercial CAM software such as SolidCAM, Mastercam, and Siemens NX automates tool path generation through pre-configured machining strategies. These systems provide multi-axis support, collision detection, and process optimization; however, they are often associated with high costs and a steep learning curve, making them less viable for resource-constrained manufacturers. The IIS proposed in this study offers a novel and cost-effective alternative by directly converting STEP file geometric data into G-code, eliminating the need for intermediary CAM software. IIS ensures high precision and automation while reducing dependency on proprietary solutions by leveraging a rule-based approach to extract and process geometric entities in STEP files. Comparative validation against SolidCAM-generated G-code demonstrated less than 0.002% deviation, confirming the accuracy and reliability of the IIS tool path generation. Despite its current limitation to 3-axis machining, future enhancements will focus on extending functionality to multi-axis CNC systems, integrating advanced feature recognition algorithms, and exploring hybrid AI-assisted methodologies to enhance tool path optimization and machining efficiency further. The development of such systems aligns with industry trends toward greater automation, interoperability, and cost-effective manufacturing solutions.

Conclusion

This study successfully developed and validated an Integrated Interface System (IIS) for automated G-code generation, enabling direct conversion of STEP file geometric data into CNC machining instructions without reliance on proprietary CAM software. The IIS effectively extracted and processed key geometric entities such as EDGE_LOOP and CARTESIAN_POINT, generating precise tool paths for linear and circular machining operations. Comparative validation against SolidCAM demonstrated that the IIS-generated G-code achieved high accuracy, with a deviation of less than 0.002% in tool path coordinates. CNC simulation results confirmed that the generated tool paths maintained smooth transitions and conformed to predefined machining parameters, including feed rate, spindle speed, and cutting depth. Physical machining tests using the IIS-generated G-code on a three-axis CNC milling machine produced workpieces with dimensional accuracy comparable to those generated using commercial CAM software. The comparative analysis of circular and linear feature machining further substantiated the system’s capability to maintain geometric integrity and machining precision. The findings indicate that the IIS provides an efficient and cost-effective alternative to conventional CAM-based tool path generation, particularly for small-to-medium-scale manufacturers. By streamlining CNC machining workflows and ensuring high precision, the system enhances accessibility to automated manufacturing.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Zammeri Abd Rahman, Saiful Bahri Mohamed, Mohamad Minhat, Mohd Shahir Kasim;* ***data collection:*** *Zammeri Abd Rahman, Razwan Rohimi, Muhammad Abdulrahim Rabbani Md Sharizam;* ***analysis and interpretation of results:*** *Zammeri Abd Rahman, Razwan Rohimi, Tengku Mohd Sharir Tengku Sulaiman;* ***draft manuscript preparation:*** *Zammeri Abd Rahman, Razwan Rohimi, Zulkifli Abd Rahman. All authors reviewed the results and approved the final version of the manuscript.*

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