

Path Calculation of 7-axes Synchronous Quasi-Tangential Laser Manufacturing

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Abstract

Quasi-tangential laser processing, also called laser turning is increasingly applied for various applications. Specifically, its ability to generate complex geometries with small feature sizes at high precision and surface quality in hard, brittle and electrically non-conductive materials. Due to the geometric flexibility, the process is well suited for prototyping in hard-to-machine materials such as ceramics, carbides and super-abrasives. However, the lack of advanced software solutions for this novel process hitherto limited the exploitation of this potential. Here, we discuss a unique computer-aided manufacturing approach for synchronous 7-axis laser manufacturing with quasi-tangential strategies. This gives the peerless possibility to process arbitrary geometries, which cannot be manufactured with conventional techniques. A detailed description of the path calculation with derivation and procedures is given. The generated machine code is tested on a 7-axis laser manufacturing setup. Following, a processed cylindrical ceramic specimen with a continuously varying profile along a helical path is presented. The profile is constituted by a rectangular over half-spherical to a triangular groove with defined pitch. This demonstrator provides the validation of this CAM solution. Measurements of the produced specimen show high adherence with the target geometry with an average deviation below 10 μm .

Keywords: Laser ablation, Computer Aided Manufacturing, Micro-machining, Tangential processing, Synchronized motion, Path generation, Tool path planning, Laser turning

1. Introduction

In the scope of rapid prototyping and flexible production routines, laser manufacturing is a versatile tool. Various technologies have been developed in the past two decades and some are extensively used in industry. Laser welding,
5 cutting, drilling, engraving, marking [1] and all-over additive manufacturing [2]

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are prominent examples. For all these technologies, the choice of beam paths, describing the relative motion of the laser and the workpiece, is crucial [3]. In general, the calculation of beam paths for complex workpiece geometries is demanding and a computer-aided manufacturing (CAM) approach is necessary. Most laser processes are carried out in a layer-by-layer manner on flat surfaces with orthogonal incidence of the laser beam. This is termed 2.5D layered manufacturing and the lateral feature size is only limited by the minimal focal diameter of the laser beam [4]. In case of laser-ablation processes, this leads to an accumulation of small deviations in each layer and therefore geometric errors [5]. For high precision manufacturing on rotational workpieces, a quasi-tangential process is favorable to hold tight tolerances with superb surface quality [6]. The principal idea of grazing-incidence laser ablation makes a self-limiting laser ablation process possible [7]. This enables smoothing of a prior rough surface under oblique irradiation with $\theta_i > 75^\circ$.

The quasi-tangential condition for laser and matter interaction leads to a small impact in terms of a heat-affected zone (HAZ) and introduced dislocations [8]. Moreover, state-of-the-art ultra-short pulsed laser systems enable a competitive production time for heat sensitive samples and small geometries [9]. The reduced HAZ and forceless manufacturing makes micrometer-scale production possible [10]. Accordingly, machining of sensitive ultra-hard materials such as diamond and Borazon are possible without phase transitions altering the mechanical properties. Recently, ultra-short pulsed laser systems are becoming more affordable and increasingly applied by industry [11]. An example is the production of cutting tools, like end mills and drills with diamond cutting edges [12, 13].

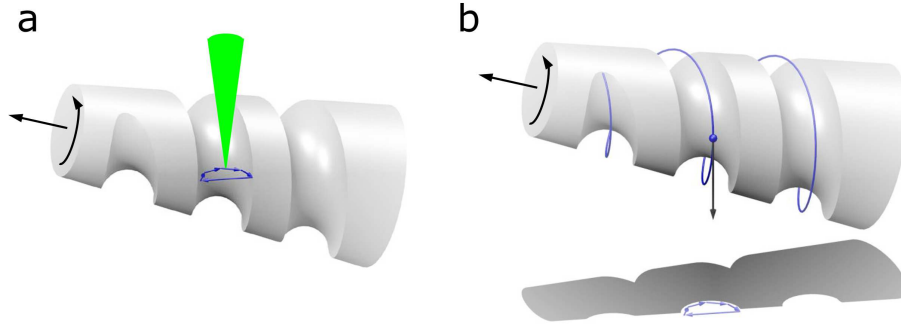


Figure 1: Principle of the quasi-tangential laser process with a helical groove. (a) The laser scans are shown in blue and the swivel axis tilted by the helix pitch. (b) The detected helical path line and the shadow projection is shown.

The kinematics of quasi-tangential laser processing is similar to the wire electric-discharge machining (EDM) process and the developed CAM models [14] can be facilitated partially. In effect, a laser can be approximated by a cone considering only the portion within the Rayleigh length. However, the

35 curvature of the specimen has to be higher compared to the Gaussian beam
caustic in order to avoid screening of the laser. A sketch in figure 1a shows the
laser beam irradiating a specimen quasi-tangentially with one scan in blue. The
incidence is tangential to the target, but the beam moved about one focal radius
inside the material and therefore termed quasi-tangential. Hence, the relative
40 movement of work piece and laser is assembled by a superposition of a spiral
motion of the workpiece and the laser scanning with highly dynamic motion
by a galvo scanner [13]. Subsequently, the laser hatches are computed for each
point on the helical path. Figure 1b depicts this helical path with the necessary
tilting of the specimen to adjust quasi-tangential irradiation conditions.

45 The simpler case of $2.5D$ radial laser ablation has been extensively studied
and the path planning is state of the art [15, 16]. Techniques like skywriting for
constant velocity during the ablation process, beam compensation strategies and
different hatching approaches are available [17]. The slicing algorithms, similar
to the procedures reported for milling and layered manufacturing [18, 19], have
50 been advanced and adapted to laser ablation processes. However, no compre-
hensive CAM solutions for quasi-tangential laser processing have been presented
to date. The capability of modern numerical controls, to enable synchronous
motion of multiple kinematic and optical axes, demands a fundamentally new
approach to this problem.

55 A novel path-calculation procedure is presented for a universal CAM and
quasi-tangential laser processing with up to five kinematic and two optical syn-
chronously controlled axes. This enables the efficient programming and man-
ufacturing of arbitrary rotational geometries. Figure 2 shows a possible axis
configuration incorporated into a laser ablation setup. This is constituted by
60 a laser, beam guidance, a 2-axes scanhead (U,V) and a mechanical axis sys-
tem consisting of a cross table (X,Y), a focusing axis (Z) parallel to the optical
axes of the laser beam, a tilting axis (B) and a rotational axis (C). Due to
the strongly varying dynamic specifications of the galvo scanner and machine
axes, the mechanical system is applied for the motion of the workpiece, while
65 the scanhead is applied for the fast laser motion. Following, a varying groove
profile on a helical pitch within the physical limitations of laser processing can
be produced. After a detailed discussion of the necessary functionality of the
CAM solution the experimental result is presented as validation of this unique
concept.

70 2. CAM Modules

There are general approaches on CAM programming for various manufac-
turing techniques like milling [20], drilling and grinding [21]. However, laser
manufacturing has to be treated differently, taking into account the non-binary
behavior with the workpiece [22]. The interaction of the laser beam with the
75 material depends on several parameters with non-linear behavior. The most
influencing dependencies concern the laser wavelength λ , polarization P , pulse
duration τ_P , fluence F , angle of incidence θ_i , the materials susceptibility χ and

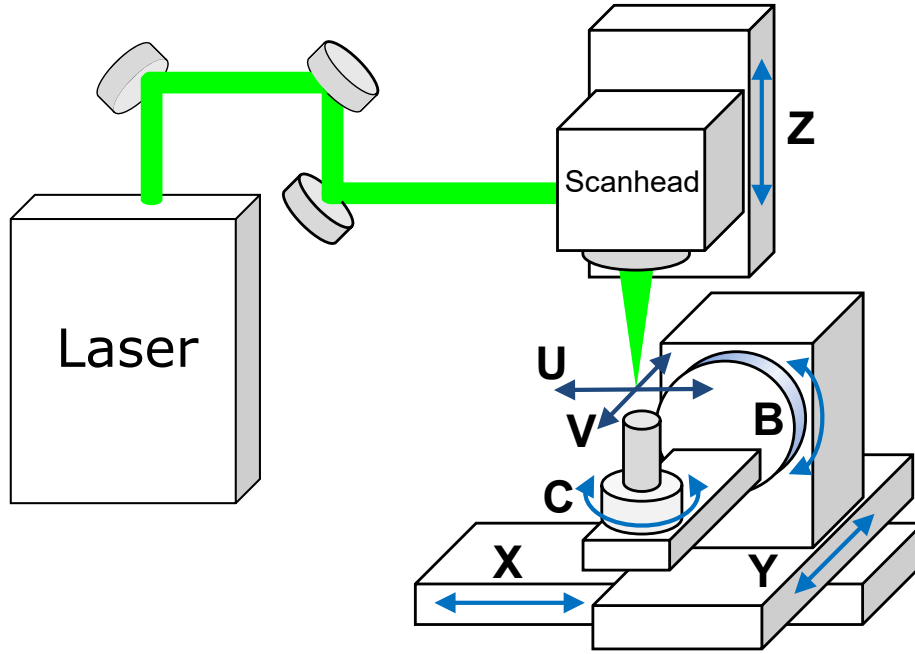


Figure 2: Experimental laser ablation setup constituted of five kinematic axes (X,Y,Z,B,C) and two optical galvo axes (U,V) aligned parallel to the XY-plane.

following reflectance R . Consequently, the process parameters have to be determined experimentally to reach the desired ablation rate and surface quality. It is necessary to follow a detailed parameter study, taking the applied material and configuration into account. If the ablation conditions for a specific set of parameters is known, the CAM tool can compute the adjacent paths and the NC code. At some point, if enough data is acquired a material database could serve as a lookup table.

In the next sections, the computation procedure of the proposed CAM tool chain is described. The steps introduced herein are realized in MATLAB, however, are in principle platform independent. The process path-calculation is not limited to ablation processes, and is applicable with modifications for selective laser melting and additive path planning purposes in general [23].

2.1. Import of the Geometry

The geometry to be imported and processed by the CAM is the part to be removed by the laser process. Commercial computer-aided design (CAD) systems generate this geometry by subtracting the target geometry from the blank geometry, depicted in figure 3. One of the advantages concerning quasi-tangential, compared to orthogonal laser processing, is the negligible influence of the blank geometry. Unknown dimensions, irregularities and surface defects

can be compensated by assuming a larger blank. Areas where the blank is defined larger than necessary, increase the processing time, but do not affect the processing result. To be flexible in terms of the used CAD system, the import is performed using the stereo lithography (STL) format. This file format was introduced in 1988 [24], but is still one of the standard formats in CAD file exchange. A closed network of triangles and the adjacent normal vectors represent the surface geometry. The proposed CAM tool encompasses a detection algorithm to control the imported geometry and calculate the adjacent normal vector of the triangular [25].

2.2. Coordinate Transformation

Generating the layers of a rigid body in Cartesian coordinates for manufacturing and rapid prototyping has been studied for years and different strategies are applicable [26]. However, positioning by the mentioned kinematic setup requires the angular information given by cylindrical coordinates. For this reason, the coordinates of the STL vertices are represented in a cylindrical coordinate system with the rotational axis coinciding with the C-axis. Furthermore, the target geometry is unrolled to use the powerful approaches available for layer separation and path calculation. The transformation is formulated as follows:

$$x' = x \quad (1)$$

$$y' = \phi = \begin{cases} \arctan(z/y) + \pi/2 & \text{if } y < 0 \\ \arctan(z/y) + 3\pi/2 & \text{if } y > 0 \end{cases} \quad (2)$$

$$z' = r = \sqrt{x^2 + y^2} \quad (3)$$

The sample geometry is unrolled over the entire circumference and the geometry exceeding 2π is stitched together in a sequential matter. If one transforms an arbitrary geometry with a constant helix pitch in this way, the helical path can be approximated by a line, depicted in figure 4a. After the coordinate transformation, the geometry parts are separated in pieces, where each piece represents one revolution of the rotational axis. This leads to closed surfaces and the paths can be computed in a more general way. Identical neighboring elements are connected, taking into account that there are no jumps allowed in the geometry. Thus, for example if a helix is present on the surface area of a cylinder, the transformation leads to higher angles for longer cylinders in x -direction. The connection faces for every revolution are sketched in figure 4a and illustrated dashed red. From now on the transformed coordinates are facilitated and denoted with y and z for simplicity of the formulas.

2.3. Path Determination

Considering the unrolled geometry in figure 4a an approximation of the geometry is calculated. The surface normal vectors, denoted in blue, are discriminated by the projected positive and negative values in z . This allows

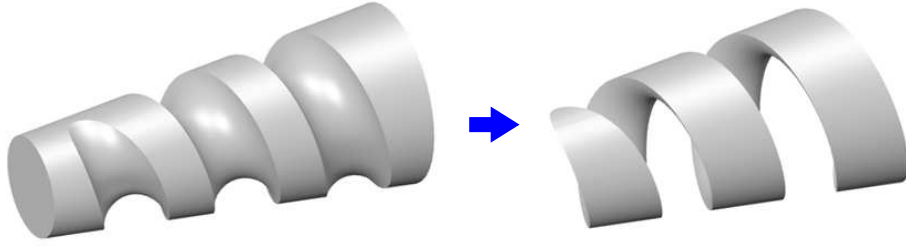


Figure 3: The target workpiece geometry is subtracted from the raw specimen. This leads to the material to be removed from the blank acting as input geometry.

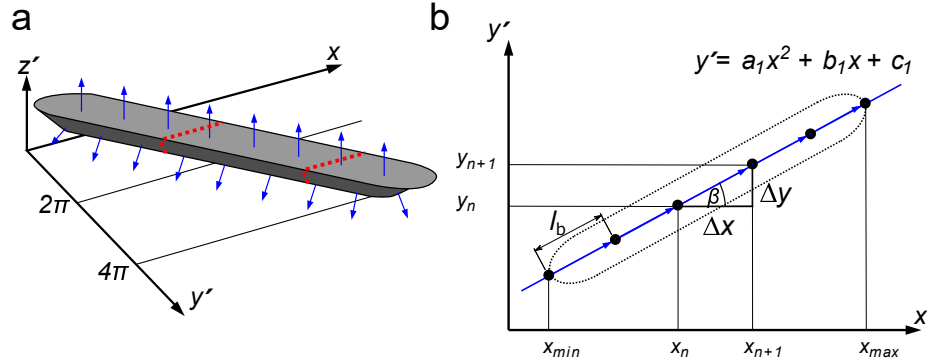


Figure 4: Rolled off and stitched geometry with vectors separating the top and bottom groove (a). The projection in the xy' -plane allows the calculation with a polynomial for each segment (b).

distinguishing between top and bottom of the groove. Following, the coordinates of the edge have to be computed. The iterative computation is carried out between the range $x_{\min}$ and $x_{\max}$. Following, the approximated path segment, see figure 4b, can be calculated from the actual x -values with adjacent coefficients a_k, b_k and c_k . For higher geometric flexibility, a second order polynomial is introduced and for the n -th y_n and z_n transformed coordinate follows:

$$y_n = a_k x_n^2 + b_k x_n + c_k \quad (4)$$

$$z_n = a_l x_n^2 + b_l x_n + c_l \quad (5)$$

The adjacent angle β_n for each segment follows from the slope with the coordinate transformed y_n and the radius z_n to

$$\beta_n = \arctan[(2a_k x_n + b_k) z_n / 2\pi] \quad (6)$$

The discretized points with constant distance l_b have to be translated to the projected axis movement in x, y and z , which can vary dependent on the slope. The angle β_n for each segment gives the necessary tilting position to hold quasi-tangential incidence during laser ablation. Subsequently, the step size in x is given by

$$\Delta x = l_b \cos \beta_n \quad (7)$$

Hence, the next iteration step for the adjacent Cartesian points y, z can be calculated with the adjacent $x_{n+1} = x_n + \Delta x$.

These equations give the approximated path for the laser manufacturing process of helical geometries. If the geometry is a cylinder or cone, having no helical groove or other non-rotationally-symmetric features on the lateral area, the path calculation is simplified. The roll off is fully defined between the angles 0 and 2π and the tilting axis set to zero having the optical axis normal to the workpiece axis. Following, the average value of $x_{\min}$ and $x_{\max}$ can be used. In order to have closed paths, the first point has to be identical to the last one after 2π . Therefore, the path distance l_b has to be modified and the adjacent path point y_n calculated for the given cylinder diameter with z to

$$l'_b = 2\pi / \lfloor 2\pi z / l_b \rfloor \quad y_n = n l'_b. \quad (8)$$

125 The adjacent next point is following equidistant on the outer contour with the modified discrete path distance l'_b .

2.4. Shadow Calculation

130 The laser hatch is determined by shading the target geometry onto the xy' -plane. A orientation vector $\vec{v}_R$ is generated, which allows to distinguish the direction of adjacent edges relative to the projection. Subsequently, this orientation vector is computed for adjacent normal vectors of the STL triangle for each segment. Therefore, a rotation of $\vec{e}_x$ around y' with β_n denoted with

Figure 5a sketches the situation of the geometry at a certain path point and the orientation vector to be determined. The adjacent top edges of the groove are depicted in pale blue and the bottom in royal blue. Only faces turned towards this orientation vector are respected and the averted are neglected, shown in figure 5b. The direction of these faces is evaluated taking the scalar product of the calculated orientation vector with the surface normal. If $\vec{n}_t \cdot \vec{v}_R < 0$, the surface is oriented towards and taken into account for further calculation. The faces on the averted side of the geometry with $\vec{n}_a \cdot \vec{v}_R > 0$ are suppressed and not considered. This generates shadow edges, illustrated by the pale blue line in 5c, for a certain angle of rotation and path point l_b .

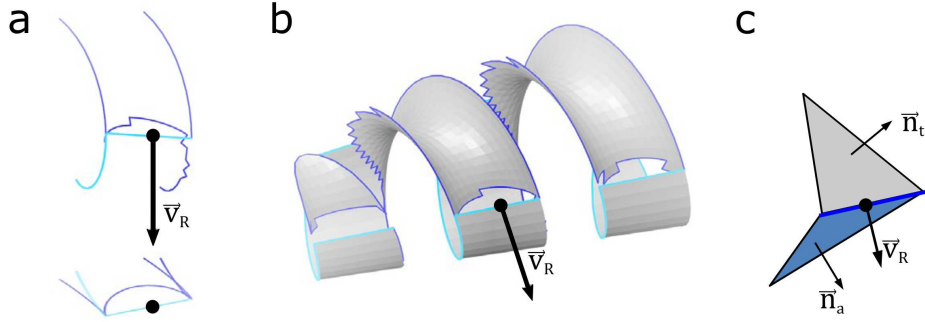


Figure 5: (a) The helical groove for each step l_b is projected on the xy' -plane and the orientation vector $\vec{v}_R$ computed. Faces on the top and bottom of the groove are sketched in pale and royal blue, accordingly (b). Two triangles from the STL with their normal vectors discriminating the orientation (c).

Subsequently, the shadow edge can be determined, which leads to the projected shadow in the XY-plane. To calculate the laser scans the edges of the bottom and top of the groove slot are handled separately, compare figure 4a. A rotation of the edge along the orientation vector is introduced and these edges are oriented opponent to the z -direction. Hence, the two dimensional projection in the XY-plane are computed and a minimal path has to be determined. Exactly, this projection and, only using parts facing the orientation vector, makes a fast computation of the shadow contour possible.

2.4.1. Contour Assignment

The described projection of the shadow edges leads to an unstructured point cloud in the XY-plane. For computation the inner contour has to be determined. Exemplary, some intersection points of the projected edges lead to a minimal closed contour as sketched in figure 6. In reality, the path is more complicated

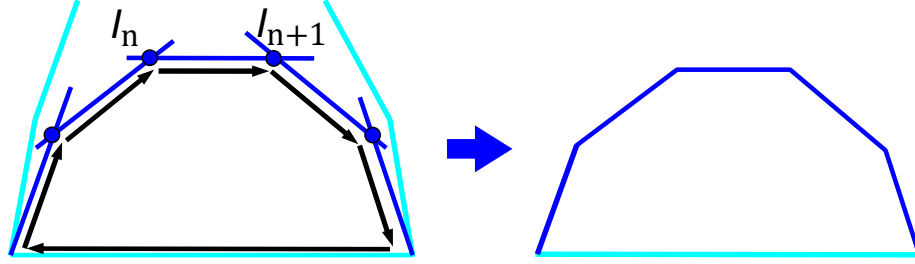


Figure 6: Construction of the minimal inner shadow contour from a point cloud in the xy -plane. The groove top is pale blue and the bottom royal blue.

and several cases have to be taken into account. Figure 7a shows the principle of the evaluation for one specific intersection point I . For illustration, considering one intersection, and the calculation the vector $\vec{v}_n$ is defined between the starting S and adjacent end point E . The slope between these points is therefore given by:

$$k_n = \frac{v_{n+1,x}(S_{n,y} - S_{n+1,y}) + v_{n+1,y}(S_{n+1,x} - S_{n,x})}{v_{n+1,y}v_{n,x} - v_{n+1,x}v_{n,y}}. \quad (10)$$

and the intersection point calculated from the adjacent starting point $S_n = I_n$ denoted with:

$$I_{n+1} = S_n + k_n \cdot \vec{v}_n. \quad (11)$$

Following, the vector $\vec{v}_n$ is evaluated considering the successor $n+1$ to determine the minimal inner contour. If the slope k_n is in the interval $[0, 1]$, the intersection is on the edge described by $\vec{v}_n$. Following I_{n+1} has to be on the same edge and the possible connection $\vec{v}_{n+1}$ can be found. In general, more than one potential linkage edge appears at the intersection point I_n and this has to be distinguished. Figure 7 depicts several cases to be discussed and evaluated to find the inner contour sketched in 6. The biggest angle φ_n between two edges is taken to guarantee the tracing of the inner contour from the shadow geometry. Therefore the angle between potential connection vectors is evaluated with:

$$\xi = \begin{cases} \arctan(v_y/v_x) + \pi/2 & \text{if } v_x < 0 \\ \arctan(v_y/v_x) + 3\pi/2 & \text{if } v_x > 0 \end{cases} \quad (12)$$

$$\varphi = \text{mod}(\pi + \xi_n - \xi_{n+1}, 2\pi). \quad (13)$$

155 In the specific case shown in figure 7a, the intersection point I is the starting point for the vectors $\vec{v}_2$ to $\vec{v}_4$. Evaluating the adjacent angle between the latter

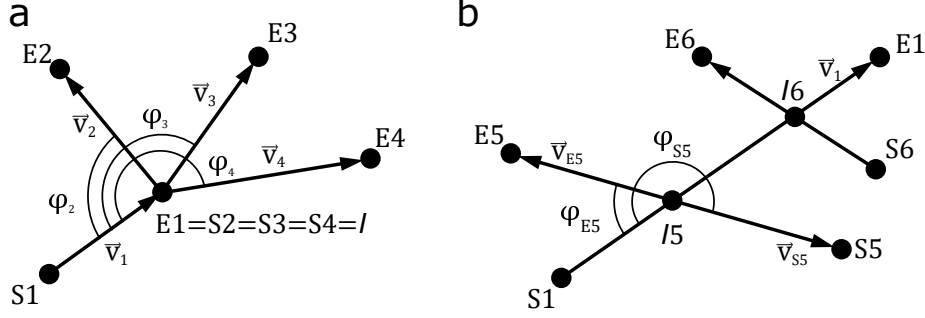


Figure 7: (a) Intersection of vectors in the xy -plane to find the minimal inner contour and (b) the determination of the angle between crossed vectors is shown.

vectors and $\vec{v}_1$ leads to φ_4 as biggest angle and therefore vector $\vec{v}_4$ has to be the successor. Each segment of the contour is evaluated sequentially in similar manner. In some cases multiple intersection points can exist, shown in 7b, and the shortest distance to the predecessor is taken.

160

2.4.2. Contour Offset

Having the shadow contour of the geometry, the hatches have to be determined. The total volume to be ablated is shown in figure 3 and for each step of the helical path the scan of every layer can be computed. The material ablation and hatching starts from the pristine surface to the calculated inner shadow contour. In contrast, the computation starts inversely to ascertain a hatch equidistant to the inner contour. A first offset distance l_e is taken into account followed by a defined offset distance l_k applied multiple times until the raw geometry, top groove in figure 4a, is reached. The contour offsets are calculated along the half angle of two adjacent vectors. This ultimately leads to challenges as depicted in figure 8a, where the hatch lines cross after two layers. An event, where a certain edge disappears from geometric constraints, has to be taken into account. Concerning the $2.5D$ case, similar events can occur [27, 28] and computational solutions were proposed. Recently, an enhancement for complex $3D$ shapes was introduced [29] and parts of the proposed features implemented in the offset calculation. In principle, the algorithm is based on Voronoi path diagrams and reduces two-dimensional shapes to one dimension. Linear offset paths are described, where edges are moving inwards in a straight manner and meet at a vertex, depicted in figure 8b. A straight skeleton algorithm for the edge events is implemented to create the contour offsets and vertex merge events. Initially, a normalized half-angle vector $\vec{n}_n$ is calculated between $\vec{v}_n$ and $\vec{v}_{n+1}$, which is in case of parallel vectors $\vec{v}_n$ normalized and rotated by $\pm\pi/2$. Figure 9a depicts the situation in more detail for one segment causing a merge event and creating an edge event point (EEP). The black solid line shows the inner shadow contour and the gray solid line illustrates the offset contour. Exemplary, two corner points $E0$ and $E1$ have to be merged and a new EEP computed. This new point has to be calculated independent of the targeted

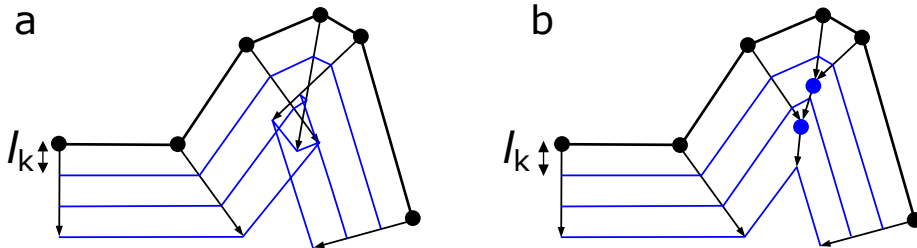


Figure 8: Contour offset calculations for ablation paths with and without edge events (a) and merge events in (b).

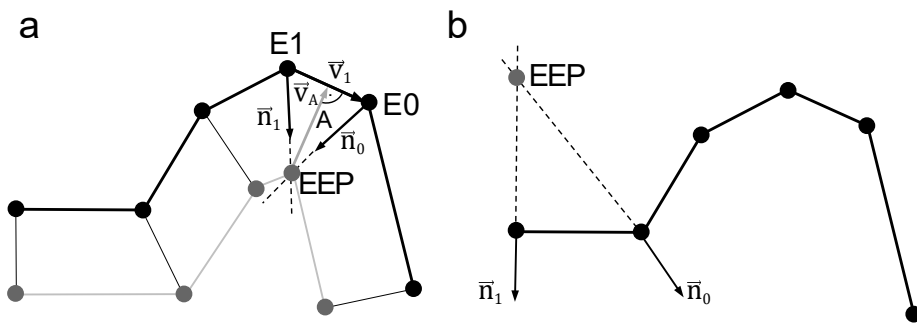


Figure 9: Possible edge event with merging corner points (a) and negligible event with the EEP outside of the inner shadow contour (b).

hatch offset distances l_k and l_e , as it may be positioned in-between two hatch lines. The adjacent edge point is shifted in direction $\vec{n}_n$ by

$$q_n = \frac{n_{n+1,x}(E_{n,y} - E_{n+1,y}) + n_{n+1,y}(E_{n+1,x} - E_{n,x})}{n_{n+1,y}n_{n,x} - n_{n+1,x}n_{n,y}}. \quad (14)$$

This leads to the new merged EEP:

$$\text{EEP} = E_n + q_n \cdot \vec{n}_n. \quad (15)$$

Subsequently, the distance of the EEP has to be calculated for each segment to ensure equidistant hatches. A normal distance A is considered to the base between the involved corner points and the EEP. Therefore, the distance follows with

$$r_n = \frac{v_{n+1,x}(\text{EPP}_x - E_{n+1,x}) + v_{n+1,y}(\text{EPP}_y - E_{n+1,y})}{v_{n+1,x}^2 + v_{n+1,y}^2}, \quad (16)$$

calculating the according distance for the EEP in sequential manner to:

$$A_n = |E_{n+1} + r_n \vec{v}_{n+1} - \text{EPP}|. \quad (17)$$

165 A has to be stored for each edge point of the geometry. Every time an edge event occurs, the geometric path is shifted outward, starting with the first EEP at minimal distance A to the shadow contour from figure 6. In principle, the direction is given by the half distance and leads to EEPs inward of the shadow contour, shown in 9b. These EEPs are virtual and do not lead to merging events and therefore are neglected with the condition $q_n < 0$ from equation 14.

2.4.3. Hatch Computation

Figure 10a schematically shows the calculation of a laser scan in direction of the new edge point according to equation 19. Following, several scans within the distance A are calculated with the layer thickness l_k before an edge merge occurs. Exemplary, several lines are depicted in figure 10b with the shadow contour in black. Blue lines show scans without edge-merge events and gray lines with adjacent points illustrate merged events. The computation of the offset uses the angle α_n , compare figure 10a, to project the layer thickness on the directional shift of the edge point this angle is calculated geometrically:

$$\alpha_n = \frac{1}{2} \arccos \frac{\vec{v}_n \cdot \vec{v}_{n+1}}{|\vec{v}_n| |\vec{v}_{n+1}|} \quad (18)$$

From the projection of the edge point, the new edge point follows to

$$E_{\text{new}} = E_n + \vec{n}_n l_k / \sin \alpha_n. \quad (19)$$

170 In case of the first scan the separate line distance l_e is facilitated, which is useful if the last scan should have a different offset distance for better surface quality or compensating the focal beam radius. Moreover, the calculated hatches are modified to incorporate a skywrite feature, which minimizes acceleration and

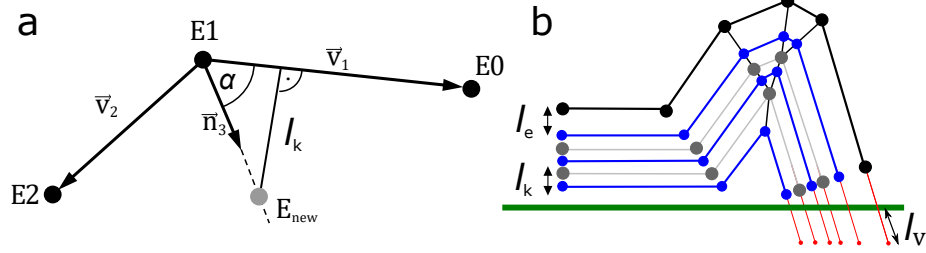


Figure 10: (a) Edge event merger and generation of a new corner E_{new} . (b) Several hatches with offset in blue and EEP merges highlighted in gray. The first hatch distance l_e , following layers l_k and the elongated hatch distance l_v are illustrated.

deceleration effects of the scanhead on the ablation. A length l_v is defined to elongate every calculated scan over the designed edge, keeping this distance constant. Taking into account the focal spot diameter and axes precision of a laser machine tool, a minimal distance l_h between two edge points of the adjacent scan is defined. This reduces the number of segments and therefore axis movements tremendously. The shadow calculation and even more the contour offset procedure leads to edge points in near proximity which do not affect the precision of the design geometry. Therefore, the computational cost and the NC code size for the laser machine can be reduced.

Following, the scan strategy and jump strategy is defined. Five computed scan lines are shown in figure 11a for subsequent path points with distance l_b . The ablation lines are shown in royal blue and connected via the jump lines in pale blue. Depending on the intended ablation rate and surface quality

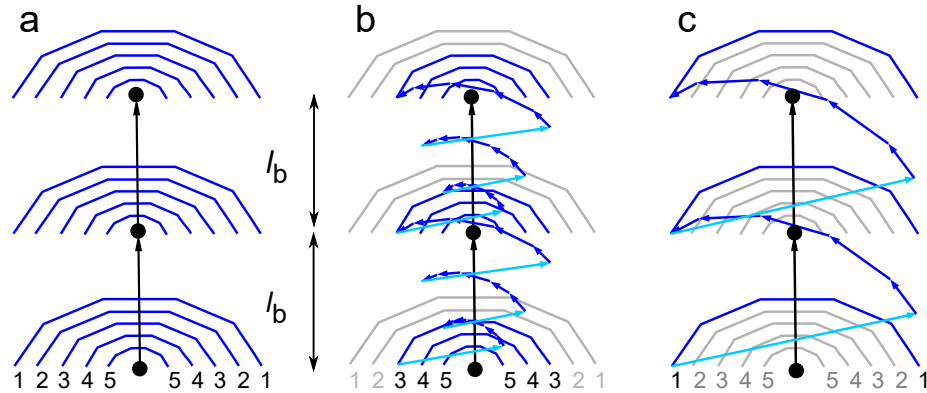


Figure 11: Exemplary hatch strategies and merging laser scan lines with the discretization of l_b on the helical path. Adjacent lines with layer thickness l_k are summed up. In (a) the hatch is depicted and (b) merges three scan lines for a roughing process. Finishing is shown in (c) following the shadow contour.

the scan lines can be collected. In case of a roughening step, figure 11b, lines starting from 3 are collected and higher ablation rates with adjacent parameters

applicable. Clearly, this will influence the surface quality and precision of the workpiece. Figure 11c sketches the finishing strategy, where the scan follows the shadow contour. In general, the subsequent laser scans can be oriented in the same direction with longer jump paths in between or the scan direction changed for each line. The latter leads to shorter jump lengths and therefore faster processes.

The total process time can be estimated by considering the hatch and jumping paths. Depending on the process and the laser machine tool the scan speed v_F and jump speed v_J are defined. Taking into account all segmented scan line to line distances, the skywrite length and jump lines gives an estimation of the total process time:

$$l_n = \sqrt{(x_{n+1} - x_n)^2 + (y_{n+1} - y_n)^2}$$

$$t_{\text{tot}} = \sum \frac{l_n}{v_F} + \sum \frac{l_v}{v_F} + \sum \frac{l_J}{v_J}. \quad (20)$$

The galvo scanner has little inertia, resulting in fast acceleration and maximum speed compared to mechanical axes. The first laser scan, starting from the unprocessed geometry, exhibits the highest rotational speed. An estimation of the required surface speed points to:

$$v_c = \frac{l_b v_F}{\sum l_n} < v_{\text{max}} = \frac{\omega_{\text{max}}}{2\pi r} \quad (21)$$

Consequently, equation 21 must be fulfilled to get the ablation paths without running into limitations of the axes. Depending on the workpiece radius, the necessary rotational speed can be calculated, or vice-versa the galvo feedrate adapted.

2.5. Parameters and Interface

The set of parameters necessary for the computation of the laser paths are given in table 1. Hence, the CAM calculation procedure realized solely depends on seven parameters and three system-dependent constants. The parameters have to be determined by a detailed experimental parameter study and set for the specific process. Depending on the utilized laser machine setup, used laser source and required surface quality these parameters can vary widely. To increase usability of the CAM solution, a graphical user interface was created. After importing the geometry to be ablated the parameters can be set and the calculated beam paths are shown, depicted in the screenshot of figure 12. The NC code is generated with machine specific settings, considering the axes configuration and adjacent machine commands. Hence, the presented CAM tool can be used on several systems with differing industrial controllers. An open-source repository hosts the MATLAB source files and a compiled version of the program licensed under the GPL-3.0 [25].

Table 1: Parameters for the path calculation acting as input to the CAM system.

Parameter	Description
l_b	Distance of the path points
l_e	First contour offset
l_k	Contour offset
l_l	Last contour offset
l_v	Elongated hatch endings
l_h	Minimal hatch distance
n	Collected hatches
v_F	Maximum scanning speed
v_J	Maximum jump speed
ω_{rot}	Maximum rotational speed

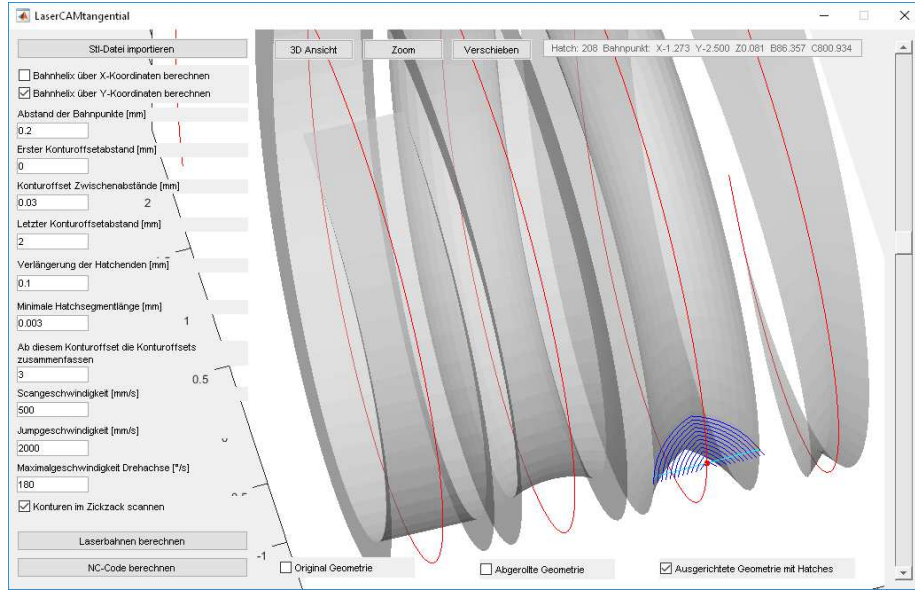


Figure 12: GUI of the compiled CAM toolbox showing the scans in blue at the geometric transition from triangle to half sphere at a certain path point.

3. Experimental Validation

A 7-axis configuration consisting of five kinematic axes (X,Y,Z,B,C) and two optical axes (U,V), as shown in figure 2, was applied for all experiments. The axes were controlled synchronously via the Aerotech A3200 motion-control software with drives from the same supplier. Therefore, the system is highly flexible in terms of motion control and embedded in a temperature-controlled environment to reach highest precision. An ultra-short pulsed laser system with an average power of 8 W, a wavelength of 520 nm, a pulse duration of 400 fs and a repetition rate of 200 kHz was applied.

The study presented was carried out on an alumina toughened zirconia (ATZ) specimen. This technical ceramic can show heat-induced phase transitions from a tetragonal phase to a monoclinic one. Following, the validation aims to demonstrate the potential of this tool set on a temperature-sensitive specimen. After a detailed parameter study, five settings have been evaluated in a control experiment. Figure 13a shows the outcome on a cylindrical specimen, keeping the ablated volume constant with varying contour offset. Clearly, the results differ in surface quality and for example the roughness changes or oxygen vacancies lead to a change in color. Phase transitions were ruled out via a Raman spectroscopy study.

Considering the quasi-tangential laser process a smoothing of a previously roughed surface is possible. Following, a portion of the material can be ablated with fast parameters and the surface quality improved with a finishing step. Table 2 gives a summary of two parameter sets, which were used on the ATZ ceramic for roughening and finishing with the facilitated ablation setup. In or-

Table 2: Parameters for quasi-tangential laser ablation showing the fluence F , scanspeed v_F , angular step per radius per scan length Δw , path distance l_b , radial contour offset l_k , ablation rate $\dot{Q}$ and adjacent surface quality R_a .

Parameter	Unit	Finishing	Roughening
F	[J cm ⁻²]	41.8	41.8
v_F	[m s ⁻¹]	0.1	0.1
Δw	[deg/mm/mm]	0.75	1.5
l_b	[μm]	13.1	26.2
l_k	[μm]	7.5	15
$\dot{Q}$	[mm ³ min ⁻¹]	0.32	1.28
R_a	[nm]	130	180

der to demonstrate the unique possibilities of this CAM approach, a specific geometry not producible with conventional manufacturing technologies was designed. Therein, the laser hatch has to vary continuously from a triangle over a half sphere to a rectangle on a constant slope of the helix. After importing the designed CAD into the CAM tool, the laser-path calculation took some minutes and the NC code was generated. Figure 13b shows the resulting specimen with the varying geometry of the groove. The process has not been optimized and

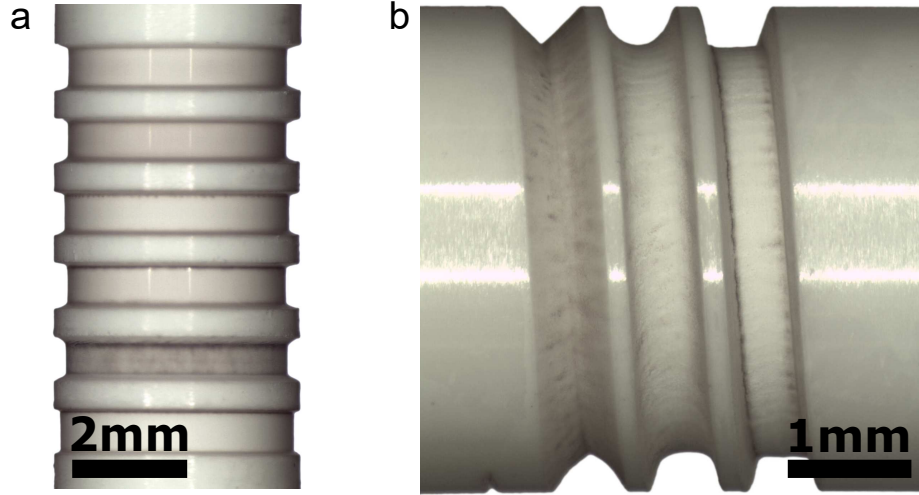


Figure 13: (a) Parameter study for quasi-tangential ablation on the ATZ ceramic. (b) Continuously varying groove of the demonstrator after roughening.

245 this is the first trial of the specific geometry with solely the roughening step serving as proof-of-concept. The contour was measured at a defined rotation angle with a Zoller Venturion. Figure 14 shows the attained contour of this demonstrator part with the deviations magnified one order of magnitude. The groove with varying cross-section could be successfully produced directly with the generated code from the CAM without further compensations. The average deviation is below $10\text{ }\mu\text{m}$, however, a larger maximal deviations of about $60\text{ }\mu\text{m}$ is measured at the steep flanks of the rectangular section. This reveals the limits

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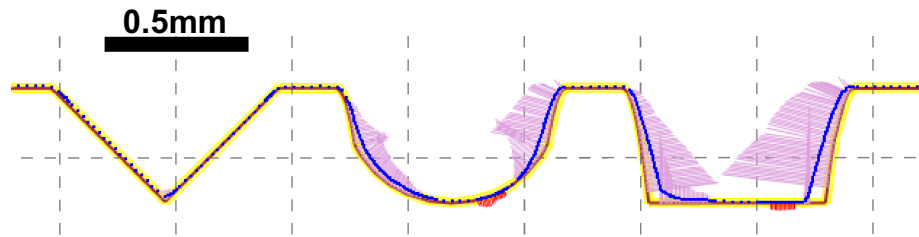


Figure 14: Contour measurement of the ceramic specimen; brown: target geometry; blue: measured geometry, violet/red: magnified deviations for visibility.

of laser processing, which is not capable of producing surfaces parallel to the optical axis of the laser beam without compensation. Steep flanks are known to be a challenge in laser ablation and taper angle compensation techniques have been proposed [30]. However, these strategies are not yet implemented in the

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presented CAM tool. Moreover, the developed CAM system was tested with different laser machine configurations and geometries pointing to a novel flexible and fast approach for laser path calculation.

4. Conclusion and Outlook

260 A complete set of CAM routines for the path calculation of synchronous 7-axis laser manufacturing of complex geometries under the quasi-tangential condition was developed. The resulting program is applicable for rapid-prototyping and successfully validated for subtractive laser manufacturing. Arbitrary geometries can be produced out-of-CAM if an appropriate laser setup is applied
265 and certain design rules, like flank-angle limitations, are followed. Limitations with regards to the achievable geometries are mostly related to very steep beam-incidence conditions on the workpiece surface. This leads to an expansion of the irradiated area and, hence, altering the ablation characteristics. The tool set is open source published and applicable for diverse path-calculation procedures
270 on varying experimental systems.

Further investigations on design limitation during quasi-tangential laser processing and suitable simulations could enhance the presented CAM solution in future. An integrated simulation and modeling environment for the inter-
275 action of the laser with different material classes would strongly improve the applicability for rapid prototyping. However, the intrinsic material properties, like reflectance, thermal conductivity and, thus, the angle-dependent ablation behavior must be known in detail. The fast growing additive-manufacturing community is intensively discussing new formats to replace the STL format.
280 Following, a change of the interfaces for this CAM solution will become necessary. Further developments will involve modification of the code package for parallel computation on graphical processing units. The long time goal is a ready-to-use CAM solution for zero-failure high-precision laser manufacturing of arbitrary shaped specimen.

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