Title:

Sample-and-Cover: A Brute-Force Approach to Continuous B-Axis Turning Toolpath Computation

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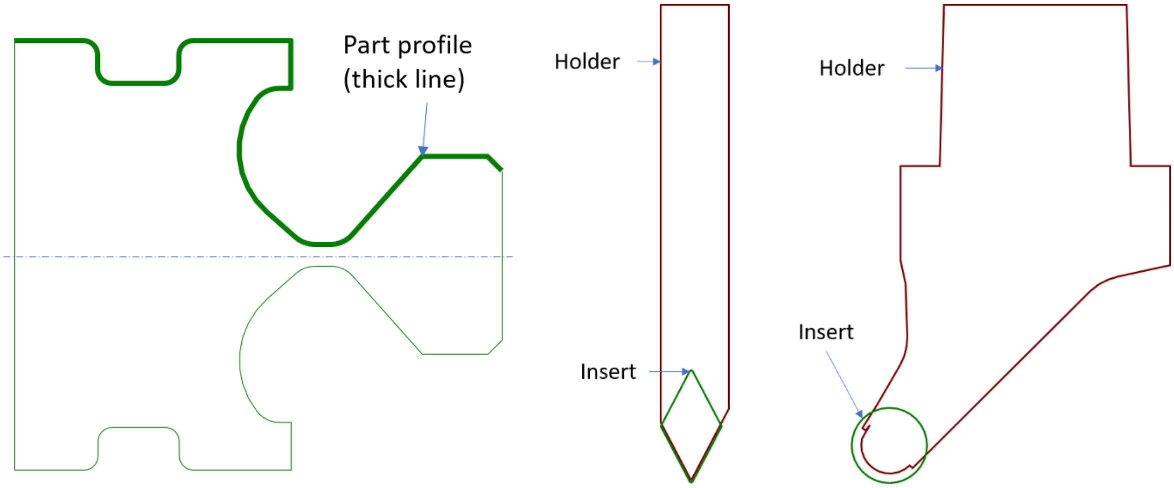
Introduction:

Turning is a versatile method of manufacturing axisymmetric parts. In a turning operation, a tool engages with a rotating stock to remove material and create the targeted part. The orientation of the mounted tool about the so-called B-Axis doesn't change during the operation in conventional lathes and turning machines. Modern turning centres have the ability to rotate the tool during the operation. This is called continuous or live B-Axis turning. The tool orientation can be suitably programmed to rotate conveniently for machining portions that would be unreachable if the orientation was static. So a larger region can be machined in a single operational setup without needing to re-mount the tool at different angles. This paper deals with generation of toolpaths for continuous B-Axis turning operations.



(a) (b) (c)

Fig. 1: Input shapes for toolpath generation – (a) part profile, tool with (b) diamond, (c) circular insert.

Input and Problem Statement:

Turning toolpaths can be planar curves as turned parts are axisymmetric. The curve revolved to model the part is called the part profile. A turning tool consists of a holder and a polygonal (e.g. diamond, triangle) or circular insert. The part profile and the cross-section of the assembled holder and insert are the input shapes needed for toolpath generation. Fig. 1(a), Fig. 1(b) and Fig. 1(c) show a part profile, a tool with diamond and circular insert respectively. All input shapes are assumed to be open chains of line segments and circular arcs. The limits of tool rotation about the B-Axis, clearance distance between the holder and stock, and front, back clearance angles between the front, back edges of polygonal inserts and the stock are parameters required as input.

The tool orientation about the B-Axis is called the tool angle hence. Given the set of input shapes and parameters, the aim presently is to generate the toolpath and tool angle along the path for live B-Axis *finishing* operations, subject to two conditions. The conditions are that the tool angle should lie within given limits of rotation and should not result in gouge and collision. Gouge is the penetration of the target part by the insert, and collision is the interference of the stock and the holder.

Prior art:

The literature on toolpaths is extensive, and increasingly focused on 5-axis CNC toolpaths. Visible directions are found and pruned at points or voxels from a mesh, which are collision-checked with the tool shape and interpolated in **Error! Reference source not found.**. Grid-based visible directions found at given points on a surface are interpolated for smooth tool rotation in [6]. Optimal orientation of a moving tool on a contact curve of a static surface is shown to require numerical solution in [3], and found at discrete points in **Error! Reference source not found.**. Points in a grid formed by iso-parametric curves on a surface are connected using graph-based techniques in [1]. Sampling is seen used in these methods, as also in applications like robotic path planning. The work in [4] analyzes two classes of methods that randomly sample the region around a point and expand the point to a path. In the spirit of all these works, the present method uses sampling of the toolpath shape to compute collision-free tool orientations.

Sampling for safe angles:

The toolpath can be close to the shape of the part profile in a finishing operation as the material to be removed is less. So, the part profile offset by the insert's nose-radius is taken as the initial toolpath. The desired or intended tool angle along the path is suggested by a strategy of tool rotation. The strategy expresses the desired overall nature of tool rotation using the tool angle and input shapes. Strategies include keeping the tool at a constant user-given angle as much as possible, or at a user-given angle to the toolpath's normal at any point among others. These two strategies are considered presently.

A tool angle satisfying the conditions checked for is called a *safe angle.* The intended angle may or may not be safe at a point on the toolpath. So a method for computing safe angles is developed. The input shapes are first pre-processed for incorporating the clearance distance and angles in the process of computing safe angles. The toolpath offset by the clearance distance is used for collision-checking with the holder. The front, back edges of a polygonal insert are modified using the clearance angles for use in checking gouge.

Methods for computing safe angles

Two methods for computing a safe angle are explored. One method is to find the range of safe angles at a point of the toolpath using the input shapes. A point separates the shapes for collision-checking into forward and backward portions. Using corresponding points on the tool shape and the portion considered, the angles making the tool contact the forward portion, θ_{forw}, and the backward portion θ_{back} are found. $[\theta_{back}, \theta_{forw}]$ is the range of safe angles. This method is complicated by the decision-branches needed to account for the states of contact of the shapes involved.

A simpler method is to iteratively search for the safe angle only when required. At a point of the toolpath, the tool placed at the desired angle is checked for intersection with the appropriate shape. If found, the tool is rotated by a small amount until a safe angle is found.

Faceting of toolpaths

The toolpath is discretized into facets; arcs are faceted into smaller arcs and line-segments into smaller line-segments. A faceting resolution deemed good for most practical input shapes is used. The tool angle is found at the end point of each facet, which is also the angle at the start point of the next facet by continuity. Facets with point(s) admitting and not admitting a safe angle are called machinable and unmachinable respectively; these are shown in an initial toolpath in Fig. 2. A systematic method to modify unmachinable facets for a continuous toolpath is presented next.

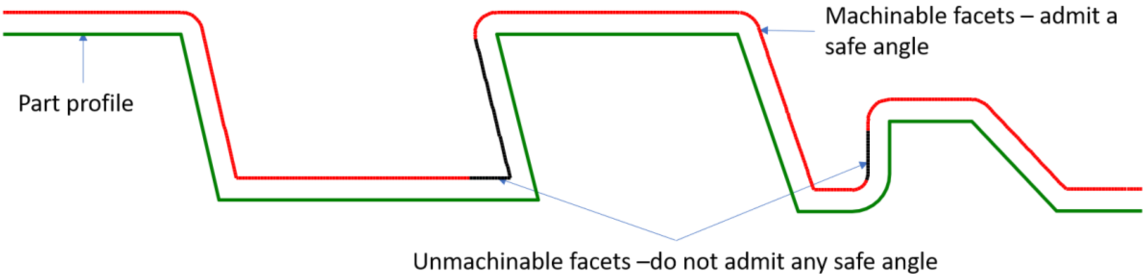


Fig. 2: Sampled initial toolpath for a part profile with circular insert after finding safe angles. Machinable and unmachinable facets shown.

<u>Convex covering of facets:</u>

Concave regions on a toolpath often contain unmachinable facets where the tool cannot reach. Motivated by this, segments that are locally convex with respect to subsets of a set of unmachinable facets are constructed. This process is termed *convex covering*. Convex covering successively connects convex points in the interior of the set starting from one end point, as depicted schematically in Fig. 3. A convex point has the angle between incident facets > 180°.

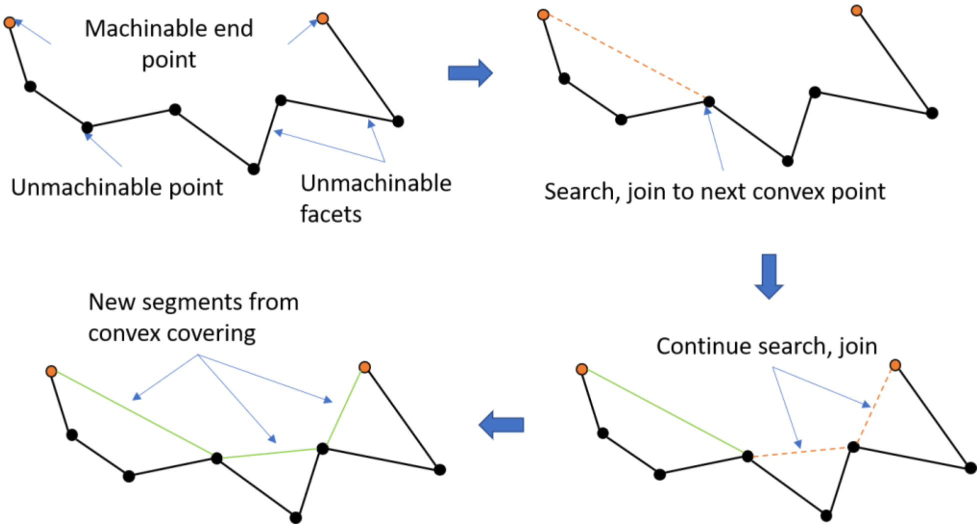


Fig. 3: Depiction of convex covering – from an end of a concave set of unmachinable facets (top left) convex points are found and joined (top, bottom right) to obtain convex cover segments (bottom left).

The above procedure requires the set to have at least one concave point. If not, then the set is expanded by including facets neighboring an end point. Expansion is tried from both ends of the set, and whichever expansion makes the set concave with a lesser number of facets is used. Then the convex-covering process described above is used.

Algorithm for toolpath generation:

The algorithm for toolpath generation begins with the offset of the part profile by the insert's nose radius as the initial toolpath. Then the following steps are repeated till termination:

1. The toolpath is faceted and a safe angle is computed in each facet. Unmachinable facets are marked.
2. The arithmetic average of the safe angles computed from a pair of consecutive facets is specified at the common point between the facets, for every pair.
3. The process of convex covering is used to introduce new segments in the toolpath.

The termination condition is one of all facets becoming machinable or unmachinable facets not removed by convex covering, whichever occurs first. Redundant facets of the output toolpath are merged based on the ratio of tool angle to facet length. The initial and final toolpaths from the algorithm are shown for a part profile in Fig. 4.

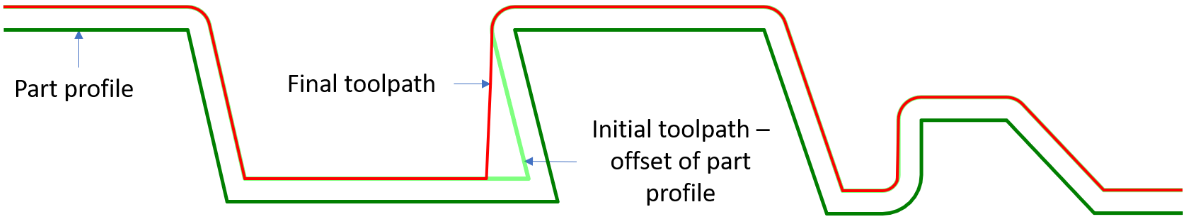


Fig. 4: Output from algorithm of toolpath generation – initial and final toolpath of the algorithm shown for the part profile and insert in Fig. **2**. Final toolpath has covered unmachinable regions seen in Fig. **2**.

Example results:

The method was tested with a range of synthetic and real-world examples of part profiles and tool shapes. The effect of the limits of rotation on the toolpath is shown in Fig. 5 for a part profile. It is seen that a greater angular range corresponds to machining of a larger extent of the profile, as expected. The toolpaths from the method was used to generate NC files to cut parts on machines. Two poses of the tool during the operation of cutting a part profile are shown in Fig. 6.

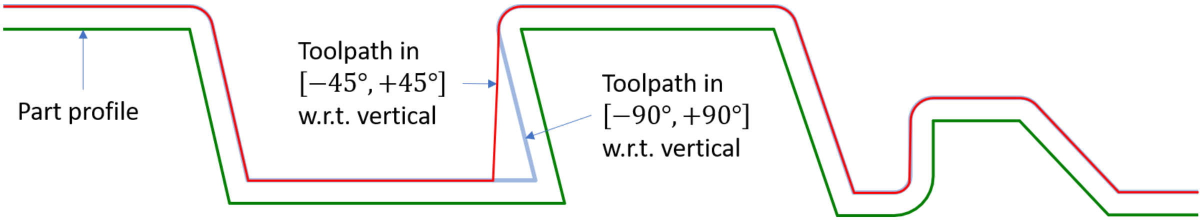


Fig. 5: Effect of angular limits on toolpath – toolpaths with [−45°, +45°] and [−90°, +90°] shown for part profile in Fig. 2. Extent machined is larger for a larger angle range, as intuitively expected.

Conclusions and future work:

The method presented is general, being applicable to any part profile and holder shape. It is robust due to the absence of heuristics or 'cases' for dealing with conditions, type of input curves. The shape of the toolpath depends on the angular limits rather than the strategy of tool rotation, with respect to the strategies taken presently. The convex covering process is a simple way to modify the toolpath, and it admits variations in the choice and manner of connecting points.

Toolpaths with other strategies of tool rotation and properties such as surface finish of the part should be investigated. The method can be extended to roughing and other operations. The use of more efficient methods for checking interference, and parallelization are other avenues of future work.

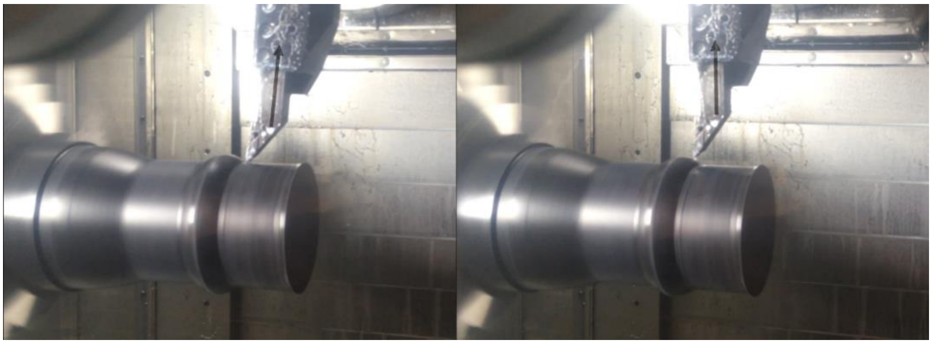


Fig. 6: Example of part cut from a metal stock using continuous B-Axis turning – two poses of the tool during the operation shown, with change in tool orientation seen. Black arrow depicts tool orientation.

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