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Improvement of the dynamic behavior of machine tools by geometrical optimization of the machine tool axes movement

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Abstract— A new approach for the geometrical optimization of five-axis-movement is presented in this paper. Regarding a five-axis-movement with large tolerances for lead and tilt-angle for example in the case of laser-cutting there are endless ways of generating motions without violating the orientation-tolerances. By regarding the movement of the involved axes it is shown that for a given 5-axis trajectory and given tolerances there exists an optimal motion with a minimal amount of mechanical excitation of the machine-tool within the tolerances. The trajectory is described by quintic non uniform rational B-splines (NURBS). The decrease of mechanical excitation is exemplified by the use of a simplified machine-model.

I. INTRODUCTION

The performance of machine-tools is given by the machining accuracy and the chosen feed-rate along the tool-path. The accuracy is directly influenced by the mechanical excitation of the machine caused by the movement of the axes. Neglecting the problems of collisions and surface properties one important topic in the field of feed-rate-generation is the geometrical optimization of the tool path. Especially 5-axis-machining with large tolerances for tool-orientation offers space for optimization because of the arising quasi-redundant degrees of freedom of the rotational axes. Regarding the movement in the Machine-Coordinate-System (MCS) there are endless ways of possible movements without violating the orientation tolerances. Taking in to account that the main part of the mechanical excitation of the machine tool is caused by the MCS-movement an optimization of this movement should lead to less excitation, a better machining accuracy, a higher feed-rate and finally higher machining-performance.

In literature, several publications deal with the geometrical optimization of the motion. By considering the drive-constraints [1] showed an approach for the smoothing of 5-axis tool paths in order to maximize the resulting real feed-rate and to reduce the machining time by local smoothing of single axes movements. With the focus on high-speed machining, in which the rotary actuators tend to have limited dynamic abilities [2] pointed out how to generate a tool path so that the maximal angular accelerations of the rotary axes of the five-axis machine can be reduced. Publication [3] optimized tool trajectories and their follow-up during machining by orientation smoothing while ensuring the geometrical conformity of the machined part. The optimization is performed using a surface model for both the tool path and the orientation with the focus on finding the best orientations so that kinematic performances of the axes are optimized. Reference [4] introduced the domain of admissible orientations (DAO). By the use of inverse kinematics the MCS-Trajectory is optimized while ensuring quality constraints at the tool-center–point. This procedure is shown at the example of a 5-axis milling machine with the focus on collision avoidance and time reduction.

All these approaches deal with the optimization of the tool paths of milling-machines with very small orientation tolerances, so there are no resulting quasi redundant degrees of freedom. Quasi redundancy shall denote the situation that motions of the Tool Center Point (TCP) can be realized by a use of more than a single machine axis. As example, a tangential component of motion in x- or y-direction of a swiveling b-axis shall be regarded.

Redundancy is an important topic for robotic researchers. At the example of a 7-axis machine tool of Fiber Placement machine tool [5] demonstrated the reducing of the manufacturing time while ensuring the quality of the final part by taking advantage of the redundant degrees of
freedom. In this paper [5], two methods are combined. In a first step the kinematic loads on the control joints are minimized by taking advantage of the redundant degrees of freedom. In a second step the tool-orientation is optimized within the DAO. For the optimization of the joint trajectories of an industrial robot with redundant degrees of freedom a generic approach is presented in [6]. Calling a kinematic and dynamic simulation model of the robot the total work for the motion is minimized. An example of the optimization of the tool path of a machine tool with redundant degrees of freedom is shown in [7]. By the use of redundancy the energy consumption of machine tools can considerably be reduced. This is done by minimizing a cost-function based on the energy which is calculated by a full electro-mechanical model of the regarded machine-tool.

This paper shows that by the geometrical optimization of the orientation along the whole tool path the mechanical excitation of a machine-tool can be reduced significantly. The further sections of the paper are organized as follows: the orientation smoothing is described in section II. A simple test geometry is presented which is a typical motion for Laser-Cutting. Furthermore the mathematical representation of the geometry and a simple optimization algorithm are described. The feed-rate along the geometry is simulated using a virtual NC-Kernel (VNCK). The resulting feed-rate for different kinds of smoothing is shown in section III. In order to show the decrease of mechanical excitation a planar elastomechanic machine-model is introduced in section IV. After simulating the feed-rate along the previously smoothed tool path with the feed rate values generated by the VNCK the resulting forces and oscillations are simulated using the model. This is done for the different kinds of smoothing and is later discussed in a comparative way in section V. Finally the conclusions are summarized in section VI.

II. ORIENTATION SMOOTHING

A. Test geometry

A very simple but anyhow quite illustrative 2D geometric example for the orientation smoothing is the C-Rotation in combination with x- and y-axis movements is shown in Fig. 1. In the field of laser cutting this trajectory is an important movement in order to avoid collisions with the work piece. It consists of 3 linear movements of the TCP in x-direction. The c-axis turns 180° degrees during the second linear consecutive movement of the x-axis (Fig. 2). The MCS-trajectory consisting of $x_{MCS}$ and $y_{MCS}$ (Fig. 3) arises from

\[ x_{MCS} = x_{TCP} + \Delta c \cdot \sin(c_{TCP}) \]  
\[ y_{MCS} = y_{TCP} - \Delta c \cdot \cos(c_{TCP}). \]  

Points of interest are the two transitions between the three linear movements of the TCP in x-direction where the additional movement of the c-axis starts respectively stops as shown in Fig. 2. At these transition zones the resulting curvature of the MCS-trajectory becomes discontinuous. Especially the second transition will lead to a high mechanical excitation because the x-axis has to turn its direction (Fig. 3) which leads to a low feed at this point as will be shown in section IV. Because it is a 2D geometry the orientation tolerance can be neglected here. For 3D orientation smoothing the DAO should be considered as an additional constraint.

\[ f(x) = a_0 x^0 + a_1 x^1 + \ldots + a_p x^p. \]  

Figure 1. Test geometry “C-Rotation”

B. Mathematical representation

Both, the x- and the c-axis are represented by piecewise polynomial functions which are connected C₂ continuously at their breakpoints. The polynomial functions for the x-axis are linear; the function for the c-axis is quintic. Assuming that a $p^{th}$-degree polynomial function

\[ f(x) = a_ix^i + a_{i-1}x^{i-1} + \ldots + a_0 \]  

shall be defined by $p+1$ parameters,
the x- and c-axis the MCS-trajectory is also C
and the objective function for the smoothing algori
thm are known as parametric speed,
\( (5) \) contains the parametric derivatives of (1) and (2), which
are known as parametric speed,
\[ x'_{\text{MCS}} = x'_{\text{TCP}} + \Delta c \cdot \cos (c_{\text{TCP}}) \cdot c'_{\text{TCP}} \]  
(6)

\[ y'_{\text{MCS}} = y'_{\text{TCP}} + \Delta c \cdot \sin (c_{\text{TCP}}) \cdot c'_{\text{TCP}} \]  
(7)

\( \text{parametric acceleration} \)
\[ x''_{\text{MCS}} = x''_{\text{TCP}} + \Delta c \cdot \cos (c_{\text{TCP}}) \cdot c''_{\text{TCP}} - \Delta c \cdot \sin (c_{\text{TCP}}) \cdot c'_{\text{TCP}}^2 \]  
(8)
\[ y''_{\text{MCS}} = y''_{\text{TCP}} + \Delta c \cdot \cos (c_{\text{TCP}}) \cdot c''_{\text{TCP}} + \Delta c \cdot \sin (c_{\text{TCP}}) \cdot c'_{\text{TCP}}^2 \]  
(9)

\( \text{and parametric jerk} \)
\[ x'''_{\text{MCS}} = x'''_{\text{TCP}} + \Delta c \cdot \cos (c_{\text{TCP}}) \cdot (c'''_{\text{TCP}} - c''_{\text{TCP}}^3) - \Delta c \cdot 3 \cdot \sin (c_{\text{TCP}}) \cdot c'_{\text{TCP}} c''_{\text{TCP}} \]  
\[ y'''_{\text{MCS}} = y'''_{\text{TCP}} + \Delta c \cdot \sin (c_{\text{TCP}}) \cdot (c'''_{\text{TCP}} - c''_{\text{TCP}}^3) + \Delta c \cdot 3 \cdot \cos (c_{\text{TCP}}) \cdot c'_{\text{TCP}} c''_{\text{TCP}} \]  
(10)

(10) contains the parametric derivatives of (1) and (2), which
are known as parametric speed,
\[ y'_{\text{MCS}} = y'_{\text{TCP}} + \Delta c \cdot \sin (c_{\text{TCP}}) \cdot c'_{\text{TCP}} \]  
(7)

\( \text{parametric acceleration} \)
\[ x''_{\text{MCS}} = x''_{\text{TCP}} + \Delta c \cdot \cos (c_{\text{TCP}}) \cdot c''_{\text{TCP}} - \Delta c \cdot \sin (c_{\text{TCP}}) \cdot c'_{\text{TCP}}^2 \]  
(8)
\[ y''_{\text{MCS}} = y''_{\text{TCP}} + \Delta c \cdot \cos (c_{\text{TCP}}) \cdot c''_{\text{TCP}} + \Delta c \cdot \sin (c_{\text{TCP}}) \cdot c'_{\text{TCP}}^2 \]  
(9)

of the different axes. Because of the linear movement at the
TCP of the regarded geometry the parametric derivatives of
\( x_{\text{TCP}} \) and \( y_{\text{TCP}} \) vanish so the contributors of the cost function
are only affected by \( c_{\text{TCP}} \), \( c'_{\text{TCP}} \), \( c''_{\text{TCP}} \) and \( c'''_{\text{TCP}} \). So
minimizing the cost function leads to the parameters of the
polynomial function which describes the movement of the c-
axis for which the resulting curvature rate of the MCS-
trajectory is minimal. For additional optimization the
parametric derivatives of the different axes can be weighted
proportional to the different inertias of the axes which is not
regarded in this work.

The optimization is done with MATLAB® using fminsearch
for finding a minimum of a nonlinear unconstraint objective
function. In order not to suffer from local minima the
optimization is done with varying starting points. For a 3D
orientation smoothing the DAO should be included as a
penalty function or a nonlinear constraint.

III. FEED-RATE SIMULATION

After optimization using the objective function the
parametric functions of the x- and c-axis are converted into
NC-Code in order to simulate the feed rate along the
smoothed tool path with the VNCK. The VNCK is an image
of the control unit of a real laser-cutting machine tool without
the closed loop controller for experimental analysis of the set
points. Outputs of the VNCK are vectors for the machining
time and the values for the axes for a given geometry. In
order to show the decrease of mechanical excitation the feed
rates of the following trajectories are simulated:

- Without C-Rotation smoothing (“default NC”)
- C-Rotation with local smoothing of the transitions
  with polynomial functions by using a commercial
  smoothing algorithm which is embedded in the
  VNCK
- C-Rotation with global smoothing with the above
described smoothing algorithm (“IWF-Splines”)

\[ K = \frac{x'_{\text{MCS}} y'_{\text{MCS}} - y'_{\text{MCS}} x'_{\text{MCS}}}{\sqrt{x'_{\text{MCS}}^2 + y'_{\text{MCS}}^2}} \]  
(4)

of a given trajectory is proportional to the force perpendicular
to the trajectory, a C2 continuous MCS-trajectory and a
minimal amount of curvature rate should decrease the
mechanical excitations of the machine tool. Because of the
C2-continuous formulation of the polynomial functions for
the x- and the c-axis the MCS-trajectory is also C2 continuous
and the objective function for the smoothing algorithm
consists of the curvature rate of the MCS-trajectory

\[ K' = \frac{-3 (y''_{\text{MCS}} x'_{\text{MCS}} - x''_{\text{MCS}} y'_{\text{MCS}}) (x_{\text{MCS}} x'_{\text{MCS}} + y_{\text{MCS}} y'_{\text{MCS}})}{\left( x'_{\text{MCS}}^2 + y'_{\text{MCS}}^2 \right)^{3/2}} \]  
(5)

(5) contains the parametric derivatives of (1) and (2), which
are known as parametric speed,

\[ x'_{\text{MCS}} = x'_{\text{TCP}} + \Delta c \cdot \cos (c_{\text{TCP}}) \cdot c'_{\text{TCP}} \]  
(6)
Fig. 4 shows the resulting TCP- and MCS-trajectories. In the upper right corner of the figure the turning point of the x-axis is visible which has obviously less curvature than the C-Rotation with a local smoothing of the transitions.

Fig. 5 and Fig. 6 show the feed rate along the TCP- and MCS-path obtained from the VNCK. Both the C-Rotation with- and without a local orientation smoothing have two considerably velocity collapses and a significantly longer MCS-path than the C-Rotation with a global orientation smoothing. Fig. 7 shows the movement of the c-axis along the tool path. Obviously the movement which results from the optimization is smoothed along the whole tool path while ensuring the boundary conditions.

In order to simulate the resulting forces and vibrations resulting from the simulated feed rate a machine-model is introduced in the following section.

IV. MACHINE MODEL

For getting an estimate about the resulting TCP trajectories, when applying the set point values discussed above on an elasto-mechanic machine structure the following machine model was used:

A. Structural Model

The machine is represented by a planar model of rigid bodies: x-slider, y-slider, c-axis body. The use of a rigid body model is possible, because in the frequency range of the movement loads, shifts primarily take place in the coupling locations [8]. The bodies are connected by visko-elastic elements representing the properties of the guideways and the rotary (c-) bearing. A schematic overview of the system is given in Fig. 8. The center of mass of the c-axis is not located in the center of rotation of the c-axis. By this, additional influences between the c- and the x- and y-axis are caused, which influence the overall behavior.
As inputs for the state-space representation the drive-forces/torque is used. As outputs, the relative motions at the reader head locations are generated. The configuration dependent stiffness and damping matrices of the corresponding state-space representation get updated during the simulation using Matlab/Simulink®. Due to the small model size (18 states in total), the simulation times for the movements under investigation are quite moderate.

B. Drive-/Control Model

For the control of the three drives, a cascaded PPI-control scheme with velocity feed-forward is used. The low-pass behavior of the drive is represented by a corresponding time-constant of 2 ms including the current control and the actual force/torque generation.

V. RESULTS

When the machine excitation is regarded, firstly the drive forces should be analyzed. These loads are due to set-point values in combination with the control scheme applied. As additional factors the location of the feed-back systems and the interaction between the frequency content of the set-point values and the characteristics of the plant lead to the resulting behavior. In this case, the means to improve the system behavior such as (velocity-) set-point filters, force feed-forward have not been applied for simplicity.

A. Set-point-TCP-trajectories

Already in the initial set-point TCP paths, the differences between the three variants are noticeable: The default NC and the additional NC-option lead to comparable paths, the IWF-Spline cause a slightly, “smoother” TCP-path geometry which is shown in Fig. 9.

B. Drive loads

Regarding the drive loads, which act as structural excitations, a comparison of the three variants leads to the following conclusions:

- For the X-forces (Fig.10), the shortening of the paths and therefore a reduction of the duration and a smaller amplitude for IWF variant are noticeable.
- For the Y-forces (Fig.11), the maxima of the IWF-variant are significantly reduced. Surprisingly, at 1sec. the forces show a strong discontinuity.
- The C-torque (Fig.12) again can strongly be reduced for the IWF variant in this case. The high absolute maxima shall be limited using the actual limits.

C. Resulting TCP trajectories

The TCP paths (Fig.13) caused by the MCS motions of the drives and transformed by the inverse of eqs. (1) + (2) show similarities for the two NC-versions and a reduced max. path deviation for the IWF-variant. The discontinuities at 1sec. (Fig.11) also appear here at 0.15m x-coordinate.
VI. CONCLUSIONS

The comparison of three different set-point trajectories for the nominally identical movement shows great potential for the smoothing of path geometries. The benefits that can be gained are a reduced machine excitation combined with a higher feed-rate. The prerequisite for these benefits are the availability of large path- and orientation tolerances, which may not be given in the case of mold and die machining, but can be the case for laser cutting. Next steps should be the inclusion of the DAO in order to optimize 3D-trajectories. The optimization criterion actually consists only of the curve rate. The inclusion of the drive should finally lead to a further reduced mechanical excitation.

VII. REFERENCES