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# REVIEW OF STRUCTURE AND APPLICATION IN THREE-AXIS CNC MACHINING: ERRORS, TOOL PATH STRATEGIES, AND EFFICIENCY IMPROVEMENTS

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Highlights:

- A significant rise in the use of CNC systems in industries due to the growing demands for rapid production.
- Enhancing the time efficiency and accuracy of CNC machines over the past decade.
- The review covers advanced tool path generation strategies.

**Abstract:** The increasing demands for rapid production have significantly boosted the use of CNC systems in industries. Over the past decade, efforts have concentrated on improving the time efficiency and accuracy of CNC machines. This paper reviews research on CNC machine structures, highlighting common errors such as geometric inaccuracies. It examines advanced tool path generation strategies, including traditional methods and next-generation algorithms like genetic algorithms and the simplex search method. The review assesses these strategies' impacts on machining efficiency and accuracy, comparing current and historical approaches. The objective is to present a comprehensive overview of advancements in CNC machining, contributing to the development of more efficient, precise, and reliable manufacturing technologies.

Keywords: Three-axis CNC machine; Tool path; Geometric error; Numerical coding; Algorithm

## 1. Introduction

Numerical control (NC) system is a computerized machine tool and it worked by means of precisely custom designed summons set up on a trendy convention. Most NC machines are ultra-modern computer numerical controlled (CNC), wherein computer has a primary influence over control (Lan, 2010). The principle NC machines have been worked 5 decades, in view of present tools that has been improved with engines that moved the controls to take after focuses served into the device on squeezed tape. These early servomechanisms had been quick broadened with the simple and superior computer systems, making the cutting-edge CNC machine tools which have modified the machining mechanism (Mukherjee et al., 2014). CNC machines are rapidly supplanting the more established advent machines because of their simplicity of setting, operation, repeatability, and exactness. Those are meant to utilize present day carbide tooling and are greater in quality with modern innovation. The part is designed using CAD (Computer-Aided Design) software, and the tool path is generated through CAM (Computer-Aided Manufacturing) software. This process is controlled digitally by the software, not physically by the engineer. The resulting file is then transferred to the CNC (Computer Numerical Control) machine for manufacturing. After setting and monitoring trials, the machine will maintain on turning out components beneath the sporadic manipulating of an administrator (Moriwaki et al., 2006). With speedy improvement in this industry, special CNC machine makers utilize numerous users, which in a few cases make it troublesome for administrators as they should be educated and updated them. With the production of cheap computer systems, unfastened running system, for instance, Linux and open supply CNC programming, the entire price of CNC machines has dropped (Suresh et al., 2012). In contemporary CNC systems, end-to-end section configuration is much robotized, making use of Computer- Aided Design (CAD) and Computer-Aided Manufacturing (CAM) applications. The applications create a word file that is deciphered to accumulate the codes and is predicted to perform a machine by means of a post processor and later sustained into the CNC cutting tools for generating. Since any module could also expect the utilization of a few equipment or tools – drills, saws, and so forth (Hao & Liu, 2017). The single unit frequently bring together with multiple instruments (tools) in advanced cutting tools. In other apparatuses, exterior of automatic or robotic controller and physical machinists are used through numerous machines that transfer the commands between the machine and others machine. In other hand, singular

CAD design has been fully incorporated to production part and assembly in high precision machine (Pawar et al., 2016).

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.

## 2. Tool Path Generation Fundamental

Initial studies were executed using the conditions described above over crucial territories for instance, tool path planning, tool orientation selection, and choice of tool geometry. Lu et al. (Lu, et al., 2016) has widely investigated tool path planning the use of traditional approaches along with ISO-planar or ISO parametric method. Several studies, for instance, Bobrow, McKay, Zhang, Yuan, Gao et al. (Bobrow et al., 1985; Farouki & Tsai, 2001; Shin & Mckay, 1985; Yuan et al., 2013; Zhang et al., 2012) have carried out the phase space analysis methods, Quan and Tikhon et.al (Bedi et al., 1993; Emami & Arezoo, 2010; Lai et al., 2008; Tikhon et al., 2004; Yang & Kong, 1994; Yeh & Hsu, 2002) performed on direct sampling method, Gasparetto, Sencer, Erkorkmaz et.al (Erkorkmaz & Altintas, 2001; Gasparetto et al., 2012; Sencer et al., 2008) conducted numerical optimization method. The observed increasing in production time could be interpreted as being a result of previous method that achieve certain accuracies, or surface characteristics (Mori et al., 2011). Misra et.al (Misra et al., 2005) reported on a new idea for the pocket milling (zig-zag) tool paths and included that is supported that the tool shifts with a horizontal line in the feed- accelerative direction while strength highlighted that the tool progresses in straight line among two following cutter contact and cutter location points. Cutter location point demonstrates the center of spherical tipped cutter while cutter contact point illustrates the coming together contact of cutter edge and the surface. Kim, Sarma, and Dutta et.al (Huran, 2012; Kim & Choi, 2000; Messier, 1999; Misra et al., 2005; Sarma & Dutta, 1997; Sarma, 1999) calls into question some past hypotheses about accessible CAD/CAM systems for creating cutter location data that require some principal human decisions, for instance, resolving of the precise gap relating to sequential toolpaths.

After the cutter location data is created, which is shown in ***Table*** **1**, that described the simple idea about toolpath generation through sheet data information, it can explain tool motion syntax in post processor, such as linear, circular (clockwise, anticlockwise). An increasing number of

studies, for example, Lo, Ülker, Jimeno et.al (Jimeno et al., 2006; Lo, 2000; Luo et al., 2017; Ülker & Arslan, 2006) have found that cutting tool machine calculates cutter location path via interpolating the cutter direction to movement paths of all axes. The distinction between parameter values is exposed in the identical proportion among the embodied factors at the surface. This permits for extra than essential variety of factors to be produced on the tool path. C. Chen (Chen et al., 2004), an authority on manufacturing and industry, affirms that tool path technology which the consultant schemes for tool path creation follows the principle of ISO-parametric and non-steady parametric. The ISO-parametric tool path creation initiates an ISO-parametric tool path by using for fixing one surface parameter and converting the alternative surface parameter. If reaches the conclusion that the ISO-parametric modus is standard for complex surface machining because the surface data are precisely applied in the tool path creation.

***Table 1.*** *Tool path of basic creation data definitions*

| No. | Item | Basic definition | Symbol |
|---|---|---|---|
| **1** | Cutter contact point | Point which tool connected with the machining surface | Cc |
| **2** | Cutter location point | Tool center location | Cl |
| **3** | Length of feed forward | Distance the tool moves in a single tool travel | L1 |
| **4** | Length of side step | Distance among the two and more parallel tool paths | L2 |
| **5** | Feed forward error | Variation of the tool path from the real machining surface | ɲ |
| **6** | Scallop height | Height of material remove between two clearances of the tool | H |

**2.1 Focus on Vital Problems and Methods in Tool Path Generation**

Oliveira (Oliveira & Diniz, 2009), an expert on cutting tool machine, affirms that the angle among a line cutting to the workpiece surface and the tool axis could be more essential for the machining force additives, if the ball nose end mills are operated, which generate tool deflection. Kecelj (Kecelj et al., 2004) focused on tool shape rather than cutting angle. A additional

problem is that the issue of stock irregularity (roughness) in the finish milling of cavities the usage of long slim tools occurs close to vertical partitions, in which the cutting force is higher and tool deflection contacts the surface roughness and dimensional precision of the workpiece. Research by Neto and Chen et al. (Neto, et al., 2016; Chen, et al., 2005; Jung, et al., 2005) has advanced our understanding of high-speed milling and tool vibration control. Neto's work introduced a novel technique to reduce tool vibration by analyzing the relationship between tool geometry and vibration, identifying three critical regions. Region 1 optimizes tool stability, Region 2 balances radial and cutting forces, and Region 3, with a higher principal angle, increases the risk of tool collision and wear. It is shown in ***Figure* 1**. Meanwhile, Chen and Jung questioned the optimization of finishing techniques and the theoretical prediction of surface roughness. Their study of ball-end mills revealed discrepancies between theoretical and practical outcomes, emphasizing the complexity of achieving the desired surface quality. Together, these studies highlight the importance of precise tool geometry and the limitations of theoretical models in practical machining scenarios. On the other hand, it is key problem with much of the literature on accuracy and efficiency. Few researchers claimed that experiments and result studying approach based on thinking about ball-stop milling that are speculated to have a massive effect on the outcomes acquired are evaluated and measured. However, the drawback of multiplying precise techniques that aren't general (Arizmendi et al., 2008; Saito et al., 2005; Toh, 2004; Vivancos et al., 2004). Chețan (Chețan & Boloș, 2011) tested a novel approach that was showed in **Figure *2***, a test for deciding on the optimal path for a tori tool that dynamic area distributed into 16 segments with different tool paths in according to the finishing method. For a non- analytic surface, the finishing method has an absolute affect to regarding the quality of surface milling. According to this method, the author only explained to finishing part of tool path, that is not completely optimized to tool motion in free form shape, controversy, also occurred to some error for geometry, and difficult to control feed rate in ball milling.

Yoon (Yoon & Shen, 2006) underlined that isolated Simulation approaches are achievable for analysis of all types of discrete tool path systems, from probing to industrialized tool change and cutting lines, and even all the way to connected CNC machine. Heilala (Heilala et al., 2010) reported on a new method for automatic tool change and concluded that uses Simulation-based scheduling and planning tools, which supports a unique set of transactions between memory consumption, computational requirements and accuracy. In this method, also has some shortcoming, complete simulation method can improve time spent, but not perfectly managing with tool direction and feed rate through programing. CNC programming only improves to tool path, however feed rate still relies on hard ware improving, probing system can connect

simulation software when measured to surface parts, but also happen some error through measure, such as dot position, adjusting to objective, wrong receive data through probing so on. the still happens in operation. Hussain and Malhotra et.al (Hussain et al., 2009; Malhotra et al., 2011) have tended to focus on tool path generation that a simple forming tool is organized through means of a cutting machine monitoring a recommended tool path in the incremental forming technique which the sheet metal is plastically deforming into the appealed form. Nevertheless, it's seems to be the most effective by far for small-batch manufacturing because of the slowness of the producing technique. This solution improves on furthers previous methods by Taguchi-based optimization technique. It is mentioned that these four process parameters, for instance, step, feed rate, sheet thickness, and tool diameter which have generally affect to SPIF process (Liu et al., 2014). According to restrained jerk, this has led author such as Zhang (Zhang et al., 2012) to investigate primarily algorithm focused on the hypothesis of velocity limiting surface. However, when the tool path is complex this approach is that the computations is more exhausted to time. On the other hand, Yeh (Yeh & Hsu, 2002) mentioned that consuming a chord errors certain to influence the feed rate if they wanted and operated a regular feed rate in other areas, However, the machine acceleration competencies were not considered. This solution improves on previous methods by polynomial-time algorithms are provided for time-optimal velocity planning of three-axis CNC machining beside every parametric tool path (Fan et al., 2015).

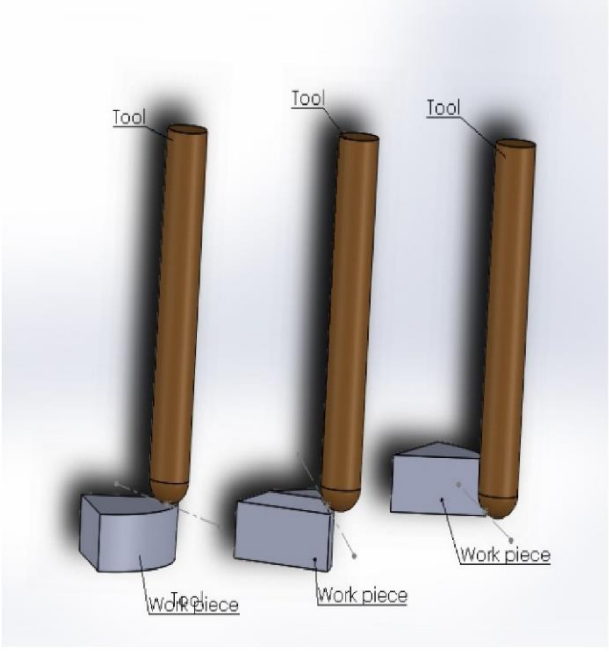


***Figure 1.*** *Tool position in relation to the workpiece along the cutting path*

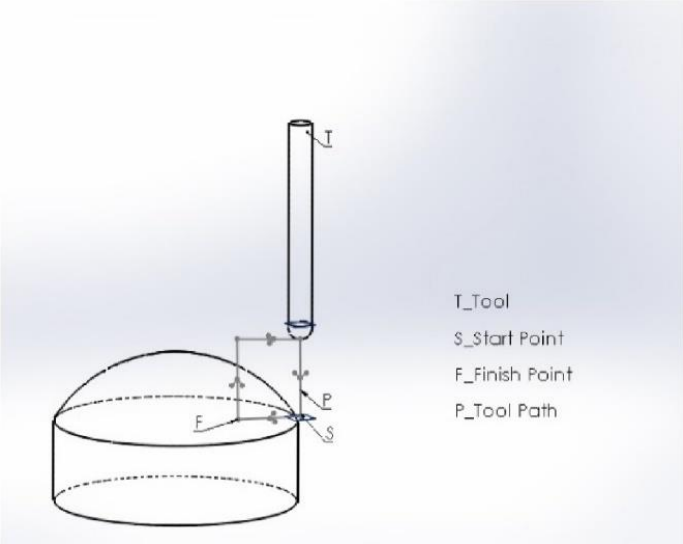


**Figure 2.** Active area divided into 16 sectors with different tool paths

## 2.2 Major Advantages for Exploring Others Type of Tool Path Generation

Incremental sheet forming is a novel suggesting method due to its tractability and the cutting cost tool stuffs as compared with regular forming techniques, for instance, stamping and deep drawing manners. And which outcomes of different system parameters on forming method while proper aggregate and optimization of procedure parameters to expand forming competence and being the best (Jackson & Allwood, 2009; Sarraji et al., 2012). On the other hand, numerical simulation in the tool path which is a popular sheet metal forming procedure can generate the specified tool path definition with right geometric and dimensional accuracy. This is the novel precept for 3-axis tool path planning (Suresh et al., 2013). An additional, the pocket milling, known as zig-zag approach, has been modified manipulate the current strategies accessible and the coding has been enacted in C++language. The software has been verified for plenty of intricate sketches, which includes both concave and convex shapes (Selvaraj & Radhakrishnan, 2006). In addition, programming control also best option in operator, that can convenient to changing toolpath and spindle speed without any hardware control or adjusting, in the real environment, using or making programing has more improving cycle time and deal with suddenly situation, such as tool collision, change tools, change spindle speed so on. Witty, Bieterman, Ibaraki, Lauwers et.al (Witty, et al., 2012; Bieterman, et al., 2010; Ibaraki, et al., 2010; Lauwers, et al., 2006) has put forward own idea of tool path generation that although Various tool path creation methods of plunge milling were mentioned, but no one has judged the radial depth during the milling approaches. Which has an extraordinary impact on the

cutting force and cutter quality. Conversely, an algorithm to create a semi-completing tool path that a regular engagement angle and cutting force is supported through a finishing path at a required level. This obviously improves the geometrical machining accuracy in pocket milling (Guo et al., 2016). An addition, tool path part conversion system is to abbreviate a processing time through individualizing a transition path, namely, a retreat path, a motion path, and a technique path of a tool, which are regularly produced in an automatic way, compatibly to every setting, and optimizing the tool path (Bureau, 2015).

### 2.3 Challenges and Future Development of Tool Path Generation

Few researchers had predicted that further work needs to be performed to establish whether improve the surface best of the component by cutting the quantity of variations located over the sheet surface after optimization, meanwhile, parameters depth and diameter could be constant or taken into regard as a layout variable. In additional, we propose that further research should be undertaken in the following optimization areas are to be experimented along with the genetic algorithm and simplex search method (Mulay, et al., 2017; Gupta, et al., 2019). Dejardin (Dejardin et al., 2010), an expert in manufacturing, which forecast the experimental alterations of the types of formed components in the parts of the process will become important to move future with the purpose to make an industrially correct technology.

Naylor addressed that future work will concentrate on the experiment of ASTM D143-09 which preferred methods for 3 points bending and longitudinal shear can be applied to signify, encompass in wooden power along the again, alternatively, Movement backward evaluation will determine a connection between the amassed cutting force statistics and the obtained mechanical stuffs (Konobrytskyi, 2013; Nasi, et al., 2019) . Further experimental investigations are needed to estimate about multiple implemented tool path planning strategies which will generate imaginable results that would create advanced path planning system on a cluster or cloud wherein every node various technique manipulated for tool path planning. Promotion of identified capabilities will finally replace advance manufacturing absolutely shrink production time and cost (Peters, 2017). Further advancements in tool path simulation will be achieved by representing each particle in Particle Swarm Optimization (PSO) using distinct processing units of a GPU. The advanced computing power provided by the GPU will enable real-time simulation of cutting forces, optimizing tool paths in 5-axis milling [69].

In addition, micro programming also deals with generating tool path. in which design in open source simulator software that can control tool feed rating and changing tool motion with G code format. While people will use to new simulator software such as NX CAM, CATIA V5,

MasterCAM2019, so on. Which are include in some function can design tool path with C++, Java script that creates more real tool path generation to performance real environment. Improving syntax of post processing is new idea that changes with new computer language, namely, Java script, pythen,C++, ISO EXPRESS format so on. Which are interpolate from human interface, and put in CAM software can run. This also more enhance tool path quality.

## 3. Summary

This paper has reviewed fundamental issues in the structure for three-axis CNC machines, emphasizing common errors such as geometric particularly in the context of tool path generation. Over recent decades, extensive research has investigated these challenges, contributing significantly to the cutting tool domain. The review analyzed traditional tool paths, including the ISO standard and zig-zag paths, noting their strengths in ensuring safety when machining complex surfaces but also their weaknesses in terms of time inefficiency. It introduced next-generation tool path planning strategies, such as multiple implemented tool path strategies, genetic algorithms, and the simplex search method, which promise enhanced efficiency and reduced machining time. By comparing current and previous methodologies regarding quality, efficiency, and measurement, the review indicates that advanced algorithmic approaches are pivotal for the future of CNC machining. Future research should prioritize the practical implementation and optimization of these advanced algorithms, comprehensive error analysis, efficiency enhancement, quality improvement, and integration with Industry 4.0 technologies. These directions will advance CNC machining, resulting in more efficient, precise, and high-quality manufacturing processes.

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