Automatic Call of CPO Toolpaths without Uncut Regions for 2.5 D Pocket Milling

Elhachemi Bahloul
Mechanical Engineering Department, Faculty of Technology, Batna 2 University, Fesdis (05000) Batna, Algeria
e.bahlloul@univ-batna2.dz (corresponding author)

Khelifa Guerraiche
Mechanical Engineering Department, Faculty of Technology, Batna 2 University, Fesdis (05000) Batna, Algeria
guer.khelifa@yahoo.com

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ABSTRACT

In order to achieve the automatic call of any toolpath generation in 2.5 D pocket milling, new tool paths with offset parallel to the contour for any concave or convex polygonal shape are proposed in this article. Focus is given on several methods for addressing issues related to trajectory generation: the disappearance of edges when transitioning from one contour to another, the residual between passes, and the center of the pocket. A few selected test cases are presented for validation. The obtained results reveal that the approach introduced offers automatic toolpath generation for any polygonal shape and ensures efficient machining simulation without the appearance of material residues between passes in the corners or at the center of the pocket.

Keywords-parallel contour; any polygonal; machining simulation; residual material

I. INTRODUCTION

In recent years, 2.5D pocket milling is increasingly used in the manufacturing of molds and aerospace components [1]. Thus, numerous research efforts have been conducted to optimize machining processes and increase productivity, either through the optimization of cutting conditions [2, 3] or by reducing machining time [4]. Reducing cutting time can be achieved through toolpath optimization. In this context, two distinct parts of pocket trajectories exist, those calculated along a specific continuous direction called Zig-zag [5, 6] and those by shifted curves called Contour Parallel Offset (CPO) tool paths [7, 8]. Pocketing following the Zig-zag strategy requires a change in cutting conditions at each back-and-forth motion. Furthermore, a finishing pass along all outer edges of the pocket is required to achieve the desired shape. However, the challenge lies in generating these trajectories for pockets with complex contours [9]. In the case of machining using "parallel contour," the outer curve of the pocket contour is utilized to perform the elementary CPO paths. Therefore, it is necessary to connect the different CPO tool paths with additional connections between passes called passage segments. Nevertheless, the contour milling can occur from the outside to the inside or vice versa depending on optimization needs. Machining in CPO maintains fairly constant conditions because the machined profiles are identical to those of the pocket boundary. With the CPO strategy, calculating machining trajectories requires employing a set of algorithms to extract the pocket geometry and create elementary contours. Yet, there are three traditional calculation methods for the generation of machining CPO paths, Pixel Based Approach [10], Pair Wise Offset [11], and Voronoi diagrams [12]. Therefore, calculating a tool trajectory for 2.5D pocket milling is one of the most important problems in Computer-Aided Manufacturing (CAM). Generally, the total tool path length for pocket milling is the sum of the length of each contour and the passage segments. Computer-Aided Process Planning (CAPP) has been widely studied and is employed as a link between Computer-aided product Design (CAD) and product Manufacturing (CAM). Modern machine tools are typically controlled by computer numerical control (CNC), and Numerical Control (NC) programming has become a primary task of CAPP to produce the desired part geometry from the workpiece [13]. In this context, numerous efforts have been made in the field of automation. CAPP aims to achieve automatic toolpath generation, but most of its approaches are tailored to specific shapes, such as triangular pocket boundaries [14] and prismatic [15] and quadrilateral parts [16] with their algorithm achieving Zigzag paths for an arbitrary quadrilateral shape. Few works and methods for automatically machining pockets with arbitrary contours are available [17, 18]. To generalize the phenomenon of automatic call of CPO tool trajectories while ensuring perfect machining without material residues between passes at the corners or at the center of the pocket for any pocket boundary shape. This paper proposes a method that automatically calls CPO tool trajectories and ensures perfect pocket milling without any residue.

II. TOOLPATH GENERATION WITH PARALLEL CONTOUR OFFSET FOR ANY POLYGONAL SHAPE

The implementation of parallel contours primarily depends on the shape of the pocket boundaries. Therefore, it is necessary to first define an algorithm that handles any form of boundary with convex or concave (line-line) features, based on segment lengths (L_{oj}) and angles between edges (α_j), where the vertices of the contour can be positioned (p_j), Figure 1.

The algorithm that describes the pocket boundary is:

```
// Input: length of segments, L_oj, α_j
// Output: pocket boundary with { L_oj, p_j}
Begin
{If j=1:
P(j, 1) = x_0, P(j + 1, 1) = x_0 + L_01,
P(j, 2) = y_0, P(j + 1, 2) = y_0,
angle = π
Else if j=2: N
P(j + 1, 1) = P(j, 1) ∓ L_0j * cos(angle)
P(j + 2, 1) = P(j, 2) ∓ L_0j * sin(angle)
angle = angle + α_(j-1) - π}
End
```

An algorithm suite has been done with the aim of achieving any orientation of the polygon in Figure 1 and is presented as:

Algorithm which executes a rotation of angle theta (θ):

```
Algorithm 1
{If j=1: n+1
x_j = P(j, 1) - x_0
y_j = P(j, 2) - y_0
x_f = x_i * cos(theta) - y_i * sin(theta)
y_f = x_i * sin(theta) + y_i * cos(theta)
p(j, 1) = x_f, p(j, 2) = y_f }
End
p(:, 1) = p(:, 1) + x_0, p(:, 2) = p(:, 2) + y_0
```

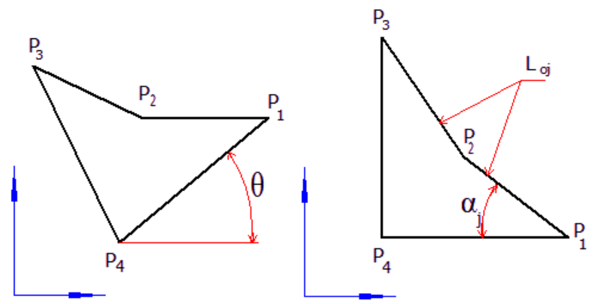


Fig. 1. Representation of polygon boundary with orientation theta.

The guide curve describing the offset parallel contours is obtained by placing the tool's central location at a distance from the pocket contour equal to the radius of the end mill plus the finishing thickness *e*.

To form the tool paths with parallel contours requires for all bisectors of the angles to be utilized as the principle intersection points of each pair of edges and then the passage from a contour to another is through the bisector of a corner of the pocket. The total length of the machining path in the inner part is the sum of the length of each pass and the sum of the passage segments between passes according to (1).

$$L_{ip} = \sum_{i=1}^{n}\sum_{j=1}^{N}\left(L_{ij}\right) + M \quad (1)$$

$$L_{ij} = L_{(i-1)j} - H * \left(cot\left(\frac{\alpha_j}{2}\right) + cot\left(\frac{\alpha_{(j+1)}}{2}\right)\right) \quad (2)$$

where *n* is the number of contours, *N*: the number of edges in each contour, and *M* the sum of the passage segments:

$$M = \sum_{i=1}^{n-1}\sum_{i=1}^{n-1} M_i \quad (3)$$

with: $M_i = \frac{H}{sin\left(\frac{\alpha}{2}\right)}$

For the first contour: $H = R + e$

Else: $H = 2 * R * \kappa$

where κ is the overlap coefficient, varying between 0 and 1 and *e* is the finishing thickness.

The generation of toolpaths in CPO is well-known in literature or in computer-aided manufacturing software, but the issues related to this generation of toolpaths in CPO remain an obstacle that must be overcome to develop a generalized algorithm for any pocket contour shapes. This algorithm must take into account the edges that disappear when moving from one contour to another, as well as the issues of material residues left after machining. The following section entails proposed solutions to these problems that are suitable for any polygon.

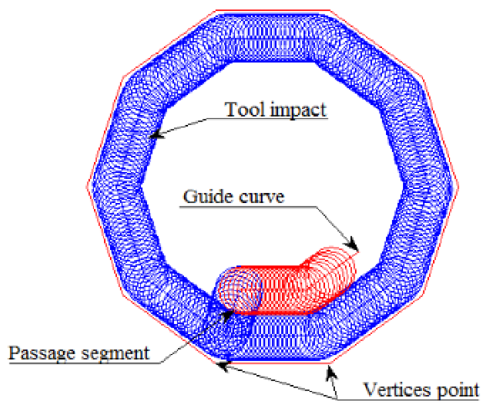


Fig. 2. Tool trajectories relative to the pocket boundary.

III. TREATMENT METHODS FOR PROBLEMS RELATED TO TRAJECTORY GENERATION

A. *Generation of a solution when Several Edges Disappear*

For an arbitrary polygonal shape, when passing from an offset contour to another, angles and edges may disappear as shown in Figure 3. This requires a recalculation of the two segments which delimit those who have disappeared in the next contour as in the example of Figure 3

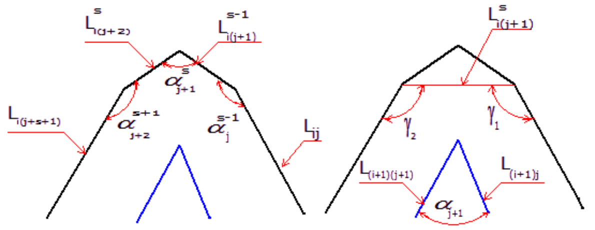


Fig. 3. Representation of CPO tool path when segments disappear.

The calculation that describes the CPO tool path when segments and angles disappeared is provided by the following algorithm:

```
Algorithm.2
// Input: pocket boundary with, { L_oj, P_j}
// Output: generation of CPO tool paths {
L_ij, n}
Begin
S: Number of segments that will disappear
    {If: L^s_ij ≤ 0 the (s+1) angles must be
replaced with a single angle:
```

$$\alpha_{(j+1)} = \left(\alpha_j^1 + \ldots + \alpha_j^s + \alpha_j^{(s+1)}\right) - s*\pi$$

```
    The two segments which delimit those
who have disappeared  L_(i+1)j , L_(i+1)(j+1)
become:
```

$$L_{(i+1)j} = L_{ij} - H * \cot\left(\frac{\alpha_{(j+1)}}{2}\right) + L^s_{i(j+1)} * \sin(\pi - \gamma_2)/\sin\left(\alpha_{(j+1)}\right)$$

$$L_{(i+1)(j+1)} = L_{i(j+s+1)} - H * \cot\left(\frac{\alpha_{(j+1)}}{2}\right) + L^s_{i(j+1)} * \sin(\pi - \gamma_1)/\sin\left(\alpha_{(j+1)}\right)$$

```
N decreases to N-S}
End
```

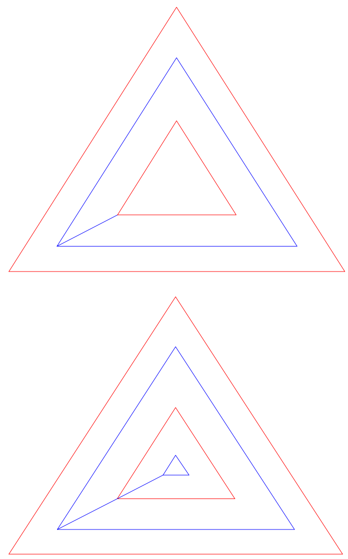
B. Removal Method for the Residual in the Center of the Pocket

The relationship between the tool and the work surface may cause a residual of material in the center of the pocket. This occurs when the normal distance (A) from the pocket center to the nearest segment of the last contour meets this condition: $R < A < 2R$ [Figure 4(a)]. In this way, a solution which is to add a reduced loop automatically at the end in the pocket center if the previous condition is satisfied has been introduced. The reduced contour and passage segment between passes will be constructed according to the following algorithm, [Figure 4(b)].

```
Algorithm. 3
// Input: last CPO tool path {L_nj, α_j^n}.
// Output: CPO tool paths {L_(n+1)j, n+1}.
Begin
For the n^th contour CPO curve {
If: R < A < 2R add a loop with passage
segment:
```

$$M_n = \kappa * 3R/2 \sin\left(\alpha/2\right)$$

```
and Break.
Else if: Break}
End.
```



(a)

(b)

Fig. 4. Removal method for center residual R = 8.5 mm: (a) without appended loop, (b) with additional reduced loop.

C. Removal Method for the Residual between Passes

In contour milling, it is essential to ensure an overlap between passes for an efficient machining. The distance between the passes should not exceed the cutter diameter, then it is necessary to find a coefficient of a value between 0 and 1, which must be multiplied by the value of the diameter: ($2R * \kappa$) which represents the radial distance between passes. In this case, if the radial distance between passes is close to the tool diameter, the probability of appearance of unmachined regions is greater (Figure 6(a)).

To remove the residual material between passes, first it is essential to find the size of the non-machined area (Figure 5), which is:

$$F = \left(\frac{R - 2R*overlap}{\sin\left(\frac{\alpha}{2}\right)}\right) - R \tag{4}$$

with:

$$overlap = 1 - \kappa \tag{5}$$

The residual material disappears when $F = 0$. In this way the residual will not occur between passes (Figure 6(b)).

The value of the recovery coefficient (κ) becomes:

$$\kappa = \frac{\sin\left(\frac{\alpha}{2}\right) + 1}{2} \tag{6}$$

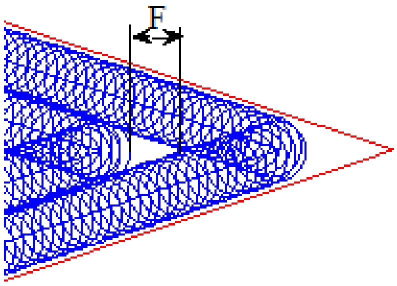
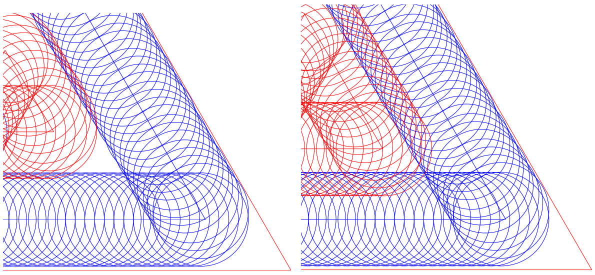


Fig. 5. Representation of the residual material size



(a) (b)

Fig. 6. Machining simulations: (a) with residual between passes in the corner, (b) without abandoned material.

IV. IMPLEMENTATION

The following program was implemented in MATLAB. It calls an algorithm called "length contour", which calculates the trajectories in CPO for any shape of pocket contour, whether concave or convex. The "Polygon Choice" function represents the shape of the pocket contour, where the input data consist of the lengths of the edges and the angles between them. This program performs machining simulation with a guide curve and considers the tool impact for any polygonal shape, calculating the tool path lengths.

Program

```
global fill
global usine;
global u;
global toolv;
global delay
delay =0.00001;
fill=0;                % colorel tool
u=0;                   %  tool impact
toolv =1.2;          %  tool speed
choice =1 ;          % Choice of polygon shape
[ A0 Af0 x0 y0 ang0] = Polygon Choice;
nar0=numel(A0);
 A0= A0;
xd=[2];
 ot=1;
   for o=ot:ot
    close all
    clc
    R0=xd(o)
    figure(1)
    scrsz = get(0,'ScreenSize');
    usine=0;
    nar=numel (A);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Define the corner points of the polygon
(Algorithm 1)
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
nar = numel (A);
P = zeros (nar + 1, 3);
z0 = 1;
grid on
i = 1;
P (i, 1) = x0;
P (i, 2) = y0;
P (:, 3) = z0;
P (i + 1, 1) = x0 + A (1);
P (i+1, 2)= y0;
P (i+1, 3) = z0;
ang=pi;
for i = 2: nar
    ang = ang + Af (i-1)-pi;
    P (i+1, 1) = P (i, 1) - A(i)*cos(ang);
    P (i+1, 2) = P (i, 2)+A (i)*sin(ang);
    P (i+1, 3) = P (i, 3);
end
P (:, 1) = P (:, 1) + x0;
P (:, 2) = P (:, 2) + y0;
P (:, 3) = P (:, 3) + z0;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Draw the polygon
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i = 1:nar
    xi = P (i, 1)
    yi = P( i, 2)
    xf = P (i+1, 1)
    yf = P (i+1, 2)
   pasoutil (xi ,yi, xf, yf, R, pass,
color );
    seg=[P (i,1), P (i,2), P (i+1,1), P
(i+1,2)]
end
 end
    usine = u;
    Lcont = LengthContour (A0, Af0, x0,
y0, ang0 ,R0);
    Lcont
    L(o) = Lcont
    grid off
    end
```

The "Contour Length" function included in the program calculates and generates tool trajectories based on the desired polygon choice.

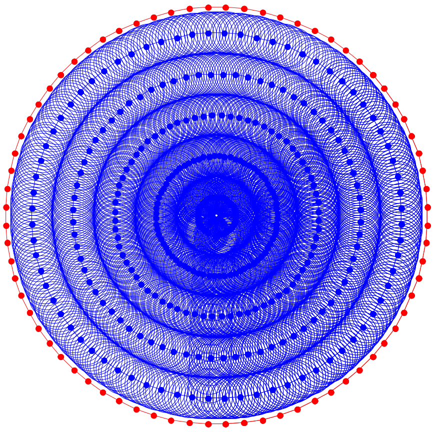
```
function Lcont = LengthContour (A0, Af0,
x0, y0, ang0 ,R)
[ A Af x y ang ] = Egale ( A0, Af0, x0,
y0, ang0 );
```

```
xi = x0;
yi = y0;
xe = xi;
ye = yi;
nbr = 0;
%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Definition of passage segment (pass =
Mi)
%%%%%%%%%%%%%%%%%%%%%%%%%
while(Dmax > R)
     if nbr == 0
        siam = R+0.00;(e=0.00 for the
first contour)
        pass = siam/sin(Af (numel(Af))/2);
    else
        Afro = Af;
        Afro(numel (A)) = [];
        siam = 2*R*Ro (Ro =K=
(sin(min(Afr0/2))+1)/2))
        pass = siam/sin(Af (numel
(Af))/2);
        rem = 0;
    end
[At,Aft,xt,yt,angt]=contoursegments
(A,Af,x,y,ang,siam );
Att,Aftt,xtt,ytt,angt]=contoursegments(A,A
f,x,y,ang,siam/2 );
    if max(At)<=0
        break
    end
    if abs (max(At)) > abs (max(A))
        break
    end
    if min (At) < 0
        ind = MinIndex(At);
 (Algorithm 2)
 [A Af x y ang] = Disappeared Edges (
A,Af,x,y,ang,ind);
        xt=xt+pass*cos (Af(numel
(Af))/2+ang);
        yt=yt+pass*sin
(Af(numel(Af))/2+ang);
   else
        nbr = nbr+1;
        x=x+pass*cos (Af (numel (Af))/2 +
ang);
        y=y+pass*sin(Af (numel(Af))/2 +
ang);
      PocketMachining (A, Af, x, y, ang,
R, pass, 'b');
        xe=x;
        ye=y;
        Lpass = Lpass + Spass;
        Lpoly = Lpoly + sum (A);
    end
    if numel(A)<3
        break
    end
end
Lpass;
Epass;
Lpoly;
Lpass=Lpass+Epass;
q=Lpass+Lpoly;
Lcont=m.*q; (m: number of contours)
end
```

A. Test Cases

Typical arbitrary pocket profiles having line-line entity combinations have been tried for testing the methodology and the algorithms. The test cases were selected to prove the effectiveness of the machining simulation for several pocket shapes, either concave or convex. For example, Figure 7 portrays a pocket with convex boundaries, where the machining simulation is realized with guide curve and tool impact. Figure 8 illustrates another example for an arbitrary convex shape, where the automatic addition loop is observed in the center of the pocket (Figure 8(b)), whose purpose is to remove the residual material. It is also noticed that few short edges are removed automatically.

(a)



(b)

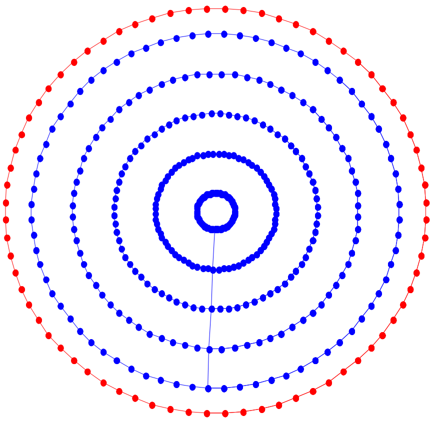


Fig. 7. Machining simulations for convex polygon: (a) tool impact, (b) guide curve.

However, many profiles of pockets can be considered to be combinations of convex and concave profiles. One case tested using this program is a pocket of a 6 pointed star shape, evidenced in Figure 9, where a simulation with a coefficient κ = 0.98 causing a residual material between passes, is presented (Figure 9(a)) with a reduced tool path length compared with that of κ = 0.8535, but without any abandoned material.

(a)

(b)

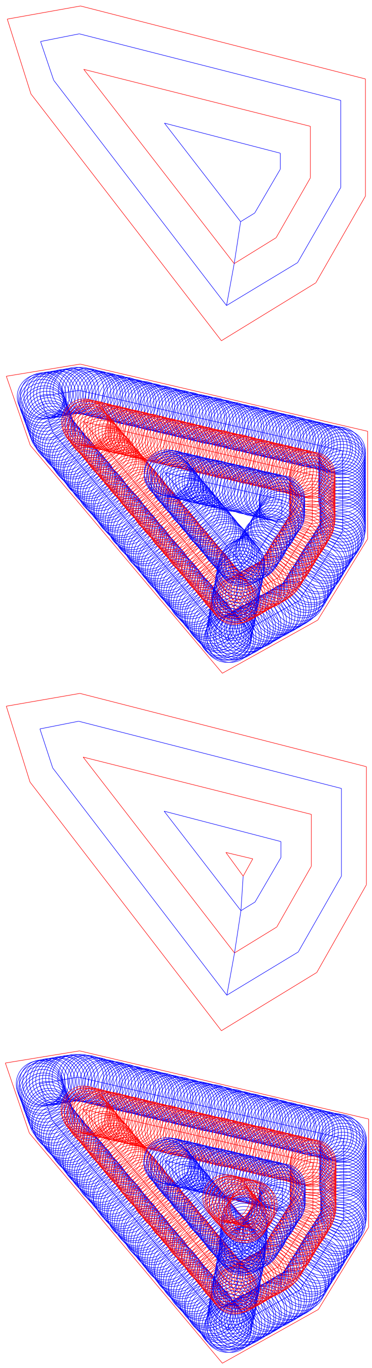


Fig. 8. Remove of center residual for an arbitrary polygon: (a) without appended tool path, (b) with a reduced loop.

B. Conversion of the program into real machining

The program presents the coordinates of the segments (*xi yi, xf yf*) of the offset contours in the result file, as displayed in Figure 10. These coordinates can be transferred directly to the machine tool for real machining with the G01 function. Figure 11 confirms that the real machining and tool impact simulation are identical and that perfect machining without residual materials between passes or in the center of the pocket has been achieved. This figure presents a simulation and real machining of a equilateral triangular pocket (80 mm of edges length) using the coordinates of the result file with tool radius equal to 5 mm.

(a)

(b)

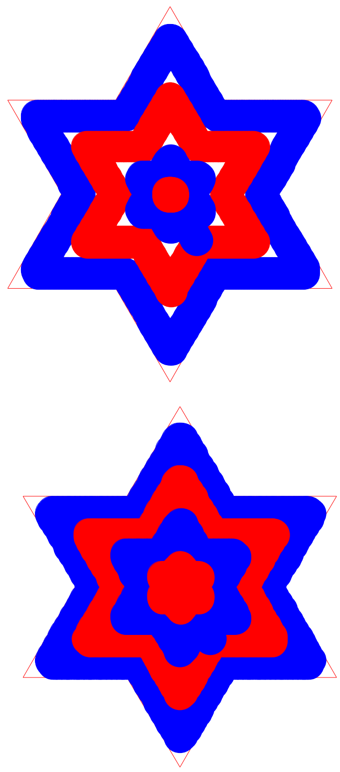


Fig. 9. Machining simulation for a 6-pointed star shape with tool radius R= 8 mm (a) with residual material (F > 0), (b) without uncut region (F=0).

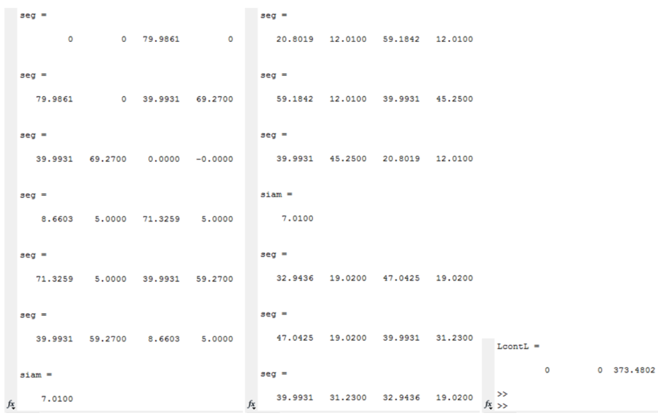


Fig. 10. Coordinates of contour segments and total toolpath length in the result file.

(a)

(b)

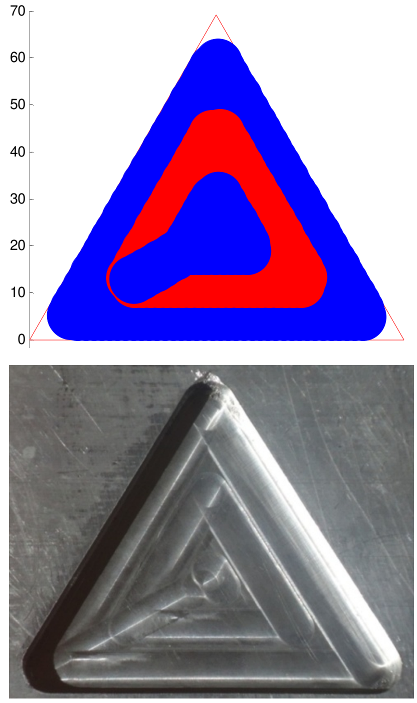


Fig. 11. CPO tool paths: (a) machining simulation, (b) real machining.

(a)

(b)

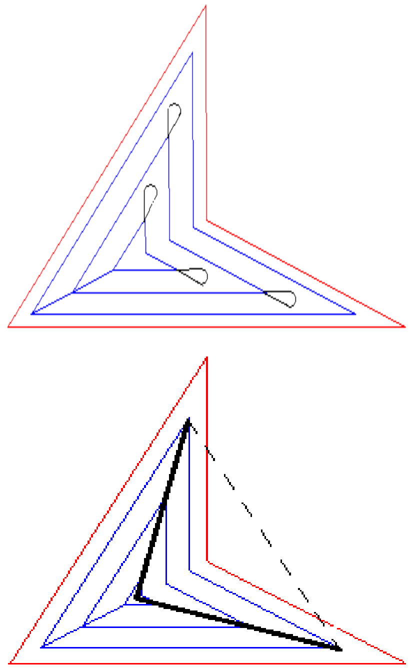


Fig. 12. Additional tool paths: (a) loops, (b) segments.

V. METHOD COMPARISON

FAO software such as Mastercam, PowerMill, generates tool paths in CPO for any polygon, with the ability to view machining simulations in animation and create a machine program in G-code. However, the drawback is that FAO software does not take into account residual material issues between contours, especially in corners, because the distance between passes is always determined by the user. As a result, the user will spend time selecting the correct distance between passes to avoid the appearance of uncut areas. On the other hand, the methods found in the literature are divided into two categories: those that generate CPO tool paths for specific polygons, namely rectangles, triangles, or regular polygons. The second category includes methods for resolving residual material problems left behind after machining. For example, authors in [20] used compensation segments to machine the uncut area overlooked in CPO tool paths. Authors in [21] introduced loops at the vertex points of the offset contours. Another method that can completely eliminate residual material without cutting compensation is demonstrated in [22] and involves detecting uncut regions through geometric analysis and eliminating them with additional segments along the bisectors.

The following examples show a comparison with these methods, whose goal is to minimize the total tool path, thereby reducing cutting time. The authors of these works utilize a wide pass distance (close to the tool diameter) to reduce the total path. However, taking a wide distance between passes causes material leftovers between the passes in the corners. To eliminate these material leftovers, additional passes are introduced in the form of segments or loops as exhibited in Figure 12.

We chose two pocket contour shapes (concave and convex), and tool diameter of 8 mm.

For the first example, when the distance between passes (siam) is taken as 7.2 mm, the areas left by the tool in the corners between passes are clearly demonstrated (Figure 13). CPO toolpaths are minimized, as depicted in Table I (584.84 mm), but adding loops at each discontinuity or segment to remove material residues makes the total toolpath longer compared to our approach (Table I).

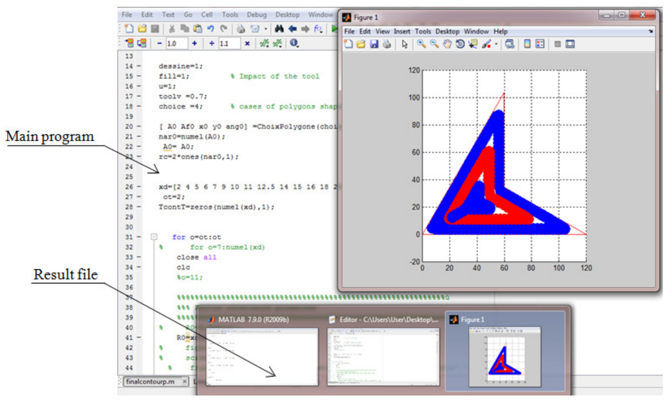


Fig. 13. Machining simulation result for the concave shape.

For the convex shape, the distance between passes is also set at 7.2 mm. Consequently, material residues are left in the corners between passes after machining. This necessitates additional toolpaths such as loops and segments along the bisectors (Table I). In contrast, the proposed approach without adding extra toolpaths provides perfect machining (Figure 14).

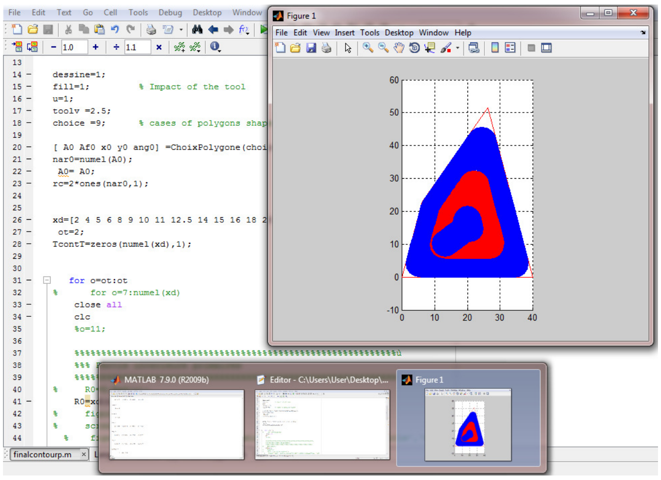


Fig. 14. Machining simulation result for the convex shape.

All these examples clearly demonstrate the effectiveness of the proposed algorithms for any polygon of arbitrary shape, convex or concave, without any uncut areas either in the center of the pocket or in the corners between passes. The considered methods employ an additional algorithm alongside the CPO tool path generation algorithm. Moreover, the additional algorithm is linked to a specific pocket contour geometry. On the other hand, the proposed approach deploys only one tool path calculation algorithm without adding segments or additional loops, which minimizes computation time. Thus, the tool path generation is done automatically based on the initial data. Additionally, a machining simulation in animation is produced simultaneously with the coordinates of the segments of each offset contour, which allows visual control of the machining process.

TABLE I. METHOD COMPARISON

Pocket shape (mm)	Methods	Tool Radius (mm)	Initial CPO-length (mm)	Add-segments (mm)	Add-loops (mm)	Total path length (mm)
Concave	Proposed	4	747.30	00.00	00.00	747.30
	[22]	4	584.84	244	00.00	828.84
	[21]	4	584.84	00.00	382	966.84
Convex	Proposed	4	194.26	00.00	00.00	194.26
	[22]	4	165.79	67.00	00.00	232.79
	[21]	4	165.79	00.00	58.00	223.79

VI. CONCLUSION

The proposed approach offers automatic CPO tool path generation for any polygon, whether concave or convex, without residual material, based on the geometry parameters of the pocket contour and the tool diameter. This also includes a machining simulation with animation, allowing for visual control of the machining process. Additionally, the result file contains the total length of the tool path and the coordinates of the segments of the offset contours, which can be directly transferred to the machine tool for actual machining.

In terms of execution speed, the comparison tests disclose that the proposed approach offers reduced cutting time compared to methods that add compensatory loops or segments, given the optimized path obtained. In terms of novelty compared to other methods, the approach introduced provides a solution that addresses the shortcomings found in FAO software and CPO tool path generation methods. The presented examples demonstrate the effectiveness of the proposed program for any arbitrary polygonal shape, whether convex or concave, without any uncut areas either in the center of the pocket or in the corners between passes.

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AUTHOR PROFILES

Elhachemi Bahlouol was born in Batna, Algeria, in 1970. He received the Ph.D. degree in the Mechanical Construction from Batna 2 University, Batna, Algeria, in 2017. He is currently a Professor in the Department of Mechanical Engineering, University of Batna 2. His research interests include machining optimization and CAD/ CAM.

Khelifa Guerraiche was born in Biskra, Algeria, in 1963. He received the Ph.D. degree in the Mechanical Construction from Biskra University, Biskra, Algeria, in 2014. He is currently a Professor in the Department of Mechanical Engineering, University of Batna 2. His research interests include Machining Optimization, CAD/ CAM, and finite elements.