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Tool-adaptive offset paths on triangular mesh workpiece surfaces

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HIGHLIGHTS

- We present a method for automatic tool-adaptive path planning for freeform surfaces.
- The method is based on an implicit (level set) path representation.
- The method is worked out for freeform workpieces represented by triangular meshes.
- We demonstrate the usefulness of this approach for milling and spray coating.

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ABSTRACT

Path-oriented, computer-controlled manufacturing systems work by moving a tool along a path in order to affect a workpiece. A common approach to the construction of a surface-covering path is to take a finite family of offset curves of a given seed curve with increasing offsets. This results in a set of quasi-parallel curves. The offset is chosen so that a tool moving along the curves has the desired impact at every surface point. In cases where the region of influence of a tool is different across the surface, an offset value necessary in one region may lead to a curve offset lower than required in other regions. The paper presents a general method of offset curve construction with tool-adaptive offsets. The offset path is obtained as a family of iso-curves of an anisotropic distance function of a seed curve on the workpiece surface. Anisotropy is defined by a metric tensor field on the surface. An application-independent algorithmic framework of the method for workpiece surfaces represented by a triangular mesh is presented. Its usefulness is demonstrated on the problem of varying cusp heights for milling and for spray coating of surfaces with a spray gun moved by an industrial robot.

1. Introduction

Path-oriented, computer-controlled manufacturing systems work by moving a tool along a path in order to affect a workpiece in a desired way. Examples of production technologies where path-oriented systems are widely used include milling, grinding, roller burnishing [1] and spraying. A central issue is to plan tool paths fulfilling the requirements. A *tool path* typically describes the motion of a tool by the motion of a frame with origin at a tool center point, e.g. called cutter location (CL) path for milling. During its motion the tool interacts with the surface. The sequence of locations of interaction may be described by an *impact path*. For example, the impact path of a ball-end cutter, often called cutter contact (CC) path, is induced by the contact points of the cutter with the desired surface (Fig. 1(a)). For spray coating the curve induced by the intersection points of the centerline of the moving spray cone with the surface may be taken as the impact path (Fig. 1(b)). In fact, the interaction of the spray cone with the surface is not restricted to a curve, but an impact path defined as curve allows performing path planning on the desired surface, as does the impact path for milling.

Since the impact on the workpiece is the central issue, a natural approach to path planning is to start with designing an impact path. Then a tool path which has the desired effect on the workpiece is derived relative to the impact path. The impact path has to be chosen so that several constraints and objectives can be achieved. They concern kinematic properties of the tool path which should take into account constraints or objectives of the tool–surface interaction, like e.g. material removal or contact forces in the case of milling, or the material feed rate of a spray gun. Furthermore, dynamic properties of the manipulator might be considered.

In the following, planning of impact paths is addressed. The task of impact path planning is to calculate a covering path on the surface such that it can be used for tool and manipulator

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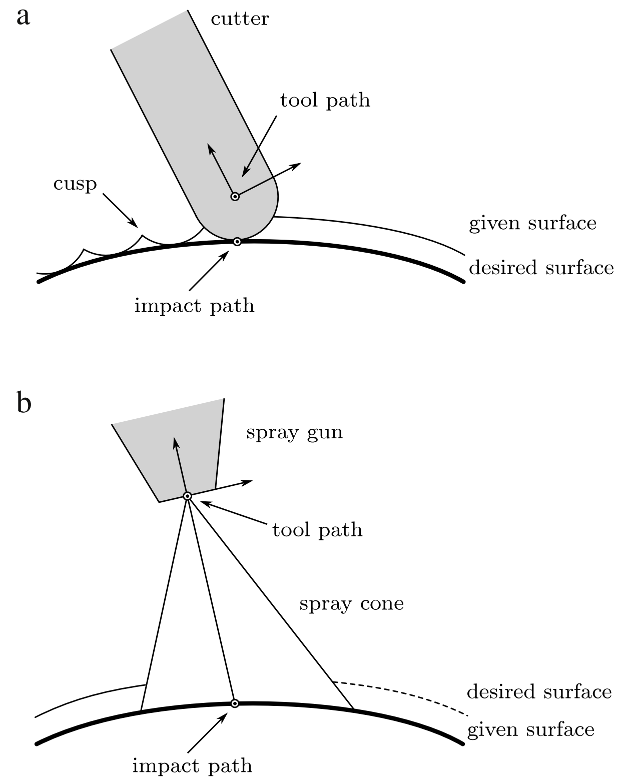

Fig. 1. Impact path and tool path of a ball-end cutter (a) and of a spray gun (b). The paths, indicated by $\odot$, are perpendicular to the image plane.

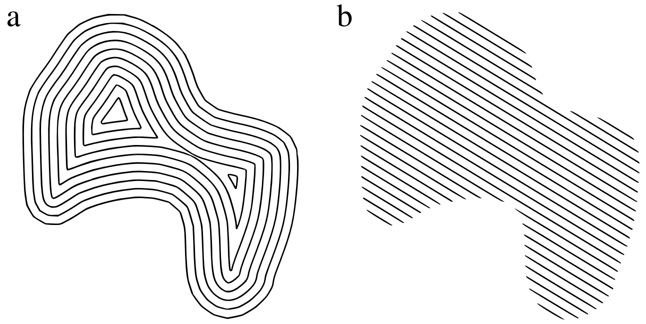

Fig. 2. Contour parallel (a) and direction parallel (b) path patterns.

path planning. Impact path topologies often used in practice are contour-parallel and direction-parallel paths (Fig. 2), and zigzag and spiral paths which may be derived from them. Those approaches of taking as uniform as possible distances in-between neighboring curve segments of an impact path lead to reasonable paths for many applications.

However, better results may be gotten by additional degrees of freedom emerging from locally adapting the inter-path-distances depending on the particular application. For example, it is common for spray coating to adapt the distance and speed of the spraying tool along a given path in order to achieve the desired coating thickness, cf. e.g. [2,3]. An alternative could be to fix either speed and distance, or both, but vary the density of the path to get the desired coating thickness. The advantage could be a more uniform distance and speed which may be favorable for the manipulator moving the spray gun.

Adaptation of the inter-path-distance may be achieved by anisotropic distance functions defined by appropriate metric tensor fields on workpiece surfaces. Kim [4] describes such an approach for planning milling paths with respect to cusp height. The goal is to achieve a uniform height of the cusps on the processed surface, independent from the curvature of the surface (Fig. 1(a)). This paper will point out the general potential of the approach as a general method for other objectives and other production processes.

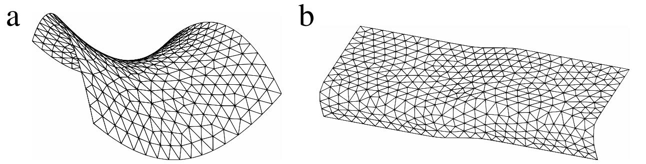

Fig. 3. The surfaces used for experimental evaluations, at a reduced mesh resolution for display purposes. (a) A saddle surface with 353 vertices and 639 triangles. (b) A workpiece surface with 396 vertices and 715 triangles.

The first main contribution is an algorithmic framework of the general method on workpiece surfaces represented by triangular meshes [5] (Fig. 3). The algorithmic framework can be implemented in a stable, reliable and efficient way at reasonable efforts and thus is well suited for practice. It uses an implicit path representation instead of a parametric representation as Kim does, and it takes into account several important achievements and results of mesh processing in recent years. Its basic idea is to define an anisotropic distance function on the mesh based on metric tensors assigned to its vertices. The metric tensors are defined specifically for the application process and they specify the necessary adaptation of the inter-path-distance. The impact paths are calculated as iso-distance curves of the anisotropic distance function by the marching triangle algorithm. If the resulting paths do not satisfy the requirements the metric tensors are adapted. This is iterated until the requirements are satisfied or no further improvement is achieved.

The application of the framework to the problem of uniform cusp height leads to an algorithmically different realization of the approach by Kim [4], with the before-mentioned advantages. Fig. 8(a) visualizes the cusp heights for an isotropic distance-parallel topology, i.e. with constant distances, while Fig. 8(b) shows a related anisotropic solution of locally varying path density.

The second main contribution is application of the method to spray coating. Two novel approaches of model-based path construction from initial information are proposed, continuing related work by the authors [3]. A model concerning the relation between velocity, path interval size, and spray time density, and a model concerning the relation between the path interval and the coating height are presented. As experimentally demonstrated, these heuristic models, although considerably simplifying, already lead to favorable metric tensors which may help to achieve a fast path calculation. Fig. 13(a) shows the errors of coating height for an isotropic direction-parallel path and Figs. 13(b) and 14 anisotropic improvements iteratively derived from it.

Section 2 gives a survey on related work. Section 3 presents the method. It is divided in subsections corresponding to the steps of the method. Sections 4 and 5 are devoted to the demonstration of the method for the path interval adaptation of impact paths of milling and of spray coating. Section 6 concludes the paper.

2. Related work

Parallel paths have found considerable interest in path-based production, in particular for technologies with tool contact like cutting [6], but also for contact-free technologies like spray painting [7] and spray coating [2]. Other path types have been investigated, too, like space filling curves [6] and trochoids [8], but with less attention in research and application.

For the calculation of parallel curves, simple approximate methods, like e.g. parallel cutting planes, of low accuracy are in widespread use [6]. True parallel paths can be determined by