A Classified Bibliography of Literature on NC Tool Path Generation Preprint version of article that appeared in *Computer-Aided Design*, Vol 29, No 3, March 1997.

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Abstract

Recently, a large amount of new research related to numerical control (NC) tool path generation has appeared in the literature. Unfortunately, finding information on a particular topic can be difficult. Not only does path generation span several disciplines, but the material tends to vary both in content and focus. In this paper, the literature is partitioned into categories and papers related to path generation classified according to the topics they cover. This should be useful to those looking for references on specific topics as well as those seeking an introduction to the literature as a whole.

Keywords: NC tool path generation, classified bibliography, survey

Abbreviated title: Bibliography of NC Tool Path Literature

Introduction

Since the late 1980's there has been an enormous amount of work published on numerical control tool path generation. However, there are three difficulties in making use of this knowledge. The first problem is the volume of work. There have been hundreds of papers published in just the first half of the 1990's alone. The second problem is that path generation, in its entirety, is a broad area, involving mechanical, electrical, electronic, and production engineering as well as computer science and mathematics. A paper related to tool path generation may focus on a specific issue from one of these fields or discuss a broad range of issues spanning several areas. The third problem is that path generation has been studied by specialists from these fields, sometimes using subject-specific (and potentially unfamiliar) terminology. Coupled with the breadth of the area as a whole and the amount of published literature, finding material that pertains to particular aspects of tool path generation can be an involved task.

This paper presents literature related to numerical control milling path generation, drawn from engineering, computer science, and mathematics. Restricting the view to milling paths is only a slight restriction as more specialized NC applications, such as punch presses and flame cutting, have some overlap with the material given here.[1] The restriction also does little to reduce the volume of literature, as milling path generation involves the following concepts:

- manufacturing process planning
- machine tool and controller hardware design
- cutting force estimation and modelling
- path generation
- machining simulation and verification

The focus of this paper is work that includes some aspect of path generation, in particular, computing and creating roughing and finishing paths for 2- through 5-axis machine tools. Papers focusing on other concepts may also contain material related to path creation because, again, there is some amount of overlap. This is especially true of the simulation and verification literature so a sampling of papers from that area is included here.

The majority of the papers listed are from the period 1989 through 1994 (approximately). This represents a period of much activity in published tool path research. A number of papers from 1988 and earlier are included. However, there is a sharp decline in the amount of material before about 1987. A number of papers from 1995 (and one from 1996) are also included. However, the CD-ROM and print indexes used (in part) to construct the bibliography were not yet complete for 1995 at the time of writing.

For the convenience of those wishing to aquire the material, there are multiple entries for authors who

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[1]The selection of papers is also limited to those published in English.

have published essentially the same material in more than one place. We apologize to those authors whose works have been omitted from this bibliography. The exclusion of any such papers is due to our not being aware of their existence and is not a statement on the quality of the work.

Classification of the Literature

The papers are grouped according to the clusterings that exist in the literature at the present time. Works have been grouped into the following categories:

- surveys
- issues
- systems
- isoparametric paths
- non-isoparametric paths
- planar pocketing paths
- sculptured surface pocketing paths
- roughing paths
- tool positioning
- offset surface method
- five axis methods
- mesh models
- pixel and point models
- simulation and verification

Some recent work has raised new issues or pursued non-traditional directions in path creation. Four such topics are the following:

- space-filling curve based tool paths
- cleanup cut tool paths
- point-based roughing paths
- region decomposition

More than half the entries in the bibliography have been classified based on the full contents of the document, having been acquired and read; another 40% have been classified based on only the abstract. Papers classified by abstract are indicated in the bibliography by a dagger field (†) at the end of the reference. A few recent papers (3%) have been classified based on title alone; such papers are indicated by a double dagger entry (‡).

Classes begin with a general description of what type of material is included in the class when it is not clear from the class name. In some cases, there are references to particular works that are useful, seminal or interesting. Papers referenced in this way are not necessarily superior to the others in the same category; such references are intended to give a very brief overview. Where material in a given class overlaps another, references are given to related classes.

Note that there is no category for "surface machining paths". Material related to surface machining can be found in the following, more specific categories: *isoparametric paths, non-isoparametric paths, systems, issues*, and *sculptured surface pocketing paths.* Note also that groupings are not exclusive. Papers may appear in more than one category.

Classified Bibliography

Surveys There are very few surveys on tool path generation. A survey by Tan, Sze, and Wong[186] appeared in 1990, just before a considerable amount of new research appeared, and it is somewhat dated now. A slightly more recent survey by Shah, Sreevalsan, and Mathew[171] appeared in 1991. It deals with both process planning and path generation, however, and slightly less than half the paper concerns NC paths. A survey by Marshall and Griffiths[141] was published in late 1994. It focuses on path construction techniques as classified by pocketing, surface-at-a-time, and whole model methods. About 30 works are cited in the paper..

References: 141, 171, 186.

Issues There are two kinds of papers in this section: those dealing with specific concepts and those dealing with more general, philosophical issues. Papers not classified elsewhere also appear here. The paper by Klass and Schramm[103] is a good overview of the issues in surface machining, while the works of Preiss,[160] Guyder,[60] and Held[70,71] present issues in 2D and $2\frac{1}{2}$D pocket machining. Dragomatz[42,43] discusses issues in path generation from a computational point of view; the papers by Awan and Besant,[7] Li and Jerard,[126] and Vickers and Quan[196] discuss issues in 5-axis milling.

References: 1, 4, 6, 7, 9, 10, 12, 17–19, 21, 25, 27, 31, 33, 36, 39, 41–43, 48, 49, 52, 54, 56, 70–72, 74, 79, 82, 82–84, 90–92, 99, 101, 101, 104, 107, 115, 115, 123, 126, 127, 129, 130, 134, 136–138, 142, 151, 153, 156, 159, 163, 165, 166, 169, 174–176, 179, 179, 182, 183, 190, 196–198, 202–204, 206, 207, 210, 213, 215, 220.

Systems Papers in this class describe entire path generation systems. The papers by Kuragano et al.[108–110] describe a Japanese system for roughing and finishing used by Sony Corporation. Lee and Chang[116] describes a system for machining sculptured pockets. The papers by Chen, Ni and Wu,[23, 24] Haapaniemi et al.,[61] and Hermann[73] describe surface machining systems for real time path generation. Two early surface machining papers are Broomhead and Edkins[15] and Loney and Ozsoy;[132] two special purpose systems are described in the papers by Ko et al.[104] and Vergeest et al.[195] The paper by Catania[16] describes a roughing path system that uses tensor product solids.

References: 1, 8, 15, 16, 23, 24, 28, 32, 38, 61, 73, 74, 90, 98, 100, 104, 108–110, 116, 129, 132, 135, 170, 208, 211.

Isoparametric Paths Works in this section develop paths in the parametric domain, where each tool pass is created based on one of the two principle parametric directions. The focus is mostly on surface machining. Interesting papers in this group include Catania,[16] who uses parameter space for *cutting depth* estimation, Cox et al.,[40] who experiment with various path patterns based on space-filling curves in isoparametric space, and Elber and Cohen,[47, 50, 51] who use an adaptive sampling algorithm to develop a series of isoparametric subpaths with uniform separation. Lee, Chen, and Lin[113] compute two isoparametric paths for each surface in a collection (one in either direction) and take the shortest one for each path. Zhu[219] generalizes slightly and additionally considers paths in the direction $u = v$ (where u and v are the principle parametric directions).

References: 1, 15, 16, 36, 40, 47, 51, 72, 73, 99, 113, 132, 148, 208, 219.

Non-isoparametric Paths The papers in this section describe methods that develop paths in Cartesian space. Some use plane–surface intersection curves to build the path while others use planar curves and selected points on them. The systems of Chen et al.,[23, 24] Haapaniemi et al.,[61] and Hermann[73] all use plane–surface intersections. Haapaniemi's system requires topological information describing the connectivity between surfaces while Chen's does not. Luo and Ma[133] also slice surfaces; however, they fit *biarcs* to the result. Bobrow[11] slices CSG solids on a per-primitive basis. Some systems use plane intersections with triangle or quad mesh approximations to the given surfaces. Among these are Kuragano et al.,[108–110] and Sakuta, Kawai, and Amano.[168]

Several systems plan the path in the plane then use selected points on the curves as a basis for positioning the tool. Marshall and Griffiths,[142] Hwang,[81] Lai and Wang,[112] and Li and Jerard[126, 127] use planar paths and a mesh model. Choi et al.[30] use planar paths with a CSG representation. Jerard, Angleton, and Drysdale[85] and Li and Jerard[126, 127] plan paths in the plane, but use a non-uniform point sample to represent the object to be machined.

The work of Chou[33] and Chou and Cohen[35] is unique; they approximate the given shape with a triangular mesh model, then create paths on a *per triangle* basis then merge the resulting subpaths.

References: 5, 11, 23, 24, 30, 33, 35, 42, 43, 55, 61, 73, 74, 78, 81, 85, 98, 108–112, 125–127, 133, 139, 140, 142, 151, 168, 189, 198.

Planar Pocketing Paths The papers in this category relate to 2D pocketing paths (a *pocket* is steep walled recess). See also: *Sculptured Surface Pocketing Paths* and *Roughing Paths*. Persson,[158] Chou and Cohen,[33, 34] and Held[70, 71] use Voronoi diagrams to create contour-parallel (or *spiral*) paths. Preiss,[160] Guyder,[60] Hansen and Arbab,[64, 65] and Kim and Jeong[97] offset elements of the given boundaries to create contour-parallel paths. Lee and Chang[120] also create contour parallel paths, but they use a convex hull method to simplify the geometry of islands within the pocket. Bala and Chang,[8] Hansen,[65] Held,[68–70] and Kramer[106] create zigzag pocketing paths. Li, Dong, and Vickers[124] experiment with various path topologies, including a number of zigzag/contour-parallel hybrids.

References: 8, 33, 34, 37, 38, 52, 57, 58, 60, 64–71, 75, 76, 94, 97, 106, 118, 120, 124, 158, 160, 161, 175, 176, 193, 209.

Sculptured Surface Pocketing Paths The approaches in this section focus on the case of pockets defined by sculptured surfaces (i.e., where the sides or bottom are not flat). See also: *Planar Pocketing Paths*, and *Roughing Paths*. Most of the work in this area is due to Lee and Chang,[116–118, 121] but the papers by Suh and Lee[181] and Chen and Ravani[22] also pertain to this topic. The work by Marshall and Griffiths[140] is not directed at sculptured pockets per se, but is similar to methods that are.

References: 22, 116–118, 121, 140, 181.

Roughing Paths Works in this category deal with more general aspects of level-by-level roughing (*roughing* is a process to remove large quantities of material quickly, leaving a coarse approximation to the final shape). See also: *Planar Pocketing Paths*. The papers by Lee, Kim and Hong,[114] and Tan, Yuen, Sze, and Wong[187, 188, 214] use octree solid models. Catania's system[16] uses isoparametric solid shapes and does not cut on parallel levels; it uses isoparametric surfaces in the solid to define a particular roughing level. Marshall and Griffiths[140] describe a stack-based algorithm for removing material from a given level using a zigzag topology.

References: 1, 15, 16, 38, 42, 43, 52, 65, 75, 76, 108–110, 114, 116, 124, 132, 138–140, 161, 187, 188, 212, 214.

Tool Positioning The papers in this group give details on finding the precise location of the tool. See also *Systems*. Papers on surface machining generally mention tool positioning, though not necessarily in detail. The use of offset surfaces as a method of tool positioning is covered in the section *Offset Surface Method*. Though some of the papers listed below discuss 5-axis tool positioning, see also *Five Axis Methods* for further references on 5-axis positioning.

Hansen and Arbab[63,65] describe a tool positioning strategy based on a recursive subdivision approach. They compare their method to the tool positioning method used by the APT language (described in their papers). Choi, Lee, Hwang, and Jun[30] describe a method for CSG solids based on the contact point of the tool with the work. Hwang,[81] in contrast, finds tool positions based on the x, y position of the tool axis and offsets of various elements of a triangular mesh model. The papers by Saito and Takahashi[167] and Thomas[191] describe tool positioning for shapes defined by pixel or image data. (See *Pixel and Point Models* for more papers on pixel-based path generation.)

References: 1–3, 26, 30, 63, 65, 81, 82, 93, 103, 122, 130, 131, 152, 180, 197, 205, 207, 217.

Offset Surface Method Papers cited here use offset surfaces or offset surface approximations (the uniform *offset surface* of a surface S is found by moving a fixed distance in the normal direction from every point on S; the offset surface can be used to develop gouge-free tool paths). Many papers have been written on the mathematics of offset surfaces; here, we will concentrate on papers relating offset surfaces to tool paths. Approximations to the offset surface may take various forms, including meshes, pixels, or CSG primitives. Sakuta, Kawai, and Amano[168] offset quadrilateral mesh elements, ignoring small gaps. As mentioned above, Hwang[81] offsets points, lines and faces of a triangular mesh to get a CSG-like collection of geometric elements. A technique that finds a discrete (pixel) approximation to the general tool offset surface called the *inverse offset method* is used by Choi et al.,[28] Kishinami, Kondo, and Saito,[102] Suzuki et al.,[184] and Takeuchi et al.[185] Kaul[94] discusses using Minkowski sums to find the approximate offset surface. Brechner[13,14] finds an analytical expression for the general offset surface of an arbitrary (smooth) surface and an arbitrary tool shape.

References: 1, 13, 14, 22–25, 28, 55, 65, 74, 81, 94, 99, 100, 102, 112, 140, 159, 168, 170, 184, 185, 189, 218.

Five-Axis Methods The papers in this section pertain to various aspects of 5-axis path creation. An important paper is that of Vickers and Quan[196] describing how the effective radius of a tilted flat endmill varies according to the inclination angle; the idea is used in several of the other papers. Warkentin et al.[205] use a flat endmill and circular contact to mill spherical surfaces. An interesting paper is that of Ko et al.[104] describing a 6-axis robot used as a 5-axis milling machine.

References: 7, 31, 33, 36, 48, 49, 79, 82–84, 99, 101, 103, 104, 107, 115, 119, 122, 123, 126, 127, 129, 131, 136, 152, 153, 179, 196, 202–205, 213, 215.

Mesh Models The papers cited below deal with triangular and quad meshes as a basis for path generation. The book by Duncan and Law[46] describes one of the first mesh-based systems.

References: 2, 3, 7, 29, 33, 35, 46, 63, 63, 65, 65, 81, 93, 94, 98, 104, 108–112, 116, 126, 127, 139, 142, 168, 184, 218.

Pixel and Point Models Works in this section deal with pixel or image data as well as non-uniform point sample sets as a basis for path generation. Various interpretations are possible for this type of representation. Saito and Takahashi[167] and Thomas[191] view the pixel model as arrays of pixel data, while Vepsäläinen[194] creates tool paths using operators from image morphology; Suzuki et al.[184] consider each pixel to be the corner of a bilinear patch. Ko et al.[104] use laser range data to define the shape to be machined; Vergeest et al.[195] describe a somewhat similar system for rapid prototyping.

References: 5, 28, 42, 43, 46, 85, 96, 102, 104, 157, 167, 184, 185, 191, 194, 195, 210–212, 216.

Simulation and Verification This section gives a sampling of some of the simulation and verification literature. While not directly related to path generation, there is some overlap that is useful to path creation. Some of the accuracy issues raised in simulation systems are applicable to pixel-based path generation systems. Likewise, information on swept tool shapes is of interest to certain types of path generation methods. More material is available, as the field contains a large body of published material. Menon and Voelcker[147] discuss issues and techniques in order to make a formal problem statement for NC verification. The papers by Drysdale and Jerard[44,45,86,87,89] contain brief surveys that describe some of the techniques used for simulation and verification.

References: 5, 44, 45, 77, 79, 80, 86–89, 95, 96, 105, 145–147, 153–155, 157, 162, 164, 167, 172, 177, 178, 180, 199–201, 207, 212, 215.

Space-filling Curve Based Tool Paths Space filling curves have been used in tool path generation both to find tool path patterns and to adaptively refine the tool path to achieve a desired machining tolerance (in this context, a *space filling curve* is a recursively refined curve that in the limit passes through every point in a rectangle). There are two primary references on the use of space-filling curves in tool path generation, a paper by Griffiths,[59] and a paper by Cox et al.[40] Griffiths' approach works in Cartesian space, using Hilbert space-filling curves, offset surfaces and ray tracing. Marshall and Griffiths[141] provide additional comments on Griffiths' method; Dragomatz[42,43] uses a variant of Griffiths' Hilbert method based on pixel models instead of offset surfaces. Cox et al. use various forms of space-filling curves and develop paths in parametric space. Work by Miguzaki, Sakamoto, and Kamijo[149,150] describes the use of Hilbert curves in a system to polish mold cavities.

References: 40, 42, 43, 59, 141, 149, 150.

Cleanup Cut Tool Paths Papers in this group mention the construction of paths that remove excess material only in specific regions of the model. Li's thesis[127] is the most detailed; the others are more conceptual.

References: 29, 46, 81, 104, 114, 127, 167, 191.

Point-based Roughing Paths The paper by Kuragano[109] is one of the only substantial references on *point-based roughing*, a method of rough machining where the cutter is plunged vertically into the work at regular, grid-like intervals. Dragomatz[42,43] uses Hilbert curves to create point-based roughing paths; the other papers mention the method, but do not go into detail.

References: 42, 43, 46, 109, 185.

Region Decomposition Papers in this section decompose the geometry into separate regions using a number of different techniques and criteria. Persson,[158] Chou and Cohen,[33,34] and Held[70,71] use Voronoi diagrams; Bobrow,[11] and Choi, Lee, Hwang, and Jun[30] use CSG primitives while Griffiths[59] and Dragomatz[42,43] divide a 2D planar region into sub-windows based on the nodes of a space-filling curve. Lee, Chen, and Lin[113] treat each *patch* separately, while Li, Dong and Vickers[124] treat each *level* differently. Elber[47,49] divides surfaces into regions based on properties such as curvature or slope; Jensen and Anderson[83] use different 5-axis tool positioning algorithms based on the curvature of the surface at the planned position. Some researchers have used feature-based decompositions[53,62] to break objects to be machined into simpler sub-parts.

References: 8, 11, 17, 19, 20, 27, 30, 33–36, 42, 43, 47, 49, 51, 53, 59, 62, 70, 71, 75, 76, 83, 84, 104, 106, 113, 118, 120, 124, 128, 134, 140, 142–144, 156, 158, 170, 173, 176, 192, 202, 213.

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