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A physically-based model for global collision avoidance in 5-axis point milling☆

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HIGHLIGHTS

- A new approach is proposed for collision avoidance in 5-axis end milling.
- The method is based on a physical modeling to compute the tool axis orientation.
- The ball-end tool is considered as a rigid body moving in 3D space.
- Repulsive forces are deriving from a scalar potential linked to check surfaces.
- Check surfaces tessellation ensures smooth variations of the tool axis orientation.

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ABSTRACT

Although 5-axis free form surface machining is commonly proposed in CAD/CAM software, several issues still need to be addressed and especially collision avoidance between the tool and the part. Indeed, advanced user skills are often required to define smooth tool axis orientations along the tool path in high speed machining. In the literature, the problem of collision avoidance is mainly treated as an iterative process based on local and global collision tests with a geometrical method. In this paper, an innovative method based on physical modeling is used to generate 5-axis collision-free smooth tool paths. In the proposed approach, the ball-end tool is considered as a rigid body moving in the 3D space on which repulsive forces, deriving from a scalar potential field attached to the check surfaces, and attractive forces are acting. A study of the check surface tessellation is carried out to ensure smooth variations of the tool axis orientation. The proposed algorithm is applied to open pocket parts such as an impeller to emphasize the effectiveness of this method to avoid collision.

1. Introduction

5-axis surface machining is an essential process in the field of aerospace, molds and dies industries. 5-axis milling is required for the realization of difficult parts such as blades and impellers and is also very convenient to improve quality for the machining of deep molds in plastic injection and casting by reducing tool length. Despite the evolution of CAM software, 5-axis tool path programming requires advanced skills and collision detection remains a challenge during tool path computation. One can distinguish two kinds of tool collision when addressing machining issues: local gouging, involving the active part of the tool and global collisions where the whole body of the tool, the tool holder and the spindle can be considered. In this paper, only global collisions are studied. In the literature numerous papers deal with global collision avoidance in 5-axis milling. Several approaches exist and are based on collision tests executed during the tool path computation or after during a post-processing of the tool path. The proposed methods often address the problem from point to point, without an entire view of the tool path, which leads to non-optimal tool paths and oscillations of the tool axis. Methods are usually based on models to represent the tool geometry and the environment (part surface, check surfaces, etc.), a collision test between the obstacle and the tool and finally a correction or optimization of the tool axis orientation to avoid the obstacle. It is during this final stage of optimization that the smoothness of the trajectory may be corrected.

Two main approaches exist in the literature: geometric methods, which are the most used, and potential methods. In both approaches the modeling of the tool and the check surface is required. In most cases, the tool is divided into implicit surfaces (cylinders,

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cones) [1] leading to the description of the tool under the APT formalism [2]. The check surface, usually designed in the CAD system by a parametric surface, is modeled as a NURBS surface [3] by its convex envelope [4] or by a tessellated representation to simplify computations.

With the geometric approach, the problem is mainly treated in a local coordinate system attached to the tool using the C-Space approach [5]. Interferences between the tool and the check surface are detected using algorithms primarily based on surface intersections [6]. These tests lead to the definition of a collision-free area in the C-Space to orient the tool axis [7].

Another geometric method frequently used to evaluate the interferences is based on the cones and maps of visibility. This problem addressed by [8,9] enables, using a Gaussian sphere, to generate a local visibility map taking into account the part surface and then to integrate the machine constraints of accessibility (tool, tool holder, environment) to reduce the space available for the tool axis (global visibility). Other works increase the visibility relevance even further by taking into account the travel range of the machine tool which reduces the available area on the Gaussian sphere [10,11].

The final step is the optimization of the tool path in the resulting C-Space collision-free domain including constraints such as smoothness of the tool postures or tool length minimization [12,13].

The other approach, based on potential fields, has been developed in the domain of mobile robotics for collision avoidance. This consists in using virtual potential fields that allow a robot to avoid the obstacle during an excessive approach [14]. Indeed, a repulsive force, calculated as the gradient of the scalar potential field, tends to infinity when the distance between the mobile robot and the obstacle tends to zero, thereby deflecting the initially programmed path. This method has been improved to handle special cases associated to the position of the obstacles and the "goal" point to reach [15,16]. In addition, taking into account the dynamics [17] illustrates the presence of oscillations when the robot moves back towards the programmed position. However, in the field of mobile robotics, this issue is less critical due to the large tolerances allowed on the trajectories.

This approach has already been applied within the context of 5-axis machining for collision avoidance in a static case. Indeed, the work of [18] uses a simplified version of the formulation of repulsive forces developed by [14] to treat local and global collisions. The distances between the tool and the part and the check surfaces are reformulated into an energy minimization problem to iteratively determine a better tool posture. However, since the proposed approach is quasi-static, i.e. applied from point to point on the trajectory, the appearance of oscillations is a problem raised by the authors themselves. Finally, this type of static application was also developed as part of a haptic manipulation to guide the tool axis [19].

Thus the aim of this paper is to show the benefit of a dynamic method using potential fields to compute the tool axis orientation along a given tool path ensuring collision avoidance and smooth trajectories in 5-axis ball-end milling. This new approach allows in particular to avoid the optimization stage of the tool axis orientation in the collision-free C-Space domain required to ensure the smoothness of the tool path. A particular attention is paid to the influence of the check surface tessellation to compute the repulsive force. The computation of the cutter location points according to a chordal deviation and a scallop height is out of the scope of this paper. Cutter location points are modeled as continuous polynomial curves.

The rest of the paper is organized as follows: the mechanical model of the tool movement computation is presented in Section 2. Simulation parameter values are investigated in Section 3. An

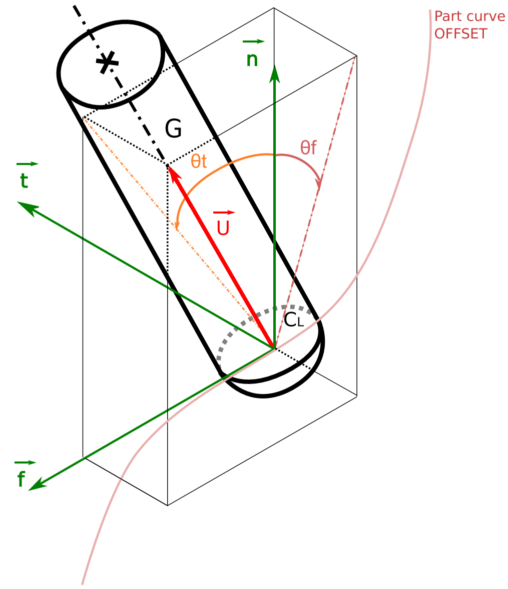

Fig. 1. Tool position and tool axis orientation set-up.

application to the machining of a 5-axis open pocket is carried out in Section 4 and results demonstrate the efficiency of the proposed method in terms of collision avoidance and smoothness. Finally, the conclusions are summarized in Section 5.

2. The potential field approach

2.1. General framework

In the proposed approach, the tool is considered as a rigid body moving in the 3D space on which repulsive and attractive forces are acting. 5-axis collision avoidance is managed thanks to repulsive forces deriving from a potential field. Thus, the aim of this section is to set up the equations of the tool movement along the tool path and between the obstacles.

In order to illustrate the effect of repulsive and attractive forces, the tool geometry is reduced to a unique point such as its center of mass G, located on the tool axis. However, the tool could be modeled as a set of points P which are distributed whether on the tool axis or on the tool surface.

In 5-axis ball-end milling, the tool axis orientation is defined in the local coordinate system $(\underline{C_L}, \underline{f}, \underline{n}, \underline{t})$ where $\underline{C_L}$ is the tool center, $\underline{f}$ is the unit vector tangent to the tool path, $\underline{n}$ is the unit vector normal to the part surface and $\underline{t}$ is given by $\underline{t} = \underline{f} \wedge \underline{n}$ (Fig. 1). In this coordinate system, the tool axis can be rotated around each of the three unit vectors without generating local collision on the active part. In the proposed method, roll angle $(\theta_f, \underline{f})$ and pitch angle $(\theta_t, \underline{t})$ are used to control the tool axis orientation.

The tool center follows the programmed tool path whereas the tool axis orientation is computed to avoid the obstacles by resolving the fundamental principle of dynamics. Furthermore, the tool velocity along the tool path is supposed to be constant and equal to a value defined by the end user. This also establishes a simple relationship between time t and the path displacement s (cumulative arc length) throughout the tool path. This principle applied to the center of mass G of the tool and expressed in the local frame $(\underline{C_L}, \underline{f}, \underline{n}, \underline{t})$, leads to the following Eq. (1):

$$\underline{\underline{J}} \cdot \frac{d\underline{\Omega}(t)}{dt} = \underline{\mathcal{T}}(t) \quad (1)$$

where $\underline{\underline{J}}$ is the inertia tensor, $\underline{\Omega}(t)$, the angular velocity of the tool, which derivates from the angular position θ_t and θ_n within the local frame, and $\underline{\mathcal{T}}(t)$ the total torque.