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Towards efficient 5-axis flank CNC machining of free-form surfaces via fitting envelopes of surfaces of revolution

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ABSTRACT

We introduce a new method that approximates free-form surfaces by envelopes of one-parameter motions of surfaces of revolution. In the context of 5-axis computer numerically controlled (CNC) machining, we propose a flank machining methodology which is a preferable scallop-free scenario when the milling tool and the machined free-form surface meet tangentially along a smooth curve. We seek both an optimal shape of the milling tool as well as its optimal path in 3D space and propose an optimization based framework where these entities are the unknowns. We propose two initialization strategies where the first one requires a user's intervention only by setting the initial position of the milling tool while the second one enables to prescribe a preferable tool-path. We present several examples showing that the proposed method recovers exact envelopes, including semi-envelopes and incomplete data, and for general free-form objects it detects envelope sub-patches.

1. Introduction & motivation

Free-form, aka sculptured, objects appear in our daily life ranging from small coffee mugs, over car cockpits, to modern free-form buildings. These curved objects are aesthetically pleasing and a result of combined efforts of designers and engineers, the latter being responsible for optimal functionality. The production of free-form shapes often involves computer numerically controlled (CNC) machining, which can follow various strategies of different efficiency. The choice of machining strategy is related to the shape to be produced. To find the most efficient CNC machining strategy for a given free-form object is still an open and very challenging task [1,2].

Our work is a step into this direction. We derive new computational methodology for manufacturing that reduces the time and cost and increases the quality of fabrication processes, particularly for free-form (NURBS) objects. The technology we have in mind is 5-axis CNC machining (milling) because it is the leading manufacturing technology [2]. A revolving milling tool is navigated along a workpiece, removing the undesired material and producing the desired shape. In particular, we consider the case of *flank* milling [3,4], i.e., the case when the milling tool touches the workpiece along a whole curve, in contrast to conventional multi-axis milling, where the designed surface and the milling tool share only a single contact point. Flank machining is more efficient because the machining strips are usually much wider since the cutting strip width is not bounded by the tool's diameter [5]. However, it is a more complicated task to generate toolpaths for flank milling in which the milling tool is aligned to and tangentially movable through the whole design surface without gouging.

Geometrically, the problem considered in this work is to approximate the given free-form object by a set of manufacturable patches. The object is represented by a free-form surface Φ and the patches are required to approximate it within a fine user-predefined tolerance. Each manufacturable patch is an envelope of a one-parameter motion of a surface of revolution. Our goal is to find both the optimal shape of the milling tool (surface of revolution) as well as its motion in 3D.

2. Previous work and contributions

The research presented in this work belongs to the flank category [5] of 5-axis CNC milling, i.e., the milling tool moves

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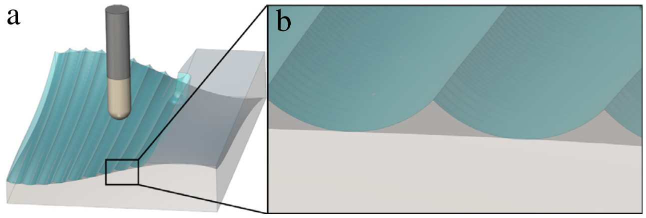

Fig. 1. Scallop cusps. (a) Ball-end milling is shown. A design surface (dark gray) and machined surface (light blue), consisting of several machined strips, are shown. (b) A zoom-in of the machined strips. The intersection of two neighbor strips introduces a sharp edge (cusp) and its distance from the design surface is known as the scallop height. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

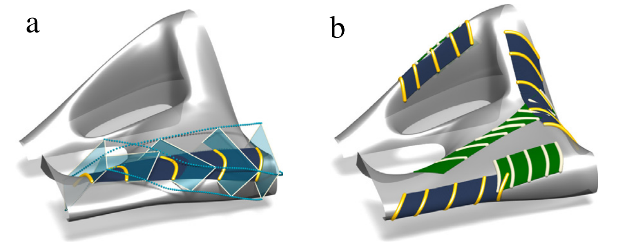

Fig. 2. Approximation of free-form skin of the Heydar Aliev cultural center, Baku, by a set of planar sweeps [29]. (a) For one large detected patch, the corresponding motion of a planar profile is shown. (b) Several larger patches together with their generating planar profiles.

tangentially along the input (designed) free-form surface, staying with it in a tangential contact along a 3D curve.

Typically, the shape and size of the milling tool is given as an input (mostly cylindrical or conical) [2,6]. A lot of research is devoted to ruled surfaces [7–15] and references cited in [5]. Using a truncated conical milling tool, Elber and Fish [7] approximate a general free-form surface using piece-wise ruled surfaces. For a general shape, however, a large number of patches is obtained and each of these ruled patches requires its own conical milling tool. Redonnet et al. [8] consider a cylindrical cutter for machining ruled surfaces and optimize its position such that it possesses a tangential contact to three particular lines: one ruling of the surface and two tangent lines of the rail curves of the ruled surface. This reduces the machining error by order of magnitude when compared with standard two-tangential arrangements. Gong and Wang [12] optimize the tool axis trajectory to minimize the error along the surface normal directions. However, the milling tool is an input as well as the initial axis trajectory (ruled surface). In contrast, in this work, we also initialize the ruled surface and search for the optimal milling tool.

The proximity of the designed and machined surfaces need not to be necessarily the only objective. The smoothness of the motion of the milling tool is equally important for machining efficiency [16–18]. Lavernhe et al. [16] optimize the tool axis orientation to satisfy certain kinematic constraints which results in a higher speed of the tool and consequently in shorter machining time. Pechard et al. [17] minimize the distance between the designed and machined surfaces while preserving the smoothness of the tool's trajectory. Zheng et al. [18] use the strain energy of the tool axis trajectory to describe the geometric smoothness and formulate it as a multi-objective programming problem. All three works, however, define a milling tool as the input and do not consider its optimization.

In the direction of selecting an optimal *general* cutter, to the best of our knowledge, it is very little known so far. Senatore et al. [6] provide analysis with respect to the size of a cylindrical tool. In order to cover large patches, a maximum radius is computed while keeping the predefined geometric error between the machined and designed surface. The work of Zhu et al. [19] is the closest one to our research as it also deals with flank milling and the simultaneous optimization for tool's motion and shape. This approach has been extended in [20], considering additional constraints such as conical tools and their stiffness. In both cases, the primary objective is to improve the machining process by reducing deflection and vibrations of the cutter. The shape of the cutter is optimized towards higher stiffness, while the trajectory surface is computed by interpolating the cutter axes. In our work, we take into account mainly geometric objectives (the forces applied to the cutter are not considered). We present an alternative formulation of the optimization where the cutter and its trajectory are both the unknowns, and a new way for quickly deciding whether a given position of the tool axis possesses a good tangential movability with respect to the reference geometry or not.

Optimization-based approaches that subdivide the design surface into sub-patches have been proposed recently [13,21]. On each such a patch, Liu et al. [21] apply a rank-two tensor field to compute the machining strip width and the optimal machining direction. Wang and Elber [13] use multi-dimensional dynamic programming to find optimal subdivisions and fit a ruled surface to each subdivided patch.

The research proposed here aims at the finishing stage of machining when the motion of the milling tool completes the desired shape of the workpiece. Typically, this is a very time demanding process because small-radii milling tools are used to eliminate or reduce the remaining scallop cusps, see Fig. 1. To optimize performance of this operation, various approaches varying tool orientation have been developed. The idea is to adapt the milling tool, usually a torus or a cylinder, such that the contact circle possesses higher order contact with the surface. This technique is known as *curvature matched machining*, see [22–27] and other references cited in [26]. However, it is possible to consider non-traditional shapes of the milling tool [28,29] to approximate Φ by a smaller number of larger, geometrically simpler, but yet-sufficiently complex patches. Conceptually, our research belongs to this modern family of techniques.

In Fig. 2 we show one of our recent results [29] where the idea of representing a complex shape by several large simpler patches was realized on a large scale, mainly for real architectural models. The patches are kinematic surfaces generated by motions of planar profiles. For purposes of CNC machining, however, we cannot in general move a planar profile so that it carves out a desired shape. We need to work with a rotary cutting tool and thus consider envelopes of rotational surfaces instead of sweeps of planar profiles.

Contributions. We investigate a class of surfaces, namely *envelopes*, generated by one-parameter motions of surfaces of revolution. By definition, these envelopes have a tangential contact with their generating surfaces of revolution at any time instant. In other words, the surface of revolution glides tangentially along its envelope. This fact makes envelopes perfect candidates for flank CNC machining and *thus we propose an algorithm that seeks a set of envelopes that well approximate the input free-form shape.* This is the main contribution of our paper and is presented in Section 4. In particular, we do the following:

⋆ Given a line l in space and a design surface Φ, this uniquely defines a rotational surface Ψ with l as its axis, as well as it defines the contact curve between Ψ and Φ. We seek an envelope Ω, that is, Ψ and its rigid body motion, such that Ω well approximates Φ. Therefore a good candidate line l yields a surface Ψ which is tangentially movable along Φ. We consider this tangential motion up to first order and explore the space of lines for those which lead to good tangential movability. Alternatively, a user defines a preferable trajectory of the tool axis.