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ENHANCING CNC PRECISION: A REVIEW OF GEOMETRIC ERRORS AND SIMULATION METHODS IN THREE-AXIS CNC SYSTEMS

Walisijiang. Tayier

Centre for Advance Materials and Sustainable Manufacturing, Faculty of Engineering and the Built Environment & IT, SEGi University, 47810 Petaling Jaya, Malaysia

Corresponding author: tzwn2012@outlook.com Tel: +60-03- 61451777

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Highlights:

- *A focus on optimizing CNC machines for time-efficient cutting tool operations.*
- *The precision of CNC systems depends on their geometric configurations.*
- *Finite element analysis (FEA) to predict and mitigate geometric errors.*

Abstract: The rapid expansion in industrial production has markedly increased the deployment of computer numerical control (CNC) systems. Recent efforts have concentrated on optimizing these machines for time-efficient cutting tool operations. The accuracy of CNC systems is heavily dependent on their geometric configurations, but geometric errors such as alignment deviations, backlash, and thermal deformation can compromise structural integrity and operational precision. This review focuses on the role of simulation in three-axis CNC machining, particularly through techniques like finite element analysis (FEA), to predict and mitigate these errors. By examining various CNC machine components, the review highlights how simulation methodologies can address geometric inaccuracies. Key findings indicate that integrating advanced simulation tools with CNC systems effectively reduces geometric errors, enhances machining accuracy, and improves overall system performance. This integration leads to more reliable and precise machining operations, thereby advancing the efficiency and effectiveness of CNC systems in high-precision manufacturing environments.

Keywords: Three-axis CNC, Geometric error, Finite element analysis, Numerical coding, Simulation

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1. Introduction

Numerical control (NC) systems are advanced automated machine tools that execute operations based on precisely programmed instructions adhering to standardized protocols. The majority of contemporary NC machines are computer numerical controlled (CNC) systems, where a computer precisely governs the machine's operations. CNC machines employ computer-aided design (CAD) and computer-aided manufacturing (CAM) software to control machining tools and processes with exceptional accuracy and repeatability. These systems are crucial in various manufacturing industries due to their high efficiency, precision, and capability to fabricate intricate parts with minimal human intervention. For a comprehensive understanding, a figure delineating the primary components and operational workflow of a CNC machine, including the control unit, machine bed, spindle, and tool holders, it is shown in **Figure 1** (Lan, 2019). With the contemporary advancement of fast machining innovation, three-dimensional contour end milling has completed a crucial requirement in the production of die and mold merchandise. This is genuine, because a large range of mechanical components are made of three axis contour and even greater multipart objects are typically created from a board through the usage of a three-dimensional roughing, semi-completing and completing processes. In three axis contour end milling, conventional offset contour CNC tool paths created by using the industrial CAM software are substantially used in machine components (Zhu, et al.,2023). Nowadays, as the high-quality demand for mechanical elements with high precision geometry and dimensional accuracy will intensify, a demand to provide those components with such prime-accuracy is greatly noted by current manufacturing industries. To this end, CNC machine tools are the most crucial way of apparatus for the production and manufacturing companies (Zhu, et al., 2022). CNC cutting tools had been extensively utilized in various area, for instance, aerospace industries. With the current advance of the CNC tools, producing advances, consisting of high speed feed rates and high-speed spindles, high- speed end milling at the CNC machine tool has emerge as continuously welcoming, and is being executed to assemble the sections with the demanded contour positioning and dimensional accuracy (Sawula, 2022). However, the positioning or geometry accuracy of the machined surface is significantly promoted by way of several errors resources area from errors existing in the cutting tool system for cutting technique. Motivated by the background and gaps on errors of structure and program or application in the cutting tool system and the cutting process which purpose positioning errors as mentioned above, and evaluation with the present studies exploration about tool route variation strategies for enhancement of positioning (geometry) accuracy in three- axis CNC cutting tool is done.

With this goal, this review paper proposes to examine or to evaluate exceptional from offset structure (such as tool path, geometric positioned) technology with the aid of advantage and disadvantage tool path modification techniques to adjust the cutting engagement angle and therefore, the cutting force at a perfect constant level, which will respond on a way to improve the machining geometric accuracy in three-axis machining center, and the way to select an appropriate approach in any segment of three-axis CNC machine.

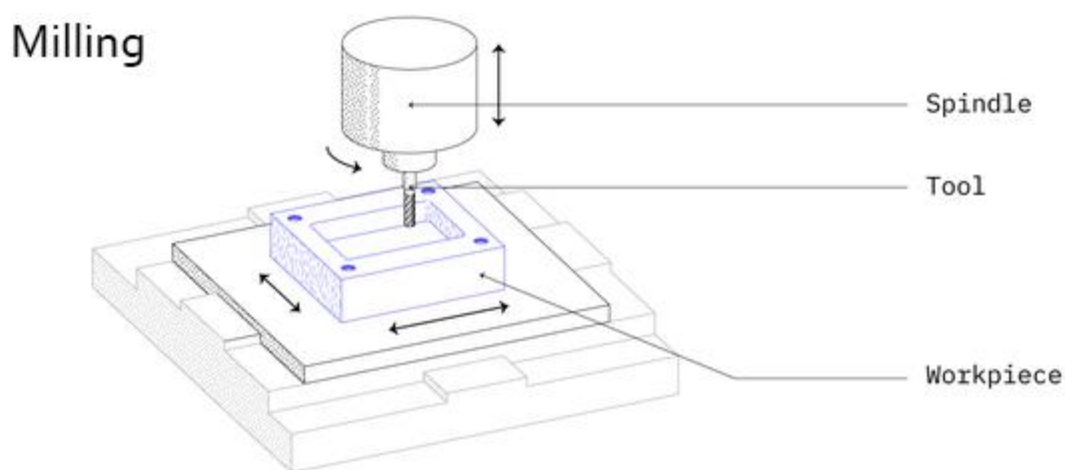

Figure 1. Basic components in CNC machine (Lan, 2019).

2. Geometric Error Fundamental

The 3-axis cutting tools have become increasingly prominent due to their capacity to machine workpieces with complex geometries and high precision, driven by advancements in manufacturing technology (Kiridena and Ferreira, 2013; Xiang, 2019). Geometric errors, which primarily arise from inaccuracies in the machine tool's structural components, are a significant source of imprecision. In vertical machining centers, which operate on three linear axes with simultaneous control of tool movement relative to the workpiece, these errors critically affect performance. The manipulation of each axis adjusts the tool's orientation with respect to the workpiece, and an advanced error model accounts for inaccuracies due to geometric and structural correlations within the machine (Vo, et al., 2017; Shimizu, 2016).

To isolate geometric errors from other sources, quantified errors are analyzed in the frequency domain using Fourier series, enabling the identification and compensation of error frequencies based on their wavelengths. This method reconstructs the error modules for motion control compensation (Hao, et al., 2020). Literature reviews indicate that structural errors in cutting tools, such as defective manufacturing of components, are primary contributors to geometric errors. Specific issues include incorrect fabrication, corrosion, backlash, and collisions between moving axes and the workpiece. Studies, such as those by Rao et al. (Rao, et al., 2016), have developed volumetric error vectors through rigorous frameworks and angular error calculations, highlighting the impact of geometric error models on the precision of machined parts by optimizing tool paths. Additionally, geometric and tool deflection errors have been integrated into the G-Code to generate 3D models of machined parts in virtual environments.

3. Geometric Errors in CNC Machining: Major Problems and Mitigation Methods

Muelaner, Schwenke et.al who is an authority on manufacturing, affirms that for extensive style of errors that can demonstrate within the machined sector. Classified errors as well as being geometric, thermal, feed rate, cutting forces, movement control and manipulate software respectively. Wrong tool dimensions, inadequately preferred cutting parameters, conflicts in quality of workpiece material and inefficient fixturing of the workpiece also disturb to machining accuracy. An axis of motion has four components to its error motion, namely, Component errors, Location errors, and offset errors, have impacted on three-axis CNC machine (Schwenke, et al., 2018; Muelaner, et al., 2020). To identify calibration methodology which delivers significant purpose for executing pursued and rapid machine tool contradiction and calibration methods to improve to quality control in low and high value machining of components (Flynn, et al., 2016). However, this calibration method has also existed to some shortcoming.in which approach need to high algorithm technique that can calculate specific item as tool position in specific purpose, tool motion in random position. Which can improve error of position, but not effectively, sometime occur wrong calculation without automatic calculation system. There is still some considerable controversy surrounding project management that is generally dealt with through noticeably skilled, as like technician. However, there are some weakness that one of the fundamental boundaries in this processing is appropriately classify the connection among product features and cycle time, as well as product errors which are happened through simulation element (Kadir, et al., 2021; Wang, et al., 2020; Möhring, et al., 2020). The three axis CNC milling system errors are implemented with the workpiece, pocket milling. The input in the application is the NC part which is three axis cutting tool. The output in the system is the novel NC application with change in profile as visualize tool path more faithfully causes shut down in cycle time. That was showed in **Figure 2** explaining to machining positioning that is displayed by visual machining software with compensation of errors. in this figure also can explain simulation part that control or edit digital format, as like spindle speed, feed rate, cutting force, tool selection. The can improve surface quality. However, this geometric data has convert NC data that still lose some main features when run in data.

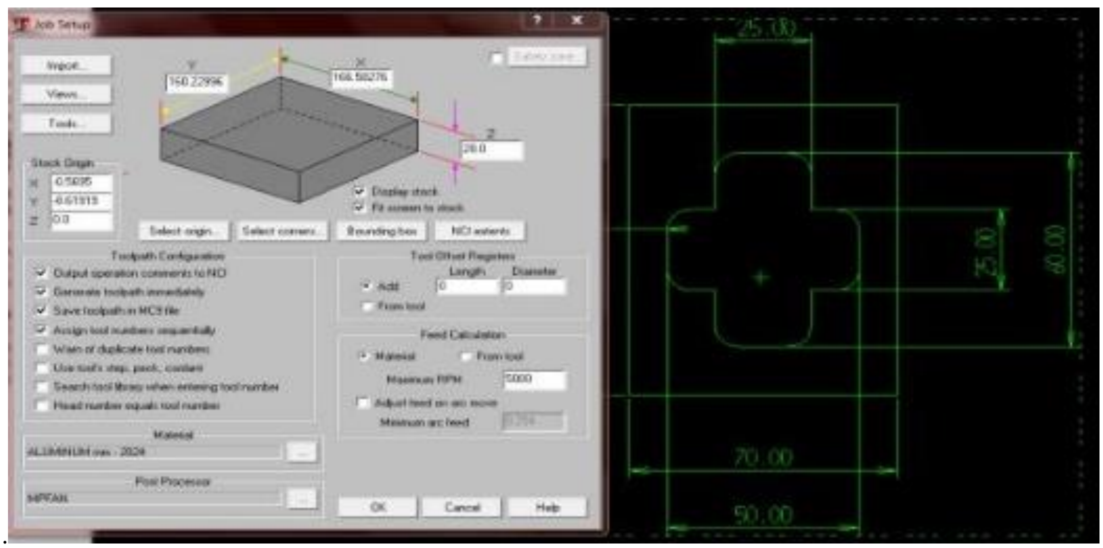

Figure 2. Machining profile with job set up containing geometric errors (Kadir, et al., 2021).

The manufacturing community has raised some issues about enhancement in machine precision for instance, vehicles, spindles, gears, size and control systems so on. Compensation errors for linear and angular positioning have not been avoided until present (Huang and Kong, 2018). On the other hand, Jerzy, Kuric et.al are discussed in systematic errors despite kind of errors namely, geometric, kinematic, and thermal, which may be compensated with accuracy based on the identification (Paweł and Bartosz, 2019; Józwik, et al., 2020). According to the Jozwik (Jozwik, 2019), using vertical machining center DMC 635 in X and Y-axis is high accuracy and efficiency which method measured through transportable laser size machine XL-80, that was showed in **Figure 3**. It illustrated the accuracy and geometry tests achieved on vertical machining DMU 635 with Heidenhain TNC 620 (left) and the testing system using as moveable laser device XL-80 and reserved application that engages with wavelength as a measurement of length (right). **Figure 4** displayed that Y-axis performed the highest accuracy where great achieves for the Y-axis acquired to bi-directional geometric accuracy and bi-directional geometric error is compared with the X-axis and Z-axis. The geometric repeatability is little unexpectable than the Z-axis. The consequence of this experiment in X and Y-axis as compared with other methods show top notch overall performance accuracy. In which the device can improve geometric error more other conventional method, however, this laser hardware most expensive and hard to control with connecting to software, which has some digital error in transfer to between CNC machine and PC computer.

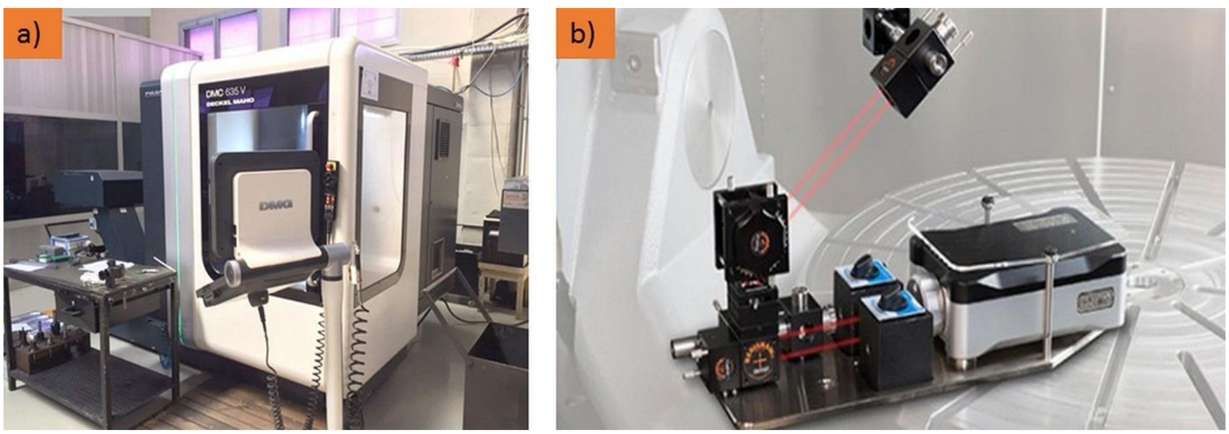

Figure 3. Diagnostic stand during tests: a) vertical machining center DMC 635 b) laser interferometer XL-80 (Jozwik, 2019)

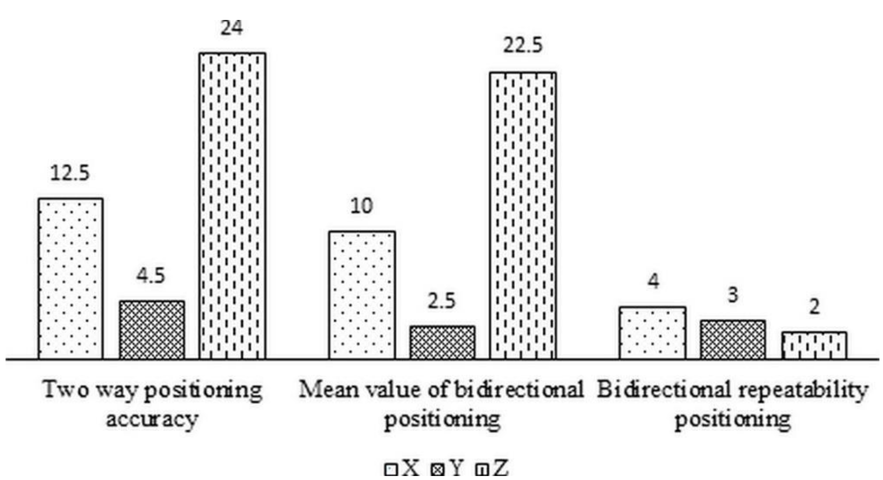

Figure 4. Diagram of positioning accuracy, positioning error, and repeatability in micrometer (Jozwik, 2019)

4. Challenges and Future Development of Geometric Error

When it comes to future work of geometric position, will concentrate on program in machine positioning that may be improved. Every module of parameter and the moving axis in cutting tool is going to influence volumetric errors. New visual program will carry out with machine tool and offset in work piece. Whereas the positioning accuracy will be progressed by either parameter components or cutting of rapid traverse distance in tool axes which impacted on volumetric mistakes (Józwik, et al., 2020). In addition, new syntax design is most effective than controlling by hardware that can dynamically fix to syntax sequence, while digital information also can improve and change when after simulation cutting location data. Such as using to Java script, C++, Python, Java so on. Further experimental investigation is needed to estimate measurement method that can provide a quick dependable platform for studies on measurement and evaluation errors. In additional, derivation of brief evaluation of the entire geometric errors for three-axis cutting tool who consider calibration algorithm of machine positioning that fully assess to kinematic errors in three- axis CNC machine. Further studies will target on correcting a small a part of positioning error. This requires dealing with parts of geometric error. On the other hand, future work on the current topic are therefore suggested to establish for modernizing NC programs, that will be upgraded to correctness on boring and milling part in floor type of heavy-duty CNC machine (Lee and Lin, 2022).

On a wider level, research is also needed to determine compensation machining errors, that concentrate on using numerical compensations, will increase in the future, approximately 50 percentage. That elevated with manufacturing necessity of precision, as well as the high accurateness cutting tools system. Work on modern control system by precision computer that performs to real time compensation exclusive of vibrant working. In addition, 50 percentage compensation will come true through new cutting tool system (Cui, et al., 2022). An important issue to resolve for future studies is novel 3D movement smart sphere or sensor which access to work piece in machine spindle accuracy and efficiency. Furthermore, the prospect of being able to do test for coordinate measuring machines with multi-axis CNC machine is probing base on calibration for original or balance error (Konka, et al., 2020).

Further experimental investigations are needed to estimate laser tracking system or positions that focus on 3D areas fundamental on concept of multi repeat. Further studies aim at progress to high precision in machining and calibration of errors in excessive work piece in machine spindle

(Ibaraki and Knapp, 2022). This research of machining position has raised many questions whether in need of further investigation that new Step diagonal measurement is one of them. According to linear position errors, which will be independently measured by laser beam direction who kind of probing system, and then common error components, for example, straightness and squareness error. this will be measured with new step diagonal measurement who aligns with laser beam direction and nominal direction (Ibaraki, et al., 2022).

In addition, open CNC machine is expected to outperform other, that has some advantages, namely, easy to fix hardware connecting, easy to change geometric position, dynamically connecting to Arnidio control panel, easy to fix probing system and convenient to testing geometric error. This can more reduce time wasting and enhance workpiece quality, and save cost to machine.

5. Fundamental of Simulation in Software

Digital manufacturing has significantly transformed traditional methods, which heavily depended on physical labor, impacting production quality and accuracy. The integration of numerical control programs into automated manufacturing production lines has led to remarkable improvements in productivity, quality, and efficiency. Cutting tools, now governed by computer simulations and material analysis software, achieve higher precision and efficiency while reducing cycle times. Key components of digital production include computer-integrated manufacturing (CIM), computer-aided manufacturing (CAM), design for manufacturing (DFM), and computer-aided design (CAD). The adoption of these technologies has divided manufacturing processes into various specialized functions, each contributing to the overall enhancement of manufacturing capabilities (Ibaraki and Hata, 2018).

Recent advancements in simulation systems have enabled comprehensive testing and analysis of structural components in the production process. CNC simulators, which are cost-effective and user-friendly, facilitate the analysis of tool path motions, thereby improving production quality and productivity. Simulation models are categorized into static, dynamic, continuous, and discrete types, each serving specific analytical purposes. Additionally, simulation software is utilized across various sectors, including product design, process design, and manufacturing resource scheduling (Mourtzis, et al., 2015). The primary significance of simulation software lies in its ability to optimize production lines and design processes, enhancing accuracy and precision. By conducting detailed pre-production analyses, simulation systems identify potential issues, optimize tool paths, and ensure correct component alignment. This leads to reduced errors, improved quality of manufactured parts, decreased cycle times, increased processing efficiency, and lower production costs. CNC simulators, in particular, contribute to surface planning, production scheduling, and assembly verification, addressing manufacturing problems such as system variations and ensuring high precision in production (Cohen, et al., 2019).

6. Focus on Vital Problems and Methods in Simulation Part

When it comes to cutting accuracy in CNC machine, it is one of the vital issues that one needs to pay attention since it impacts production activities. There are several common errors, such as thermal, geometric, cutting force, feed rate and so forth. As well as tool deflection errors have been considerable problem till now and they need to improve by using the cutting edge simulation method. Lin, Kadir, Yao et.al whose authority on CNC manufacturing technique, have been demonstrated that rule library and structure library are developed through virtual cutting tool frame part in CAM structure system. While online virtual cutting tool system in algorithm modeling has offered sufficiently to process of real CNC machine system, 3D workpiece modeling are also expected to position errors in turning machining. However, these methods are not enough to process in common errors (Chryssolouris, et al., 2019; Lin, et al., 2016; Yao, et al., 2016). For example, positioning errors and modeling methodology can promote to producing positioning of novel tool path, and automatic calculate for tool wear and cutting force. **Figure 5** explains the average of the tool wear error in the real practicing with a dialog package. Which software only simulate to tool path and tool feature, but the main cutting location data has not been received or referenced by human interface, while which approach have not more improving federate and cutting force data from NC generating. still using G code have not improving or replacing new schema and format. A growing body of literature has examined complex shape manufacturing, which divided two parts, namely, process schedule and machining. The process schedule has descripted to model in parameter that associated with computer aid design application. And then machining method has operated with computer aid manufacturing. However, the tool path and stock (work piece) need unique condition that should be preserve temperature and cutting force within essential requirement when machine was operating, thus, novel application system must be needed in processing (Merdol, et al., 2018; Wang, et al., 2018). Wojciech has widely investigated the NC code variation software, which is to improve accuracy in productivity, as well as cutting cost and reduce cycle time. If a group of complex shapes is to be manufacture (Zębala and Plaza, 2019). Meanwhile, **Figure 6** displays a flow chart to standard parts of process planning and strategy optimization that is the geometry part, original manufacturing process data, physical process simulation and optimization of control parameters.

In addition, according to the complex shape processing, the surface positioning is machined correctly through the CAM application, whereas, surface quality has acquired feedback from major parameters, for instance, feed rate, cutting force, spindle speed, radial depth so forth. This has impacted on the cycle time and production accuracy (Lavernhe, et al., 2018). Yann et al, suggested that three dimensional topographies of complex machined surfaces which improved scallop length and tool inclination, and then which parameters that are linked to real CNC machine. This result can improve surface quality in complex shape, while shutting down machining time (Quinsat, et al., 2021). **Figure 7** shows (a and b are related to dialog of cutting force measurements) the definition of experimental design. This is a three -dimensional surface model that acquired real measuring data by simulation for several of machining parts. The milling plane taking into account several machining parameters, for instance, machined feed rate, tilt angle and yaw angle. The machining is implemented on three axis machine tools using an end milling tool new tooth for command tool geometry that influences to final part.

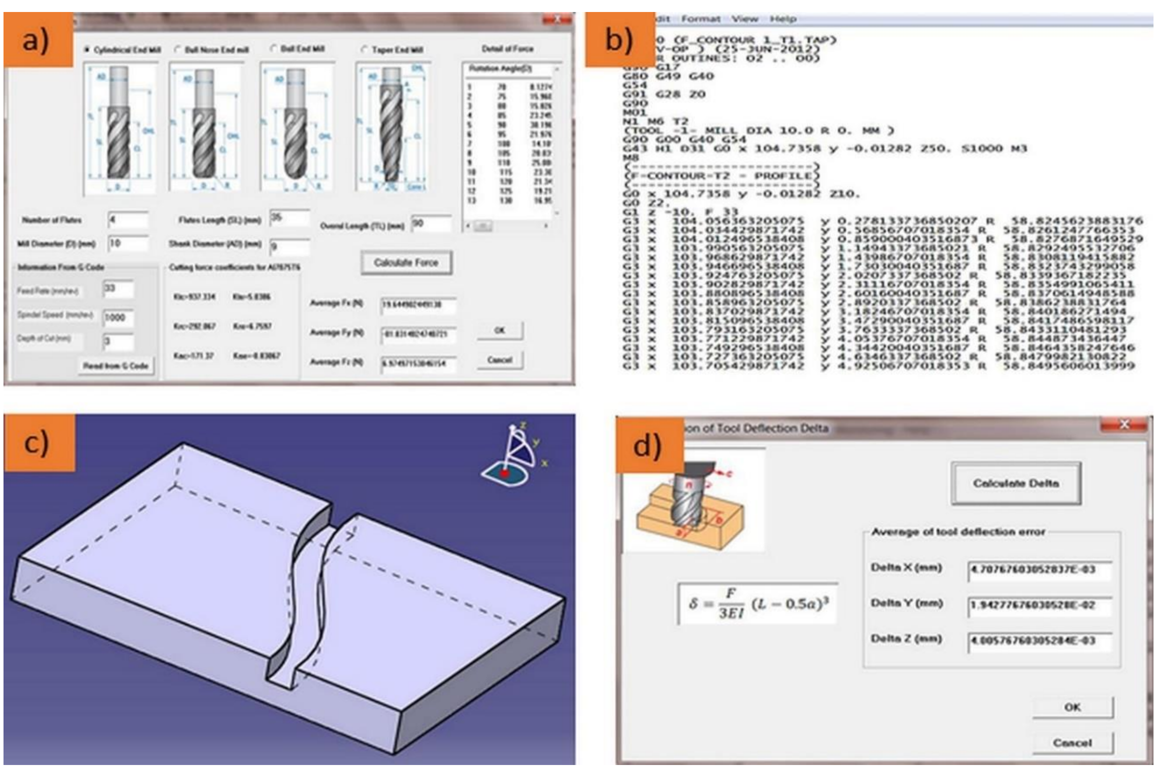

Figure 5. a) Dialog box of cutting force calculator b) Dialog box for tool deflection error calculator c) Profile of the workpiece, d) Error enforced G-Codes produced by the developed software (Chryssolouris, et al., 2019)

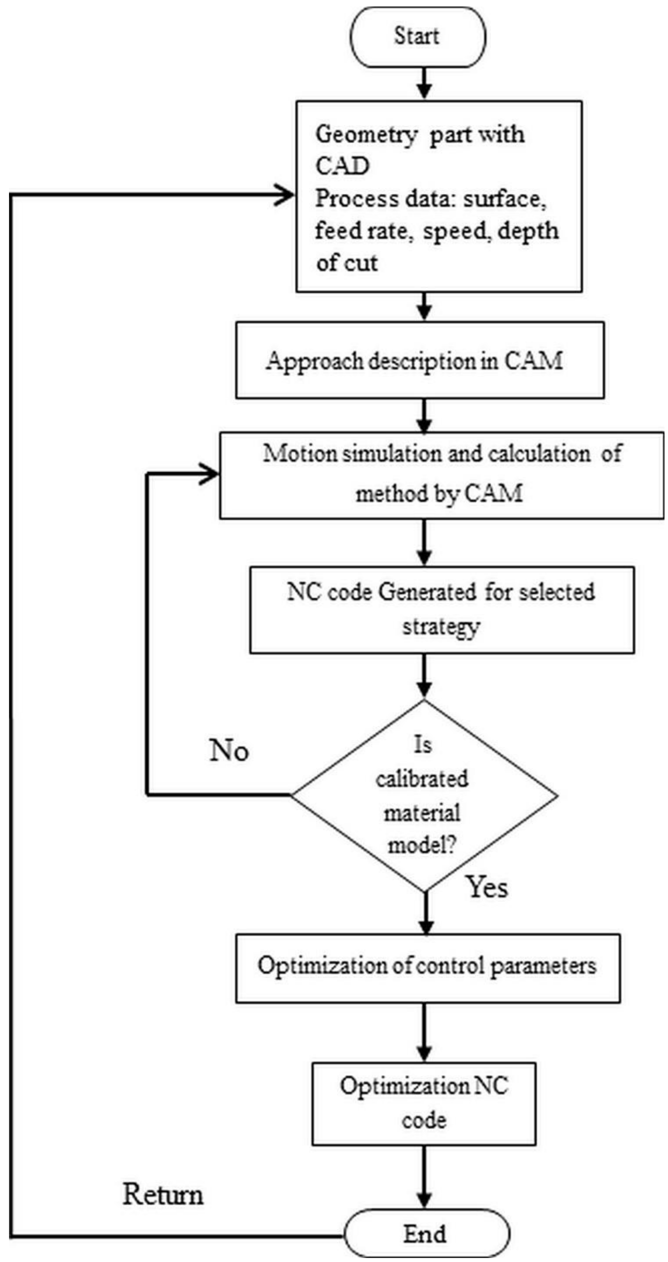

Figure 6. Micro activities in the process planning flow chart (Merdol, et al., 2018)

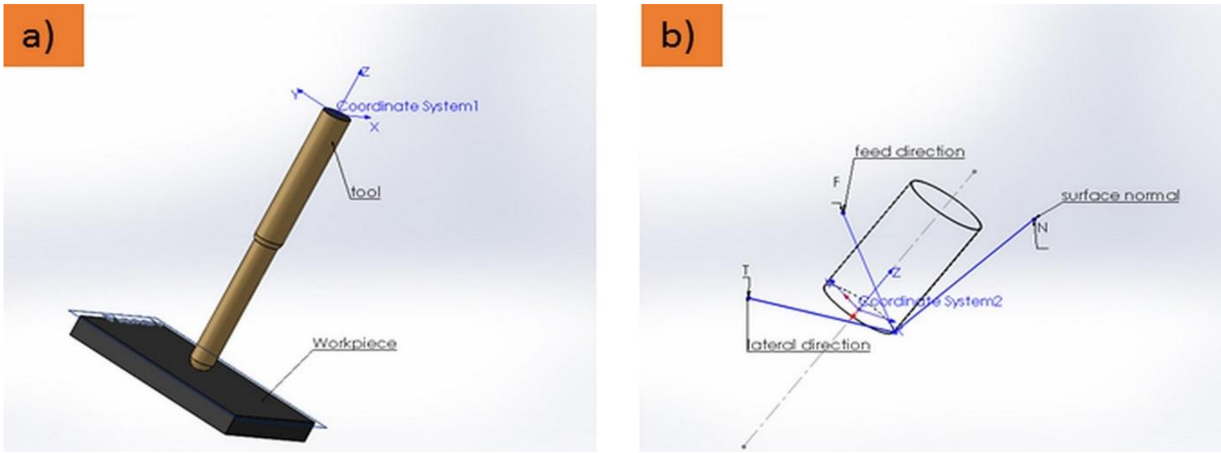

Figure 7. a) Experimental design b) Schematic diagram of the experimental design (Quinsat, et al., 2021)

7. Challenges and Future Development of Simulation

Although the number of manufacturing systems generally improve their own software box, when they reduce time in avoiding damage product in workshop, the numerous application system can perform basic similar function in each other. Further experimental investigations are needed to estimate CG Vericut program that is not only unique application, but also combines CAD and CAM system. This software is using with three-axis and five-axis milling and turning, which exhibited three-dimensional prototype and workpiece, and real manage to toolpath motion as shown in **Figure 8** (Wu, et al., 2022).

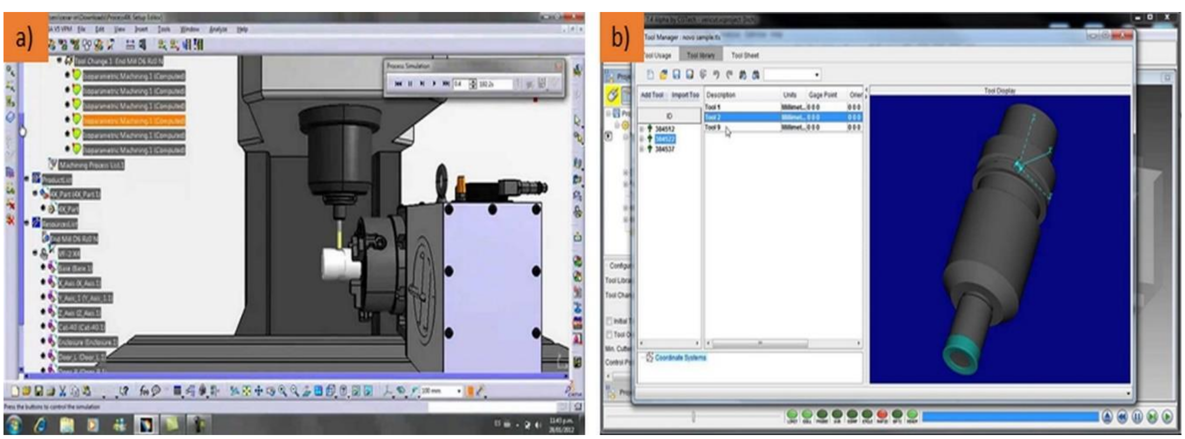

Figure 8. Vericut Version 7.3 a) Simulation b) Tool block to choose proper tool size and path that gives optional tool direction (Wu, et al., 2022)

Future work should concentrate on enhancing the quality of machine sensor, which has been vital role to play in the machining part. Although the sensor system still uses the entire of machine, the sensor device has not yet abled to fully fulfill the needs of the manufacturing system. It has to be made more intelligent, for example, smart probing system, smart detector to stock so forth. The performance speed can be improved and so do the cutting cost and cycle time as shown in **Figure 9.**

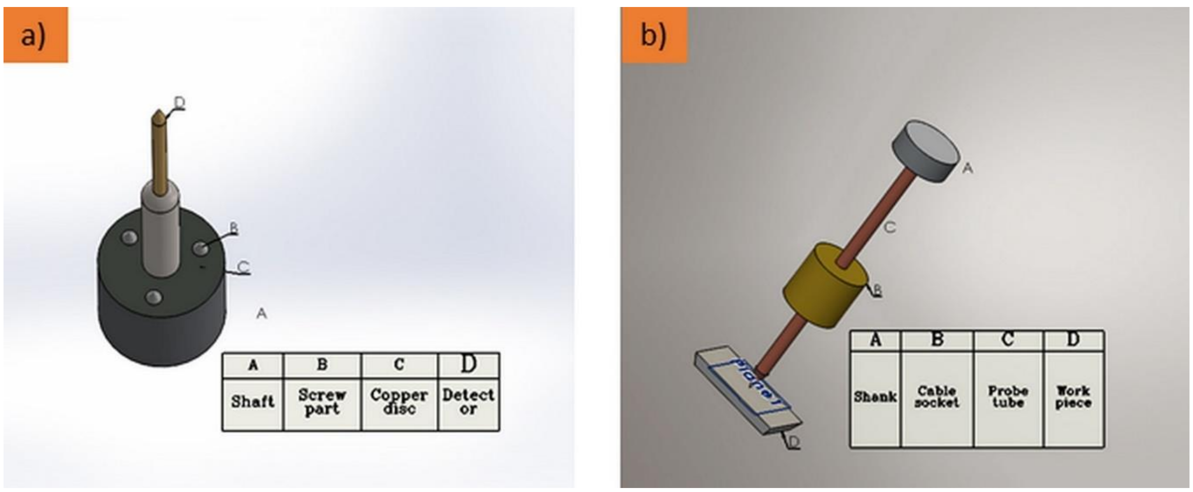

Figure 9. Linux CNC probing

For further studies, the Omative system will need to be undertaken, which needs support by application to control common parameters, for instance, cutting force, feed rate, geometry so forth. And then numerically manage the product's demand, as well as that, this software only fully analyzes the signal variations and is able to autocorrect the cutting motion without operating. On the other hand, this application has eliminated any errors, for instance, geometric, cutting force, and feed rate so on and lead to downgrade the cost of machine and machining time. During the development of the internet system in recent period, big data has been welcomed in whole manufacturing field, especially machine learning which has absorbed the most innovative things from the Internet. According to 'Industry 4.0'drive, numerous assembly has been promoted to own production level or technique level, such as data collection, automatic process, automatic control so forth. This is regularly lauded as 'intelligent plant', as it is an active connection between humans and machines through wireless skills, machining methods of mathematically, robotics which are effect on increasing data interpolation and cutting processing and downgrade machine cost and time consuming. In addition, future studies should target real progressing software that will eliminate some virtual errors, namely, do not displayed removal chips from stock so on. Which tremendous support to operator and student practicing in CNC machine. For instance, the user will be able to enjoy real processing target and fasten deal with common errors and forecast the workpiece motion when user learned this system. The real target software will be replaced to enhanced machine control version 2(EMC2) application system in future.

In the future, STEP-NC machine can replace CAD/CAM, and that machine carry on 3D model in CAM software, and then simulates tool path with cutting location data, finally transfer to STEP postprocessor, and get STEP-NC format in STEP-NC machine. The high -quality protocol that is guaranteed by the bidirectional transfer data system, that can more conveniently transfer data between CNC machine and PC computer. This more effective simulate tool path and feed rate in running same time between CNC machine and STEP-NC machine. This machine focuses more on the 5-axis CNC machine. Unfortunately, this STEP-NC machine has not completely tested by commercial production system in an actual factory.

MTconnecting will consider in several CNC researchers, that carry on more information between PC computer and real CNC machine, in which the transfer of data information is faster when both devices are in the same simulation time. This has more merits, namely, data transfer correctly and realistic, enhancing time saving when both simulating between PC and CNC machine, easy to change federate data depend on real situation, improving tool path generation, reducing geometric error with new schema and syntax.

8. Summary

A review of basic problem for structure and application or software in three-axis CNC machine has reviewed in this paper. When it comes to common errors, for instance, geometric error, feed rate error, cutting force error are highlighted through four main chapter, namely, tool path generation, geometric position, feed rate generation and simulation. In past several decades, number of studies has been investigated these issues and contributed significantly to cutting tool area. Overall, this review paper compares the current with the previous major methods in aspects pertaining to quality, efficiency, and measure. Following as beneath parts:

a) In the geometric generation part, this paper concentrates more on geometric error, and some methods that were carried out in previous, for instance, vertical machining center DMC 635 in laser machine, which has more accuracy in machining system by laser machine. However, the cost of machine is higher than others and more complex to be implemented. After that, some experts have demonstrated calibration methodology that is executed by rapid motion and high value quality. On the other hand, this paper predicted the unique method about visual program, which can eliminate directly geometric errors.

b) In simulation section, It is suggested that the few previous methods that have been carried out by studies, such as, positioning errors and modeling methodology, NC code variation software, three dimensional topographies of complex machined surfaces so forth. Which are all promoted to production quality, machining efficiency, and saving cycle time. Furthermore, this paper mentions future work, for example, CG Vericut program, enhancing the quality of machine sensor, real progressing software so forth. This can improve machining process and machining time, while reduce the cost of machining and complex errors.

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