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Automated process planning method to machine A B-Spline free-form feature on a mill–turn center

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ABSTRACT

In this paper, we present a methodology for automating the process planning and NC code generation for a widely encountered class of free-form features that can be machined on a 3-axis mill–turn center. The free-form feature family that is considered is that of extruded protrusions whose cross-section is a closed, periodic B-Spline curve. In this methodology, for machining a part with B-Spline protrusion located at the free end, the part is first rough turned to the maximum profile diameter of the B-Spline, followed by rough profile cutting and finish profiling with axially mounted end mill tools. The identification and sequencing of machining volumes is completely automated, as is the generation of actual NC code. The approach supports both convex and non-convex profiles. In the case of non-convex profiles, the process planning algorithm ensures that there is no gouging of the work piece by the tool. The algorithm also identifies when sections of the tool path lie outside the work piece and utilizes rapid traverses in these regions to reduce cutting time. This methodology presents an integrated turn–mill process planning where by making the process fully automated from design with no user intervention making the overall process planning efficient. The algorithm was tested on several examples and test parts using the unmodified NC code obtained from the implementation were run on a Moriseiki mill–turn center. The parts that were produced met the dimensional specifications of the desired part.

1. Introduction

In machining, the ability to automatically generate a correct process plan is an essential step towards achieving automation, higher productivity and better accuracy. Process planning can be thought of as the selection of manufacturing operations, the parameters of these operations, and their sequence in order to machine a component. Process planning is very time-consuming and tedious, and the results vary based on the person doing the process planning. Hence, there is a need to automate such a process. Computer-aided process planning (CAPP) is a vital link between CAD and CAM. CAPP provides some automation in the process planning of the component. Identification of machinable volumes, generation of cutter path locations, checking of tool interference, selection of machining parameters, etc. can be done automatically.

In today's consumer driven world, aesthetic and ergonomic aspects play an important role in product design. As a result, design and manufacturing of free-form surfaces is very much in demand. Sometimes, the functional requirements of the surface also require the use of free-form profiles. Typically, these free-form surfaces are machined on 4- or 5-axis milling machines, while a turning center is thought of as a facility that can be used to produce axisymmetric components. But with the introduction of live tooling, turning centers can function as mill–turn centers which are capable of machining non-axisymmetric and free-form features. Components which are predominantly axisymmetric with some non-axisymmetric features are called mill–turn components or turn–mill components. The live tools are typically mounted on the turret of the turning center. In addition to the turning capability, the mill–turn machines have either 3- or 4-axis motion similar to a milling machine. For turning, the machine has motion along two axes; one for the longitudinal motion of the tool parallel to the work piece axis (*Z*-axis), the other for the radial motion of the tool perpendicular to the work piece axis (*X*-axis). The third axis is the programmable work piece rotation, which is called the *C*-axis. The fourth axis, if available, is called the *Y*-axis, and it allows the tool to move along the common perpendicular to the longitudinal (*Z*-axis) and radial (*X*-axis) directions.

The authors in El Mounayri, Spence, and Elbestawi (1998) developed a generic solid modeler based milling process simulation system for 3-axis milling of complex parts. Parts are described using a boundary representation solid model, and cutting edges on the tool are modeled as cubic Bezier curves. For every completed

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tool path, the tool swept volume is generated and intersected with the part, yielding the corresponding removed material volume. The tool cutting edges are then intersected with that volume to produce tool-part immersion geometry. Lee (1998) presented mathematical methods and algorithms to compute milling cutter placement and machined surface error for 4- and 5-axis finish surface machining. In Ralph and Loftus (1993) a simple method was proposed to extend the machining capability of a 3-axis machining center to that of a 5-axis machine. This is done by allowing the inclined end mill machining strategy to be used on a 3-axis machine. The method involves tilting the work piece instead of tilting the end mill during the machining process. The authors in Yu, Duan, Sun, Li, and Li (1993) addressed the issue of determining cutter paths for free-form surfaces for NC machine tools with cutters other than ball end mills. The method for determining a cutter path is based on automatically adjusting the angle between the cutter axis and the free-form surface normal, in the osculating plane, at the cutting point.

The authors in Lee and Chiou (1999) presented a new method to analyze the effective cutting shapes and machined surface errors for mill–turn machining of non-coaxial parts called the Unfolded Projection Method. This method maps the part surface and the cutter into an unfolded domain to calculate the distance between the part surface and the cutter. A feature-based geometric reasoning system is presented in Kim, Kim, Pariente, and Wang (1997) for part modeling and process planning as applied to mill–turn machined parts. A feature recognition system based on convex decomposition and a mapping method to relate machining process classes are applied to mill–turn parts. Some experimental work done to understand the phenomenon of orthogonal turn-milling especially in relation to the effects of work piece revolution, cutter diameter and depth of cut is presented in Choudhury and Bajpai (2005). It is shown that surface quality obtained by a turn-milling process is better than that of a conventional milling process.

In addition to the references cited above, there is a lot of literature available on 3-, 4- and 5-axis machining. However, there are very few papers on the use of turning centers for machining free-form non-axisymmetric surfaces. With the development of live tooling, *C*-axis motion and *Y*-axis motion, the NC turning center has become a viable option for free-form surface machining. Almost every NC turning center manufacturer offers a model that allows *C*-axis programming, thus allowing the chuck to become a programmable tooling fixture for secondary operations using live turret tools (Miller, 1989).

This combination of turning and milling machine is ideal for small to medium sized work pieces that require cylindrical or prismatic machining. The authors in Henderson and Anderson (1994), developed a feature-based design environment, called the Quick Turnaround Cell, QTC, for prismatic, turned and mill–turn parts, as well as hybrid parts such as turned parts with prismatic features, which are created as parametric features. In Tseng and Joshi (1998) a method was presented for feature recognition of mill–turn parts with interacting rotational and prismatic features. It is based on a machining volume generation approach to recognize and classify rotational and prismatic feature volumes. The feature volumes are generated by sweeping boundary faces along a direction determined by the type of machining operation. Algorithms to calculate the cutter location points for flat surfaces and ruled parametric surfaces for machining on a 3-axis mill–turn center are presented in Qian and Ben-Arieh (2006). Li and Shah (2005) presents efficient automatic feature recognition algorithms for interacting turning features from geometrical CAD models of mill–turn parts. The authors in Tseng and Liu (2001) present a feature-based fixturing analysis method for calculating the fixturing parameters for machining prismatic features and rotational features of a mill–turn part. A branch-and-bound method is developed to analyze the feasible machining sequences to find the best sequence.

In commercial packages such as Pro-Manufacture, SmartCAM, MasterCAM, SurfCAM, etc., the user has to select the manufacturing processes like turning and milling and select the respective machinable volumes and tools to generate the tool path. There is not much support for integrated turn–mill process planning which can automate the entire process planning with no user intervention. Although the mill–turn centers have the geometric degrees of freedom that are required for producing free-form features, the process planning for this generally requires input from a skilled process planner. Process planning is usually not fully automated, and as a result the free-form machining capabilities of mill–turn centers remain vastly underutilized. Also, looking at the available literature, we notice that there has been little work done in this area to achieve complete automation of integrated mill–turn process planning.

In this work, we attempt to automate the process planning for a free-form feature in the form of an extruded protrusion to be machined on a mill–turn center by using both the turning and milling operations. This feature has the cross-section of a B-Spline curve, which is extruded along the axis of the component. *C*-axis programming will be used with an end mill which is oriented axially on the machine for machining the B-Spline protrusion located at the free end of the part. For the process planning of B-Spline protrusions that are not at the end of the part, a radially mounted end mill may be needed to machine the feature as described in Date (2000).

2. Feature definition

The choice of B-Spline curve is made for making the modeling simple and there are many properties of a B-Spline which make it an attractive choice. As compared to Hermite or Bezier curves, it usually consists of more than one curve segment. Each segment is defined and influenced by only a few of the control points, which allow local control of the curve, i.e., by moving selected control points, we can change the shape of the curve in one region without changing it outside the region. This methodology can be extended to a more general case where the feature is modeled using NURBS.

As discussed earlier, we model the protrusion as a free-form feature in the form of an extrusion. This feature has the cross-section of a B-Spline curve, which is extruded along the axis of the component.

As shown in Mortenson (1997), B-Spline curves are parametric piecewise polynomials, which are defined as follows:

$$\mathbf{p}(u) = \sum_{i=0}^{n} \mathbf{p}_i N_{i,K}(u) \tag{2.1}$$

where u is the independent parameter of the B-Spline, $\mathbf{p}_i$ is the position vector of the ith control point, $N_{i,K}(u)$ are the B-Spline basis functions, $n + 1$ is the total number of control points, K is the order of the B-Spline, which determines the degree $(K - 1)$ of the basis polynomials, $\mathbf{p}(u)$ is the position vector of the point on the B-Spline curve corresponding to a given value of parameter u.

To complete the above definition of a B-Spline, we also require the knot vector $\mathbf{T}$ which consists of integer values of the parameter u in the range $0 \leqslant u \leqslant n - k + 2$, with appropriate multiplicities. These knots define, in parameter space, the points on the B-Spline curve where the curve changes its local explicit polynomial definition. The corresponding points on the B-Spline itself are called geometric knots. The portion of a B-Spline curve between two successive geometric knots is called a segment of the B-Spline.

Even though Eq. (2.1) is a convenient global representation of a B-Spline, for our purposes the segment wise form of the B-Spline