Optimization of non-cutting tool paths

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Abstract. The focus of CAM systems is on effectively creating cutting tool paths. However, collision risk is very high on multi axes machines when performing non-cutting traverse moves. If available, CAM systems offer limited setting options for non-cutting tool moves. In this paper an approach is presented that allows to automatically generating non-cutting tool paths. Process planners will not only be released from developing and simulating time-consuming multi axes traverse moves. The automatically calculated traverse moves will also machine-specifically optimized with respect to various optimization criteria.

Introduction

The existing trend of manufacturing complex products with a minimal number of clamping sets leads to the application of multi axes processes. Designing tool paths for multi axes milling processes is a challenge for all process planners. High tech products require a sophisticated process planning chain \cite{1}, Fig. 1.

Whereas in the modern approach workpieces are designed with CAD software (Computer Aided Design), the tool paths for designing the manufacturing process are developed with CAM software (Computer Aided Manufacturing). Essentially, a post processor is needed to translate the tool paths into NC code (or G code) that can be interpreted by the chosen machine tool. Additionally, the manufacturing process can be virtually verified with help of NC simulation software reducing time consuming commissioning and avoiding real-world collisions \cite{2}. These process chain elements are known as the CAD/CAM chain.

The fundamental idea of CAM software was to allow machine independent, but tool oriented path planning. Not until the post processor is applied the tool paths remain machine independent. Since the main focus of process planning is on removing material, the need for machine dependent information is mainly based on accomplishable feeds and speeds \cite{3, 4}.

The application of multi axes processes forces the process planner to enlarge the focus to enabling collision free repositioning moves which causes high additional effort: Nowadays CAM tools do not offer either sufficient support for adjusting non-cutting tool paths with mixed tool orientations. Nor offer these tools an automatic optimization since kinematic constraints and motion information are not available at that stage.

Multi axes machines use different machine axes realizing translational and rotary movements connected by a kinematic tree. Furthermore, rotary axes generally have a worse dynamic
performance. In order to gain machining performance machine-specific information has to be taken into account into the path planning process [5, 6, 7].

The aim is to enabling automatically generated collision-free as well as machine-specific optimized multi axes traverse moves. Also aiming at a simplified utilization the solution will be aligned along the existing tool path development process. The kinematic tree of a machine tool combined with the dynamic characteristics of the machine axes represents a complex traverse problem that cannot easily be solved.

Solution Approach

In the following the chosen approach is presented to meet the defined aims. For the purpose of simplification the travelling salesman problem (TSP) was chosen to solve the multi axes machining optimization task. The travelling salesman problem is a well known real-world challenge in computer science [8]: Supposing a salesman, who has to visit several cities, the challenge is to find the best path. If each city is visited only once this tour is admissible. The so-called state search space $S$ contains all admissible tours. Referring to the salesman problem the challenge is to optimize the distance $\delta$ of an admissible tour. Thus, the aim is to find the minimum cost $g_0$.

\[ g_0 = \min \delta_S. \]  

The TSP suits as a test-bed for new algorithms where a good performance on the TSP is often taken as a proof of an algorithm’s usefulness. Many algorithms have been developed that are able to effectively solve the TSP. Thus, the challenge is to reduce a complex real-world problem to a plain TSP representation. Heuristic algorithms have already been applied to real-world machining problems with different optimization criteria [9, 10, 11, 12, 13].

Despite this, algorithms referring to multi axes traverse path minimization have not been researched yet. The chosen optimization procedure is given in Fig. 2. It depicts the optimization alignment along the CAM path planning process chain.

![Fig. 2: General optimization procedure implemented into CAM](image)

The process planner should concentrate on the development of cutting tool paths. Therefore, the automatic optimization of non-cutting tool paths is intended to start right before the post processor activation. The automatic optimization takes just a few input parameters. Whereas the kinematic tree is fundamental for machine-specific optimization, further information as dynamics, power consumption etc. can enhance the optimization focus. The last input parameter assigns the algorithm to solve the TSP representation. For this purpose several algorithms have been implemented (simulated annealing, genetic algorithm, ant colony optimization).
At the current development state the optimization criteria is focused on optimizing the sum of single machine axis moves with respect to the achievable feed rate.

**Application and Validation**

In order to examine the chosen approach a complex test part has been developed the meets the requirement of inducing many traverse paths. For examination and verification purposes a real five axes machine tool was used.

Since the focus is on non-cutting movements an appropriate test part should contain a sufficient number of repositioning tasks.

Furthermore, the machining tasks should not distort the optimization result. For this reason, a test part containing simple drilling operations has been developed (Fig. 3). Within the given dimensions 196 drilling points with 153 different tool orientations have been designed. It is approved, that all drilling positions can be reached without any collisions.

The vast quantity of drilling points avoids that the task can be solved by a human process planner effectively. In Fig. 4, the result of the human approach is shown: Starting from the lowermost left corner the planner decided to operate all drilling points in regular sequence. It seems obvious that the task can be better solved by a heuristic algorithm. But, solving the TSP at this stage will only reduce the relative tool moves.
Aiming at reducing machine axes moves as well as traverse time the approach requires including machine kinematics into TSP optimization.

In Fig. 5 the five axis machine tool is shown that has been used for testing. The machine has three translational axes (X, Y, Z) and two rotary axes (A, C) where the spindle moves along the X and the Y axis. Both rotary axes are connected to the Z axis. Due to the given kinematic configuration a small rotary movement causes a large compensation motion of the translational axes.

Thus, the vast amount of different test part drill orientations causes this machine to process many machine compensation moves. It follows from the machine tool properties in Table 1 that if traversing simultaneously with 5 axes the C axis restricts the maximal speed of tool moves.

<table>
<thead>
<tr>
<th>Axis</th>
<th>Distance</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>1,250mm</td>
<td>60,000mm/min</td>
</tr>
<tr>
<td>Y</td>
<td>1,000mm</td>
<td>60,000mm/min</td>
</tr>
<tr>
<td>Z</td>
<td>1,200mm</td>
<td>60,000mm/min</td>
</tr>
<tr>
<td>A</td>
<td>-25° to +120°</td>
<td>12,600°/min</td>
</tr>
<tr>
<td>C</td>
<td>n·360°</td>
<td>7,200°/min</td>
</tr>
</tbody>
</table>

The result of the non-cutting tool path optimization of the test workpiece is shown in Fig. 6.
In this case the simulated annealing algorithm was chosen to solve the TSP representation. In contrast to Fig. 4 the displayed tool path is much longer. Without having the machine axes’ moves visualized the result seems rather confusing. In Table 2 the change of axes moves after optimization is shown for each machine axis individually.

Table 1: Change of machine axis moves after optimization

<table>
<thead>
<tr>
<th>Axis</th>
<th>$I$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>-17.1</td>
</tr>
<tr>
<td>Y</td>
<td>-24.7</td>
</tr>
<tr>
<td>Z</td>
<td>-38.4</td>
</tr>
<tr>
<td>A</td>
<td>-59.3</td>
</tr>
<tr>
<td>C</td>
<td>-79.1</td>
</tr>
</tbody>
</table>

It follows that in comparison to Fig. 4 all machine axis moves have been reduced. First and foremost, the slowest rotary C axis moves has been reduced by 79.1%. Using the example of the C axis the density distribution of single move distances in Fig. 7 shows that the optimization algorithm reduced the number of long distance moves.

The verification of the tool paths on the real machine resulted in shortening of traverse time from 5.8 min to 3.5 min (39%). The presented approach offers to change the optimization criteria by adding weights or change given parameters. This provides new application areas. For example, in case of a machine tool axis damage the aim should be to maintain machining whereas unnecessary stress to this axis should be avoided.
Table 3: Machine axes moves change after single machine axes slowdown

<table>
<thead>
<tr>
<th></th>
<th>lx [%]</th>
<th>ly [%]</th>
<th>lz [%]</th>
<th>la [%]</th>
<th>lc [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1%</td>
<td>-70.2</td>
<td>72.1</td>
<td>62.1</td>
<td>85.7</td>
<td>56.6</td>
</tr>
<tr>
<td>Y1%</td>
<td>60.3</td>
<td>-49.4</td>
<td>-24.3</td>
<td>-10.4</td>
<td>40.0</td>
</tr>
<tr>
<td>Z1%</td>
<td>34.8</td>
<td>-22.4</td>
<td>-65.9</td>
<td>-37.8</td>
<td>58.3</td>
</tr>
<tr>
<td>A1%</td>
<td>24.7</td>
<td>4.2</td>
<td>-22.4</td>
<td>-91.5</td>
<td>25.2</td>
</tr>
<tr>
<td>C1%</td>
<td>-15.1</td>
<td>-15.4</td>
<td>-18.8</td>
<td>-26.1</td>
<td>-92.0</td>
</tr>
</tbody>
</table>

In Table 3, the optimization results are shown after changing the maximum speed of one axis to 1% of the original value (Table 1). Assuming the maximum speed of machine tool X axis is limited to 1% of the original value, the X axis moves will be reduced by 70.2% whereas all other machine tool axis will travel a longer distance.

Conclusion and Outlook

The presented approach enables process planners to automatically develop collision free non-cutting tool paths optimized for a particular machine. Due to the alignment right before the post process procedure the process planner can concentrate on developing cutting tool paths while the approach fits straightforward to the CAD/CAM chain. A workpiece has been developed that meets the requirements to be used as a test-bed for optimizing non-cutting tool paths for multi axes machining. The validation of the optimization approach resulted in a massive reduction of machine axes moves and in the shortening of traverse time. This leads to a reduction of secondary time and to a higher productivity. The implementation of the machine properties acceleration and jerk will lead to more detailed results of traverse time. The implementation of further machine properties as for example power consumption can lead to energetically optimized machining processes.

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References


