

3D Animation of Workpiece Transformation during Milling Operation

Slobodan Ivanović^{1*}, Aleksandra Petrović², Ljubomir Lukić², Marina Pljakić²

¹ High Technical Mechanical School Trstenik, Serbia

² Faculty of Mechanical and Civil Engineering in Kraljevo, University of Kragujevac, Serbia

Engagement zone is determined as instant intersection of workpiece and tool which is changing during milling operation. Engagement zone is identified as key parameter whose variations throughout the milling process causes the variations of cutting force. Knowledge of changes in engagement zone along the tool path is necessary for simulation and monitoring of the cutting force during the machining process.

In milling process workpiece geometry is changing from blank shape to finished product. For determination of engagement zone geometry it is necessary to have accurate instant workpiece geometry and tool position. This paper presents geometrical representation of blank, tool and tool path used for animation of current workpiece geometry and tool position. Calculation and animation of engagement zone geometry is also shown.

Keywords: Animation, Milling operation, Workpiece geometry

1. INTRODUCTION

Cutter engagement or engagement zone in milling operation is described in literature [1] as measurement of portion of the cutter which is actually involved in machining at a given instant of time. Geometry of engagement zone is determined by radial and axial depth of cut and engagement angle [2].

Accurate cutter/workpiece engagement calculation is a key requirement for process modelling [3], and therefore engagement zone is identified as key parameter which variations during the process causes the variations of cutting force in milling operations [2]. Simulation of engagement zone elements can be used for determination of cutting force and cutting force variation during machining.

In general, there are two groups of approaches to model the cutting engagement:

- exact methods, using vector analytical geometry and Boolean operations to calculate exact positions and magnitudes of contact points, lines or surfaces in volumetric space [4],[5];
- discretized methods, based on bitmap image analysis in 2D (pixel-based methods) or finite-element methods in 3D [6], [7], [8], [9].

Approach used in this paper is combination of those two approaches.

For calculation of engagement zone elements it is necessary to determine tool position and current workpiece shape in each point of tool path.

Required elements of the cutting process can be calculated if, in addition to data contained in the generated NC programs, geometric characteristics of blank and geometric and technological characteristics of the tool are defined.

To calculate geometrical parameters, first of all, NC code data generated by some of the CAM packages have to be imported into a database and processed. For each path segment the coordinates of start and end point, interpolation parameters, cutting conditions and geometric characteristics of the tool are obtained [10].

This paper presents animation of tool position, tool movement direction, workpiece current shape and contact lines generated in intersection of tool and workpiece during machining.

2. GEOMETRICAL DESCRIPTION OF BLANK

Blank workpiece is imported in Matlab as a bitmap image representing view of blank from above, where each colour corresponds to an appropriate height of the blank (Figure1), detailed description is given in [11].

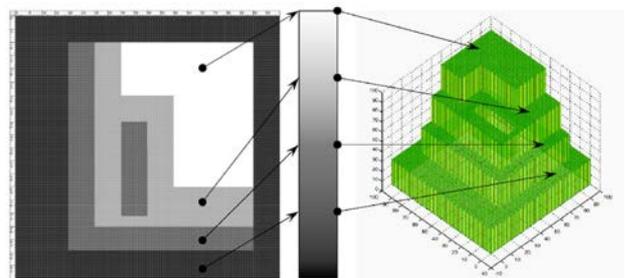


Figure 1: Transformation of bitmap image into blank network

Dimensions of rastered basis of the blank, the coordinates (position) and colour of each pixel are read from a bitmap file (Figure2). Blank matrix Wc containing the colours of all the pixels in the XY coordinate plane, is created (Equation 1).

Matrix Wc contains colours of each pixel in coordinate plane XY .

$$Wc(b_l + 1 - j, i) = B_c(j, i) \quad j: \begin{matrix} 1 \\ -1 \\ b_l \end{matrix} \quad i: \begin{matrix} b_w \\ 1 \end{matrix} \quad (1)$$

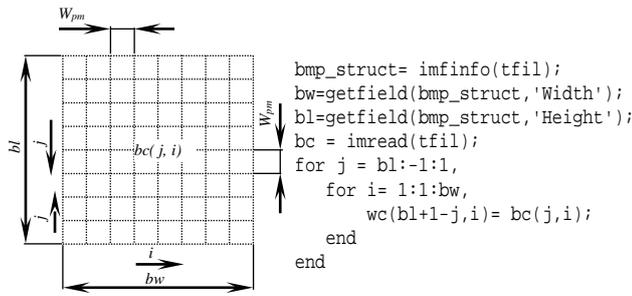


Figure 2. Bitmap data reading

Based on matrix Wc , given maximum blank height w_{zmax} and given length of pixel in millimetres w_{pm} matrices of point coordinates at blank net are calculated:

$$\begin{aligned}
 W_x(j, i) &= (i-1) \cdot w_{pm} \\
 W_y(j, i) &= (j-1) \cdot w_{pm} \\
 W_z(j, i) &= \begin{cases} NaN, W_c(j, i) = 0 \\ w_{zmax} \cdot \frac{W_c(j, i)}{255}, 0 < W_c(j, i) \leq 255 \end{cases}
 \end{aligned}
 \quad j: \begin{matrix} b_l \\ i \\ 1 \end{matrix} \quad i: \begin{matrix} b_w \\ 1 \end{matrix} \quad (2)$$

Blank boundary in XY plane is rectangular shape with length b_l and width b_w , and value of each pixel inside that boundary is determined by reading its colour from bitmap data.

On the basis of the matrix W_c , given maximum height of blank w_{zmax} and length of pixels in millimeters w_{pm} , matrix of points coordinates on the blank net are calculated.

If pixel colour is 0 (black), in that point there is no material in the workpiece (hole), otherwise, height of point at blank net $W_z(j, i)$ corresponds to value of pixel colour.

Corresponding matrix of blank in Matlab is formed. Blank don't have to be prismatic, it can have vertical holes and grooves, but may not have the horizontal holes.

3. GEOMETRICAL DESCRIPTION OF TOOL

Geometrical description of the tool is based on ASCII database in which diameter and shape of tool are written. Based on tool diameter d_t and radius r_t , as well as millimetre net division w_{mp} matrix of points on cylindrical tool net are calculated. Program is developed for three different shapes of tool: cylindrical (flat endmill), conical (tapered endmill) and spherical (ball endmill),

Tool net U is described by matrix U_x, U_y and U_z :

$$U = (U_x, U_y, U_z) \quad (3)$$

and U_x, U_y and U_z matrix dimensions are:

$$u_j = u_d, \quad u_i = u_d \quad (4)$$

Matrix of tool points coordinates are written in ASCII files together with other tool data. Along with tool net U , based on tool radius r_t , maximum tool height t_{zmax} , and millimetre net discretization w_{mp} coordinates of points on tool generatrix are generated (Figure 3).

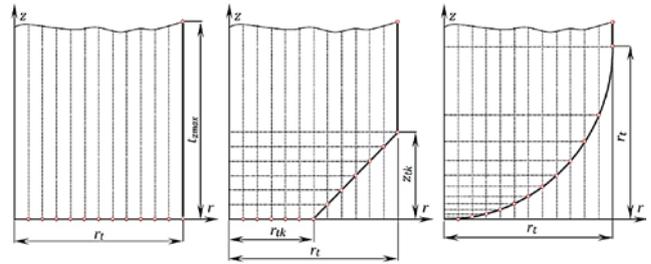


Figure 3: Matrices of points on tool generatrix coordinates for three types of tool: cylindrical, conical and spherical mill

The result of previous tool description are tool nets for cylindrical, conical and spherical mill (Figure 4) in Matlab program.

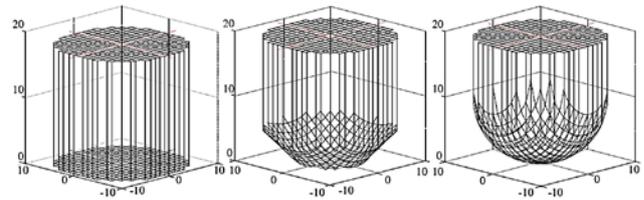


Figure 4: Tool nets for cylindrical, conical and spherical mill

4. GEOMETRICAL DESCRIPTION OF TOOL PATH

Geometrical description of tool path is obtained by transformation of NC program into ASCII file.

According to database, for each program sentence, tool path segment is reproduced (Figure 5). Tool path segments which corresponds to machining are presented with solid lines, and those that refer to positioning and rapid movement of tool are shown as dashed lines.

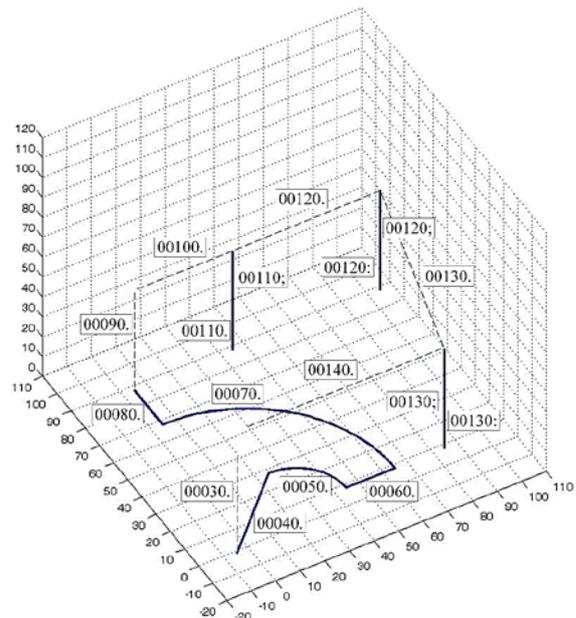


Figure 5: Tool path segments corresponding to ASCII file

Tool path defined by ASCII file is segmenting to elementary tool path segments $P(m)$ corresponding to each data row (Figure 6). To each tool path segment $P(m)$ following data are assigned: interpolation type - $Pg(m)$, feed rate- $Pf(m)=s$, spindle speed $Ps(m)=n$, start point

coordinates - x_1, y_1, z_1 , end point coordinates - x_2, y_2, z_2 , circular interpolation centre point- x_c, y_c, z_c , circular interpolation radius r , circular interpolation start angle- α_0 and circular interpolation angle- α .

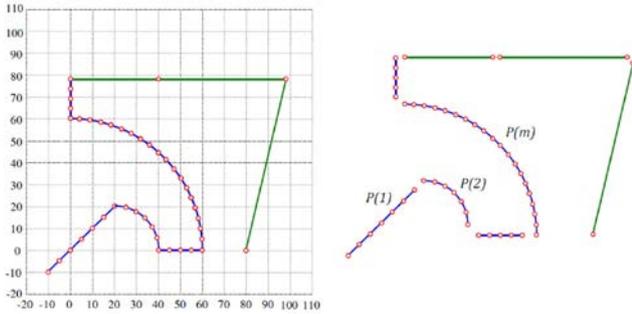


Figure 6: Tool path segmentation

For each tool path segment, length of segment $P_l(m)$, number of points on segment p_n , matrices of points coordinates at tool path $P_x(n), P_y(n), P_z(n)$ and angles of tool path in that points $P_a(n)$ are calculated. In each of these points, tool - workpiece intersection will be determined.

5. WORKPIECE TRANSFORMATION

For determination of tool - workpiece intersection, blank net is defined as line Wp which consists of parallel lines at part of blank net W at current tool position, and tool circumference is defined as polygon Op in XY plane.

Polygon $P1$ is defined by matrices of vertices coordinates in XY plane $P1 = (px1, py1)$. Line $P2$ is defined by matrices of line end points coordinates in XY plane which contains members NaN (Not A Number) as $P2 = (px2, py2)$. Members NaN divide line $P2$ on segments. Result of line and polygon intersection $Pi = P1 \cap P2$ are matrices of intersection points coordinates $Pi = (pxi, pyi)$. Dimension of matrices pxi and pyi are mutually equal and determine the number of intersection points.

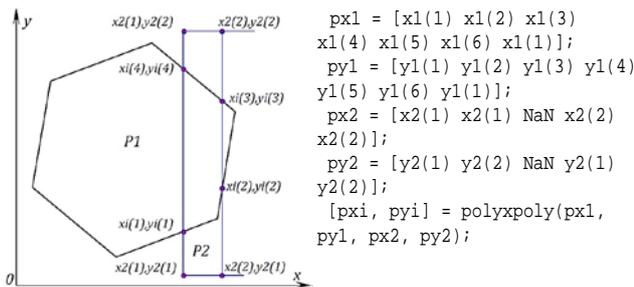


Figure 7: Definition of polygon Wp as line consisting of parallel lines

Connecting horizontal and vertical segmented lines gives Wp consisting of parallel segments and determined by matrices of points coordinates Wpx and Wpy on part of blank matrix W .

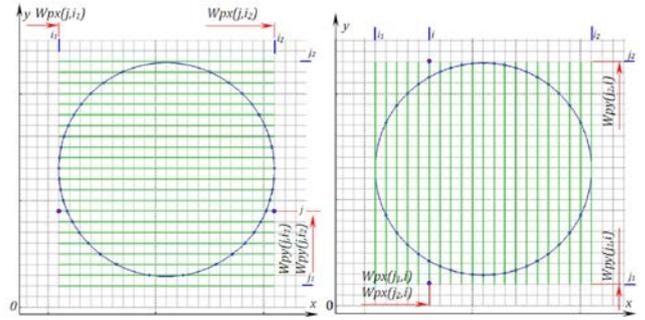


Figure 8: Lines consisting of horizontal and vertical segments of Wp

Intersection of polygon Op and line Wp results in matrices of coordinates $Ox(k)$ and $Oy(k)$:

$$[Ox \ Oy] = Op \cap Wp. \quad (5)$$

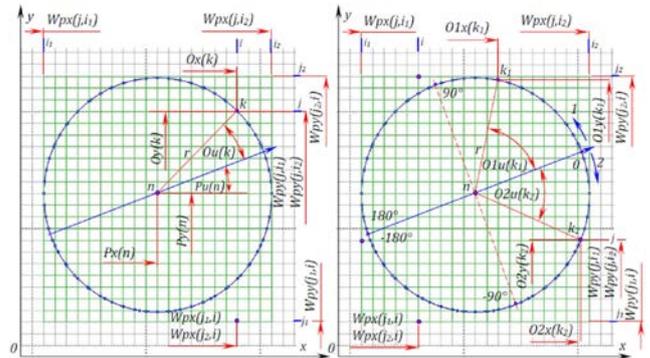


Figure 9: Intersection of polygon Op and line Wp

5.1. Contact points determination

Points of contact between blank and tool circumference are determined based on matrices of coordinates on blank net $Wx, Wy, Wz, W2x, W2y$ and $W2z$ and matrices of points coordinates in which tool circumference intersects workpiece net $O1x, O1y, O1z, O2x, O2y, O2z$. For each pair of adjacent points on tool circumference (Figure 10) with coordinates $O1x(k), O1y(k)$ and $O1x(k+1), O1y(k+1)$ elementary unit of workpiece net intersect by tool is determined by coordinates $Wx(j,i)$ and $Wy(j,i)$ and point position (j, i) in coordinate matrices Wx, Wy и Wz .

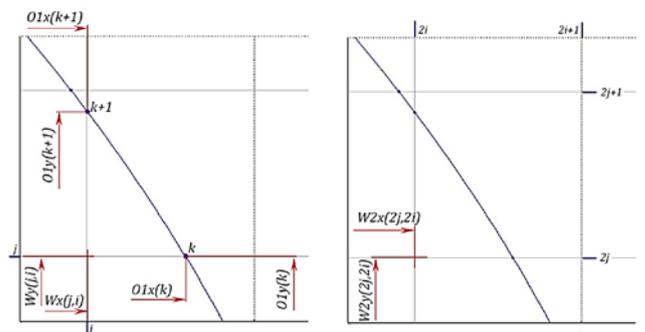


Figure 10: Two adjacent points on tool circumference: coordinates $Wx(j,i)$ and $Wy(j,i)$ and point position (j, i)

Ratio of coordinates $W2z(2;j,2\cdot i)$ and $O1z(k)$ defines if intersection point on tool circumference is in contact with workpiece (Figure 11). For $O1z(k) \geq W2z(2;j,2\cdot i)$ (Figure 11a), there is no contact between tool and workpiece. For $O1z(k) < W2z(2;j,2\cdot i)$ (Figure 11b), contact point z coordinate is $W2z(2;j,2\cdot i)$. For $O1z(k) <$

$W2z(2-j,2-i)$ and $O1z(k) < w_{z0}$ (Figure 11c), contact point z coordinate is w_{z0} .

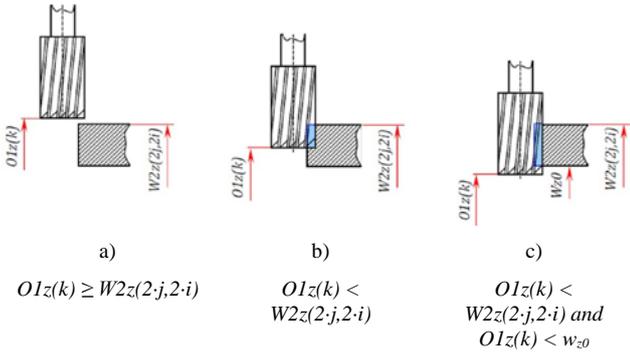


Figure 11: Checking for contact in intersection point of tool circumference and workpiece for different tool positions relative to workpiece in z direction

For contact point matrices of coordinates for bottom contact points $K1x, K1y, K1z, K2x, K2y, K2z$, matrices of central angles $K1u, K2u$, matrices of differences between angles $K1i, K2i$ and matrices of projections of distances between points on tool path direction normal $K1a, K2a$ (Figure 12), are formed.

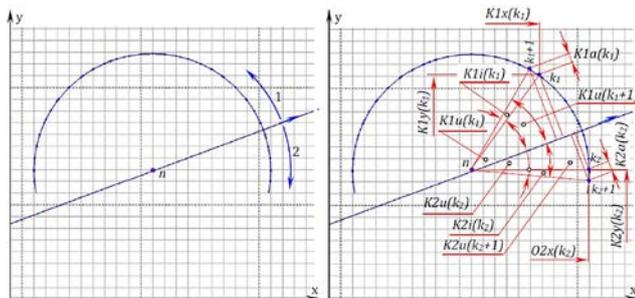


Figure 12: Tool-workpiece intersection: contact line and contact points from both sides of tool movement direction and respective geometrical elements

Besides coordinates of bottom contact points $K1z, K2z$, respective coordinates of upper contact points are calculated $K1w, K2w$. They depend on maximum tool height t_{zmax} (Figure 13).

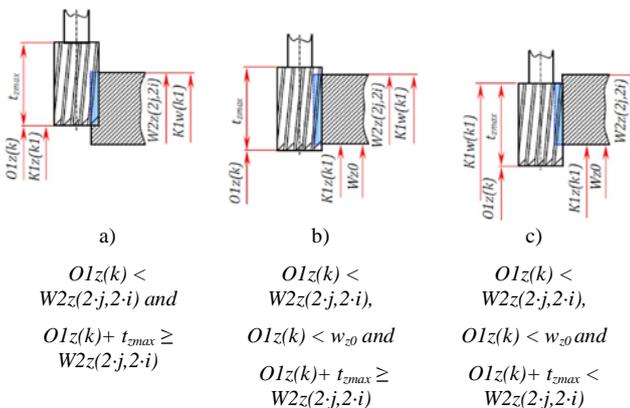


Figure 13: Coordinates of upper contact points $K1w$ for different tool positions relative to workpiece in z direction

For cases a) and b) in Figure 13, $K1w$ is equal to $W2z(2-j,2-i)$ and for case c) in Figure 13, $K1w$ is equal to $O1z(k) + t_{zmax}$.

Bottom contact points, obtained by presented procedure in each tool position at elementary segment of

tool path, are shown in Figure 14, left. Bottom contact points and corresponding upper contact points are shown in Figure 14, right.

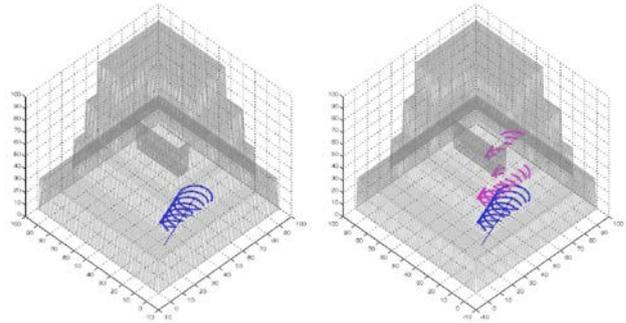


Figure 14: Bottom and upper contact points on elementary segment of tool path

Figure 15 shows contact points in two different points at elementary segment of tool path.

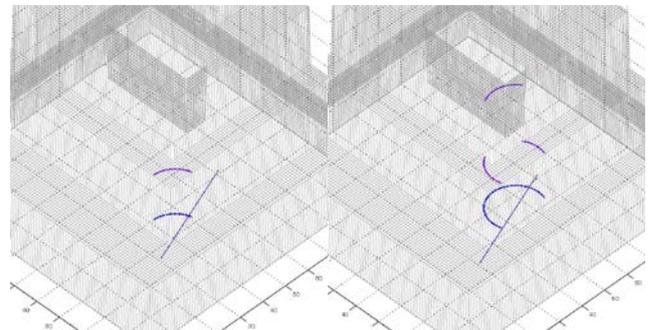


Figure 15: Contact points in two different points at elementary segment of tool path.

Figure 15, left, is an example for constant axial depth of cut, and Figure 15, right, shows case with two different axial depths of cut in single tool rotation.

5.2. Example of workpiece transformation using 3D animation

Process of workpiece transformation is illustrated by animation steps explained above (Figures 16-22).

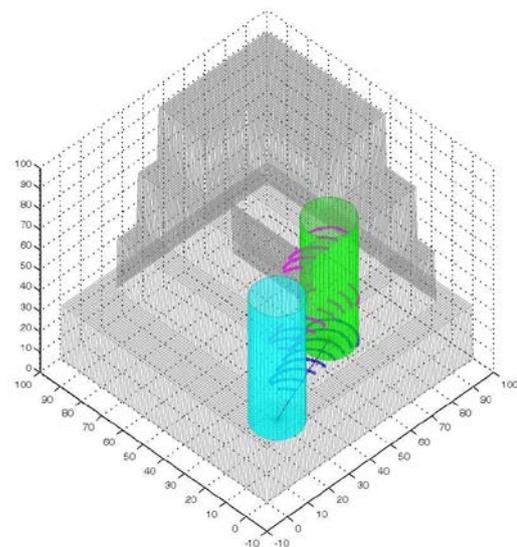


Figure 16: Bottom and top contact lines and tool positions at the start and the end of the first tool path segment

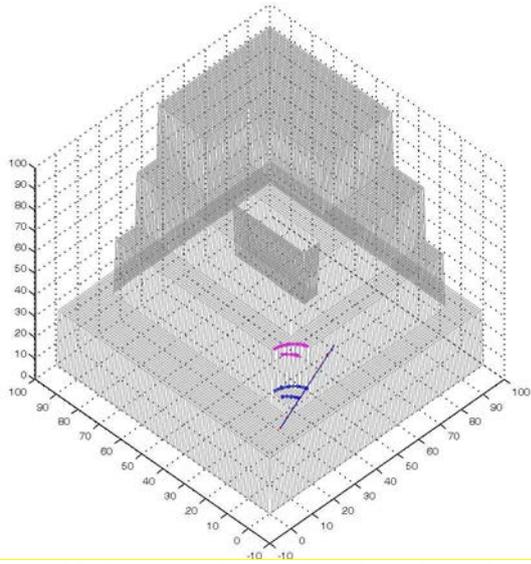


Figure 17: Bottom and top contact lines formed in two consequent tool rotations at the beginning of tool path segment

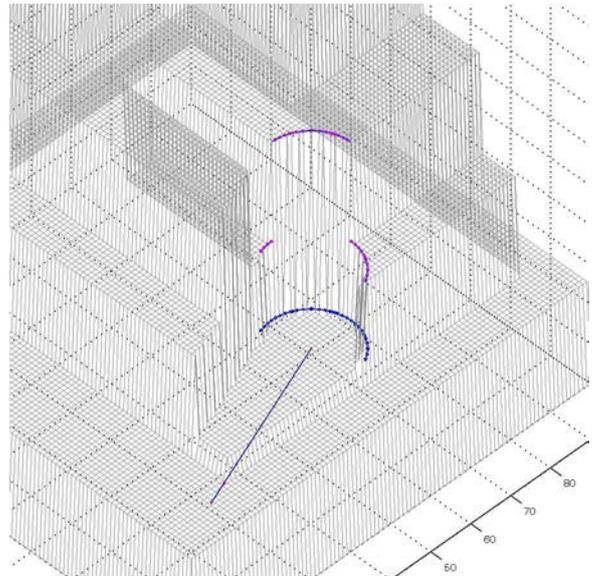


Figure 20: Enlarged view of bottom and top contact lines at the end of the first tool path segment

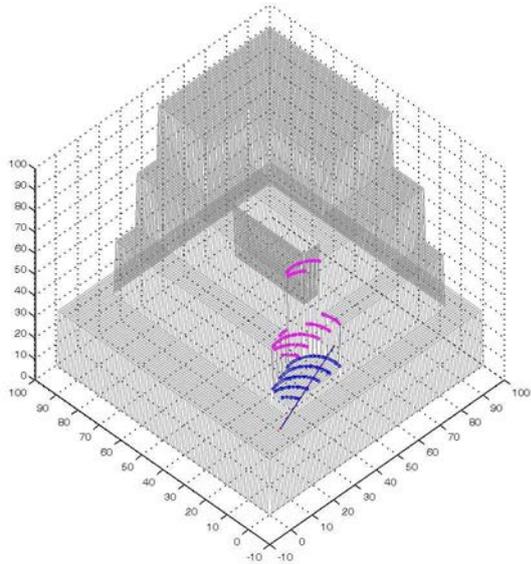


Figure 18: Bottom and top contact lines formed in consequent tool rotations at the first tool path segment

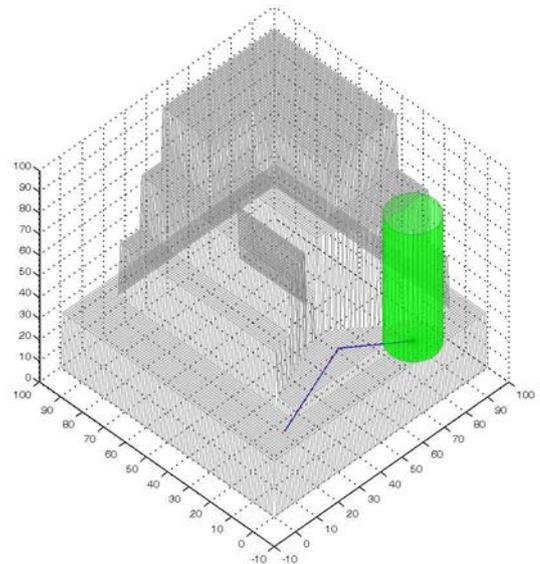


Figure 21: Tool position and transformed workpiece shape at the end of the second tool path segment

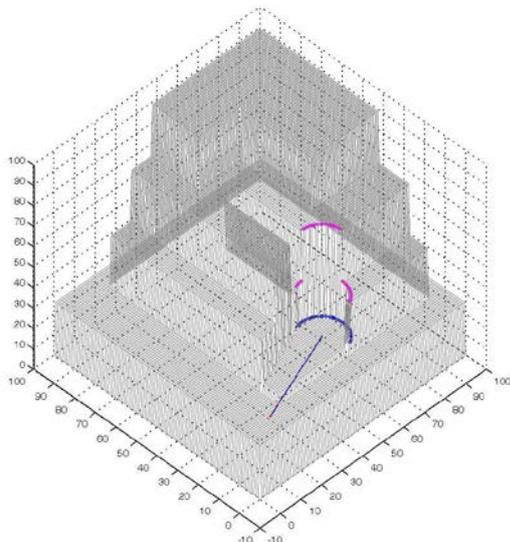


Figure 19: Bottom and top contact lines at the end of the first tool path segment

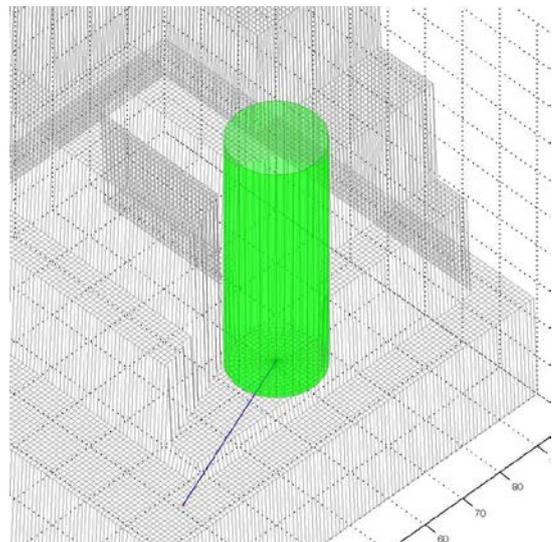


Figure 22: Tool position and transformed workpiece shape at the end of the first tool path segment

Figures show process of determination of bottom and top contact lines between tool and workpiece, tool positions and transformed workpiece at one segment of tool path. Presented animation of milling process and workpiece transformation is used for calculation of engagement zone elements and visual machining error detection on machined workpiece.

6. CONCLUSION

In this paper animation of engagement zone and workpiece current shape during milling operation is presented. Engagement zone is changing during the peripheral milling of pockets or islands. Variation of engagement zone causes variation of other milling factors such as cutting force or productivity. Knowledge of engagement zone elements along the tool path is therefore necessary for calculations of cutting force and other characteristics of milling process.

Presented methodology is part of program developed for optimal tool path selection based on different criteria such as minimum cutting force, minimum cutting force variation, type of milling (up or down), total tool path length etc.

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