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INVESTIGATED AN ALGORITHM OF CIRCULAR INTERPOLATION FOR CNC-MILLING OPERATION

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ABSTRACT :

In this research an algorithm to generate NC tool path had been developed for machining sculptured surfaces depending on the preparation functions (G02, G03) which are special type of circular interpolation and compare it with the other paths of the linear interpolation that generated using (G01) function from package program. In the design stage Bezier technique had been used to represent the proposed surface. Mathematical equations to estimate (radius of curvature, normal vector of the curve, cutter contact & cutter location points) had been driven to generate a tool path and get the (G-code).The MATLAB program had been utilized so as to facilitate the process of calculation. In addition, four types of tool path strategies had been selected based on linear interpolation using (UGS) program which are {Zig, Zig-Zag, Zig in (w) and Zig- Zag in (w) direction}. A comparison between G-code type of circular interpolation and G-code type of linear interpolation had been done for each type of selected tool path strategies with the original data of the proposed design form. A practical aspect side had been implemented using 3-axis vertical CNC milling machine for eight specimens which are divided into two groups: four specimens for the G-code that generated using the proposed method and the others for the G-code generated using the (UGS) program. The proposed algorithm had been implemented and the results showed that the specimen of the type Zig in (w) direction that generated depended on circular interpolation gave closer to the original surface results, compared it to linear interpolation of the path type Zig-Zag in (w) that generated using UGS program.

Keywords: tool path generation, free form surfaces, Bezier technique, circular and linear interpolation.

تحقيق خوارزمية للاستكمال الدائري لعملية التفريز باستخدام ماكنة السيطرة الرقمية

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الخـلاصـة :

في هذا البحث تم بناء وتطوير خوارزمية لتوليد مسار العدة لبرامج مكائن التفريز ذات التحكم العددي لتشغيل السطوح المتعرجة واستحداث (G-code) بالاعتماد على نوعين من الدوال التحضيرية (G03،G02) والتي هي نوع خاص لدالة الاستكمال الدائري ومقارنتها مع مسارات اخرى من نوع الاستكمال الخطي والمتولدة باستخدام دالة (G01) من برنامج جاهز. حيث تم استخدام مفهوم "Bezier" للمنحنيات والسطوح لتمثيل السطح المقترح. كذلك تم اعداد المعادلات الرياضية لحساب (نصف قطر منحني التقوس، المتجه العمودي على المنحني ،نقاط موقع العدة للماكنة ونقاط التماس مع السطح والحصول على ال (G-code) وتوليد مسار العدة. حيث تم استخدام برنامج (MATLAB) لتسهيل عملية الحسابات. بالإضافة الى ذلك تم اختيار اربعة انواع من استراتيجيات مسار العدة والتي هي :

(Zig، Zig–Zag، Zig in (w) ، Zig– Zag in (w)) . وقد تم مقارنة (G–code) من نوع الاستكمال الدائري للطريقة المقترحة و (G–code) نوع الاستكمال الخطي لكل نوع من استراتيجيات مسار العدة التي تم اختيارها مع بيانات الشكل المصمم الاصلي ، وقد اجري الجانب العملي باستخدام ماكنة تفريز عموديه ذات تحكم رقمي للعينات الثمان والتي قسمت الى مجموعتين (اربعة عينات بالاعتماد على (G–code) المتولد باستخدام برنامج (UGS) واربعة باستخدام (G–code) المتولد من الطريقة المقترحة) . اظهرت النتائج للنماذج المصنعة التالي: عينة المسار من نوع ((Zig in (w) المتولد بالاعتماد على الطريقة المقترحة اعطت نتائج اقرب الى بيانات السطح الاصلي ،مقارنة مع عينة المسار من نوع ((Zig–Zag in (w) المتولد ببرنامج (UGS) .

1. INTRODUCTION :

The development of a new product is an iterative process, which includes: product design, analysis of performance, safety and reliability, product prototyping for experimental evaluation and design modification, where computer aided design is usually associated with interactive computer graphics, and the designer can conceptualize the object to design it more easily on the graphics screen and consider alternative designs or modify a particular design quickly to meet the necessary design requirements or changes . **As for** the tool path generation method that can be used generate tool path curves, in recent years, many algorithms had been developed. [Chen, et al-2008] studied tool-path generation for three-axis ball-end milling. Although their study was based on triangular meshes, a fourth-order polynomial derived using differential geometry was proposed for determining path intervals. **[Zhang, et al-2012]** addressed four tool path strategies such as equal-interval tool paths, parallel tool paths, parallel–tangency tool paths and free form tool paths. The objective of their study is to understand how 3D tool paths influence their machining efficiency, surface quality and form accuracy. [Tao Chen and Peiqing Ye-2002] presented a strategy to generate interference free tool path for machining sculptured surface. The proposed algorithm generated optimum CL data with the determination of path interval . The objective aim of this study is to develop an algorithm of generate NC tool path for machining sculptured surfaces depending on the preparation functions (G02, G03) which are special type of circular interpolation and compare it with the other paths of the linear interpolation that generated using (G01) function from package program.

2. CONSTRUCTION OF PROPOSED METHOD :

Fig. (1) Illustrate the structure of the proposed method in the present research.

3. REPRESENTATION SURFACE DEPEND ON BEZIER TECHNIQUE:

In the present research Bezier surface was selected, which is a direct extension of a Bezier curve. The underlying principle in defining a Bezier surface is that to let a point trace out of Bezier curve and then let this curve sweep out a Bezier surface [Tong,et al-2001] .

The simple extension for three dimensional free–form surfaces from 3-dimensional free-form curve is by incorporating another parameter (w) to the vector equation of the curve to obtain the surface equation:

$P(u,w)= [x(u,w)\ y(u,w)\ z(u,w)]$

Where: $0 \le u, w \le 1$ (u,w) are independent variables.

This equation is called bivaraite parametric equation since it includes two variable parameters in two various directions.

The Bezier's curve of n-degree with the control points can be represented as(Mortenson 1997):

$$P(u) = \sum_{i=0}^{n} B_{n,i}(u)\, p_i \qquad \textbf{(1)}$$

Where the basic function are [Prahasto -1999]:

$$B_{i,n}(u) = \frac{n!}{i!(n-i)!} u^i (1-u)^{n-i} \qquad \textbf{(2)}$$

The use of higher degree causes small oscillations in curve and requires heavy computations. So in this research Bezier surface with order $n \times m = 6 \times 6$ was selected.

By the mathematical derivation, the general equation to represent the Bezier surfaces of higher degrees can be shown as follow [Akeel S. B.-2006]:

$$P(u,w)= [U]\ [MB]\ [P]\ [MB]^T\ [W] \qquad \textbf{(3)}$$

$[U] = [\ u^5\ \ u^4\ \ u^3\ \ u^2\ \ u\ \ 1]$

$[W]= [W^5\ \ W^4\ \ W^3\ \ W^2\ \ W\ \ 1]^T$

Where the final Bezier matrix has been derived bellow:

$$MB = \begin{bmatrix} -1 & 5 & -10 & 10 & -5 & 1 \\ 5 & -20 & 30 & 10 & 0 & 0 \\ -10 & 30 & -30 & 10 & 0 & 0 \\ 10 & -20 & 10 & 0 & 0 & 0 \\ -5 & 5 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

So, according to these equations above and by select a different control points across x, y and z –axis using MATLAB program, it can be obtain the surface as shown in **Fig. (2)**:

It must be notice that the M-program that was built to obtain the surface in **Fig. (2)** should be saved in (dat) extension so as to can open it in UGS program.

4. REPRESENTATION SURFACE USING UGS PROGRAM:

After saving the program that described the sculpture surface in the form of dat-extension using the program that was built in MATLAB language, now it can be use CAD/CAM program (UGS) to open this file which represent all points of the surface in X,Y and Z direction.

Procedure:

- Import the dat-extension file from MATLAB files and open it in UGS program using Spline order. Then it must be select the order through points. After that it can be detect the path of the dat-extension file that was saved .
- Draw splines that pass through all the points using Through Curve order. Then select (Ok) so as to get the surface of the points after connected them and the convent the surface to solid **Fig. (3) .**

- Make a program for this solid surface of work piece so as to get the tool path in 3-axis direction, and then make simulation for the machining. Four types of tool path strategies will be presented in UGS and will be adopted in this study as shown in **Fig. (4).**

-Get the G-code in 3-axis for the four types of tool path using the postprocessor order **Fig. (5).**

It can be noticed from **fig. (5)** that the shape of sculpture surface that created using MATLAB program is the same shape when it was opened in UGS program. Also, it can be noticed that the proposed shape include concave and convex surface and it's not just a plane. So, this means that the program and the procedure that followed in the proposed research is prosperity with complex surface.

5. PROPOSED MATHEMATICAL ALGORITHM

For the purpose of implemented a program to get G-code for tool path generation, an algorithm had been adopted to obtain the (G-code) based on the mathematical equations that have been derived in the present research. MATLAB program had been utilized so as to facilitate the process of calculation depending on circular interpolation using (G02, G03), to demonstrate the investigated method it was necessary to calculate the variable bellow:

1. Radius of curvature and normal vector of a curve.
2. Cutter contact and cutter location points.

5.1 Radius of curvature and normal vector calculation at a point on the curve

Curvatures is the measures of how much a curve or surface "bends", These measures have applications in determining the quality, or isolating imperfections of the curves and surfaces produced by a designer using a CAD package. If the curve is described parametrically, an expression for curvature is shown below: let C(t) = {(x(t), y(t)} is regular parametric plane curve ,then The curvature of this curve can be calculated from this equation [Marsh, Duncan-2005]:

$$k = \frac{|\dot{C}\times\ddot{C}|}{|\dot{C}|^3} \qquad \textbf{(4)}$$

Where:

$\dot{C}$=the first derivative for the parametric equation of the curve C(t) respect to x & y direction.

$\ddot{C}$= the second derivative for the parametric equation of the curve C(t) respect to x & y direction.

Let t and n denote the unit tangent and normal vector (normal line) of a curve C, defined by the equation: or (let t & n represent the unit tangent and normal vector of C (t) curve):

$$n=b\times t \qquad \textbf{(5)}$$

The t tangent vector can be calculated by (unit tangent vector can be defined by):

$$t = \left|\frac{\dot{C}}{\ddot{C}}\right| \qquad \textbf{(6)}$$

b=unit vector which is perpendicular to the osculating plane, is called the binormal vector:

$$b = \frac{\dot{C}\times\ddot{C}}{|\dot{C}\times\ddot{C}|} \qquad \textbf{(7)}$$

The radius of curvature can be calculated depend on the curvature value by:

$$R=\frac{1}{K} \tag{8}$$

Fig. (6) Illustrate the curvature, radius of curvature, normal and tangent vector.

The absolute value of the curvature (k) of a plane curve at its regular point is equal to the curvature of **. its** osculating circle. The sign of (k) depends on the orientation of the normal line at this regular point.

5.2 Cutter Contact and Cutter Location Points detection:

the Cutter Location **(**CL) point is the point on the offset surface of the work piece, while the Cutter Contact (CC) point is the point on the cutter that contacts the work piece surface. Let (Pcc) be the CC point, r be the radius of the ball-end mill, the CL point (Pcl) is given by **[**Rogers, et al- 1989] :

$$P_{cl} = P_{cc} + r.n \tag{9}$$

Where r is the radius of the ball nose end mill cutter and n is the surface normal at cc point on the surface as shown in **Fig(7)** [Rogers and Adams-1989]**..**

according to this equations CC and CL points had been calculated and represented as shown in **Fig.(8)** for the proposed case study.

By using the mathematical calculations an algorithm had been suggested and developed depending on two types preparation functions (G02, G03) which are special type of circular interpolation. MATLAB program has been utilized to build up program to obtain G-code generate four types of tool path strategies which are {Zig, Zig-Zag, Zig in (w) and Zig- Zag in (w) direction}. Flow chart in **Fig. (9)** demonstrate the procedure of the proposed program.

- G-code for the four types of tool path had been generated **Fig. (10)** represent text file of one of the tool path type that was generate. Simulation of the G-code generated had been achieved with CIMCO software program (version 5.10.28) as shown in **Fig. (11)**.

6. EXPERIMENTAL WORK:

Experimental work must be done so as to compare the dimensions of the final shape with the profile that proposed .The effectiveness of the proposed strategy for both design and manufacture was demonstrated by actual machining with 3-axis CNC milling machine. As follow **Fig.(12)**:

7. RESULTS AND CONCLUSIONS :

The proposed algorithm for tool path generation of circular interpolation was developed and implemented successfully; through the integration of mathematical description used for calculating radius of curvature, normal vector of the curve, cutter contact & cutter location points, into the core of the proposed algorithm, additional contribution is related to representation of manufactured surface through the use of parametric curve and surface depended on Bezier technique .The results of the implementation of the eight specimens with different tool path strategies are presented. Then the variance and standard deviation for the data values between actual and experimental work had been analyzed. The specimens of the proposed algorithm and the specimens of (UGS) program had been compared with the reference to dimensions of the original design shape using a Digital 3D-Touch Probe. Minitab software program (version 17) had been used to make statistical analysis for the data obtained, the results of the manufactured specimens showed that the specimen of the type Zig in (w) direction that generated depended on circular interpolation gave closer to the original surface results with variance 0.119 and standard deviation 0.344, compared with linear interpolation of the path type Zig-Zag in (w) that generated using UGS program also gave the closest results compared to the original designed surface with variance 0.383 and standard deviation 0.394.

Fig. (13) and **Fig. (14)** Show the result of the measurement data for MATLAB and UGS programs in Microsoft Excel.

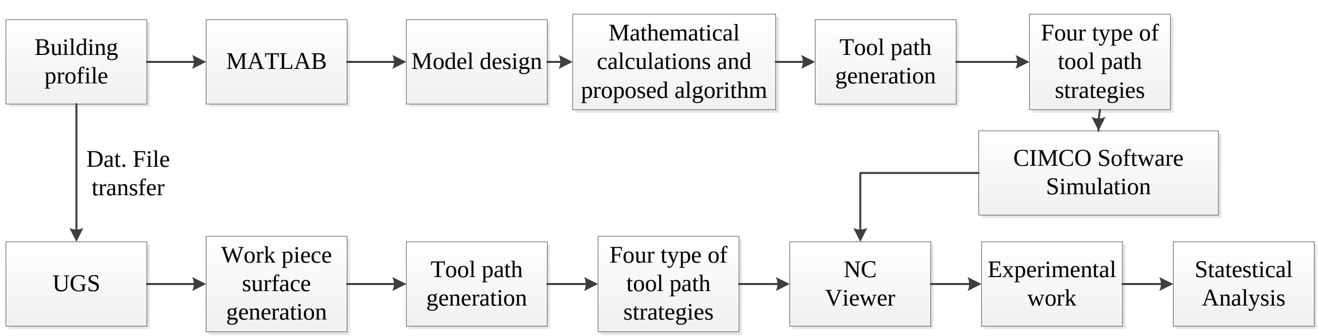


Figure (1): structure of the proposed method.

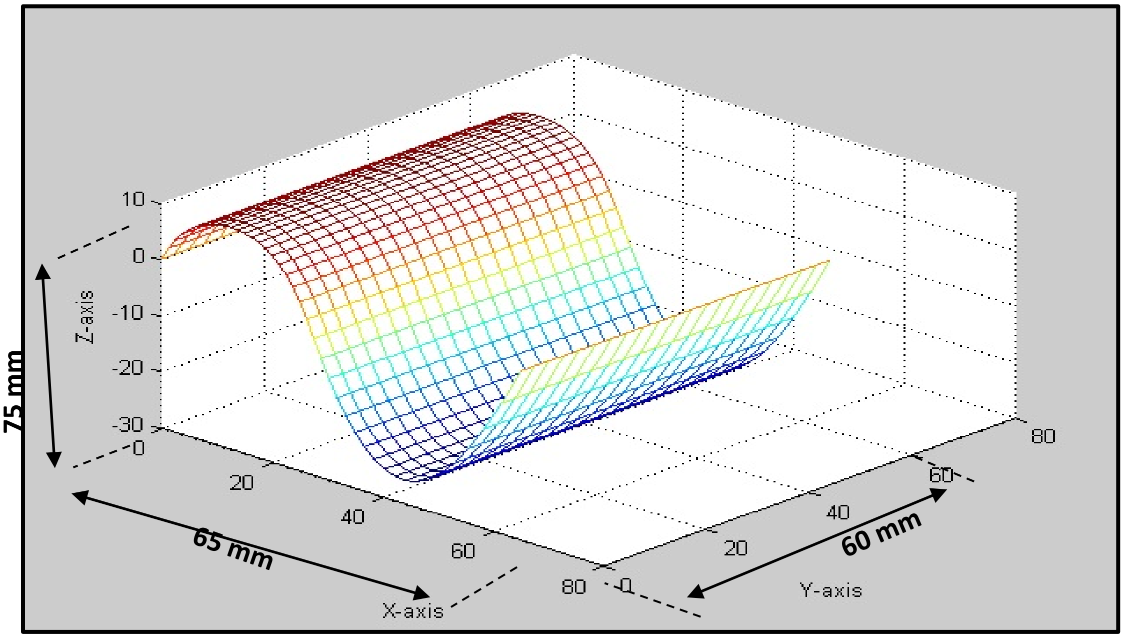
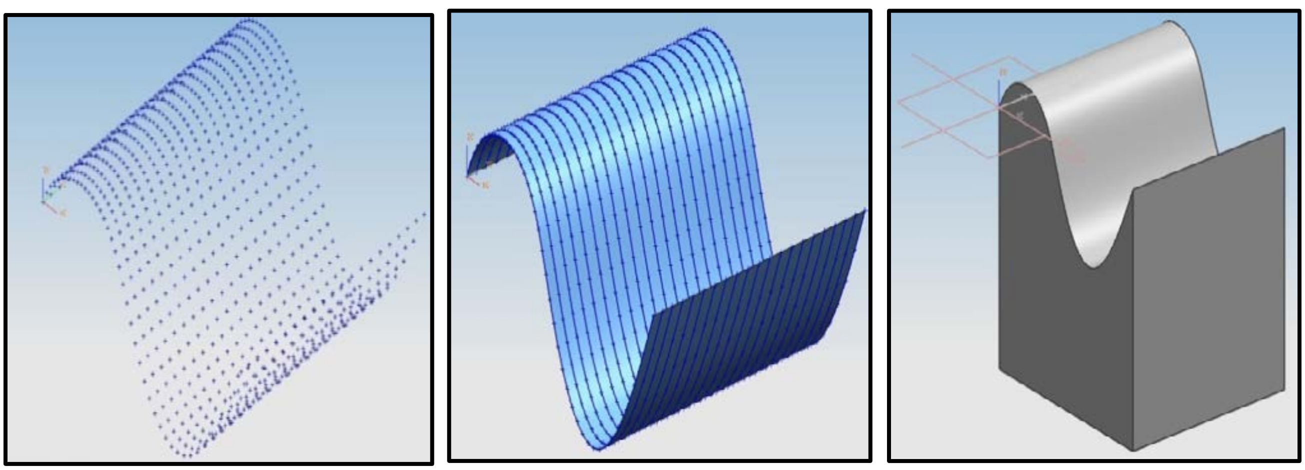
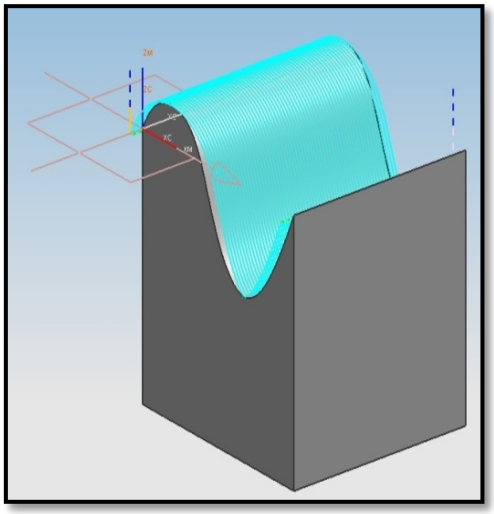


Figure (2): higher degree Bezier's Surface in graphical mode.

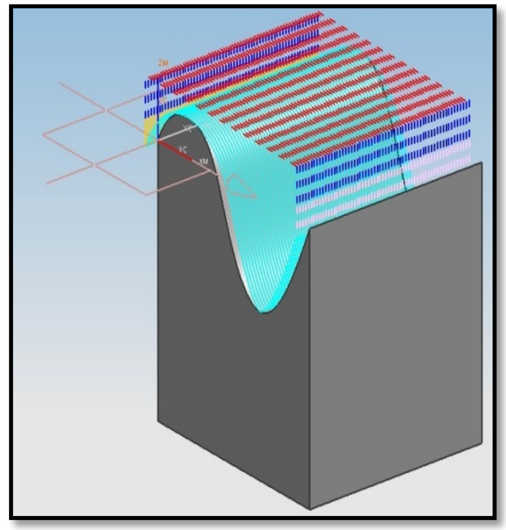


(a) (b) (c)

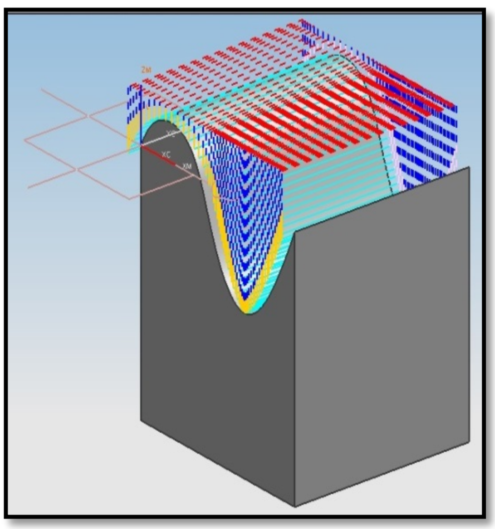
Figure (3): (a) The points that it can be import the dat-extension file and open it in UGS program.
(b) Surface of the points after connected them to each other.
(c) Block of work piece with the sculpture surface.



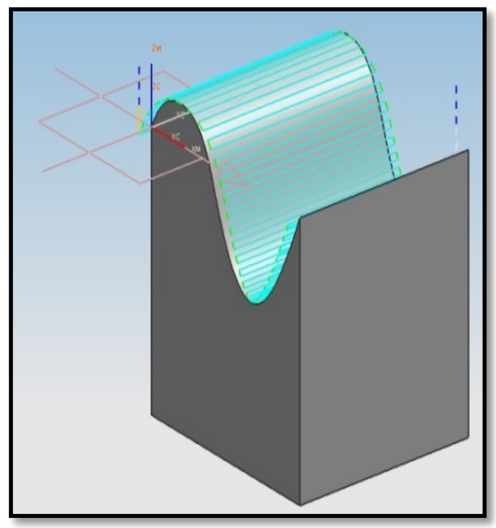
(a)



(b)



(c)



(d)

Figure (4) : (a) Zig tool path generation for the sculpture surface.

(b)Zig-Zag tool path generation for the sculpture surface.

(c) Zig in (w) direction tool path generation for the sculpture surface.

(d) Zig-Zag in (w) direction tool path generation for the sculpture surface.

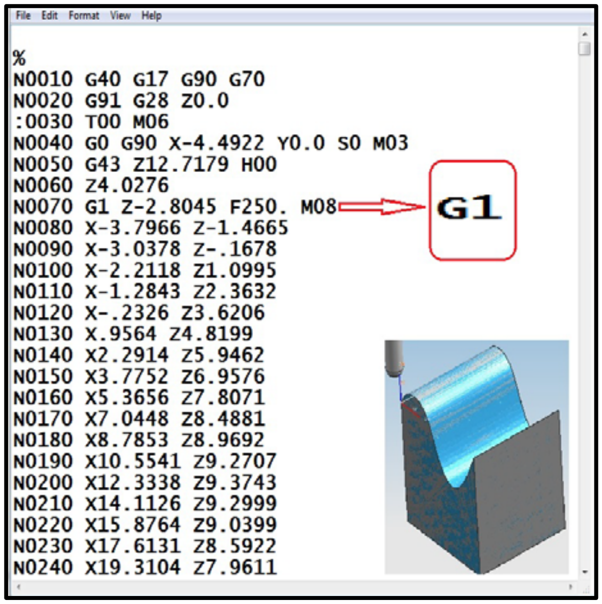


Figure (5): the G-code of one of these types of the tool path From UGS program.

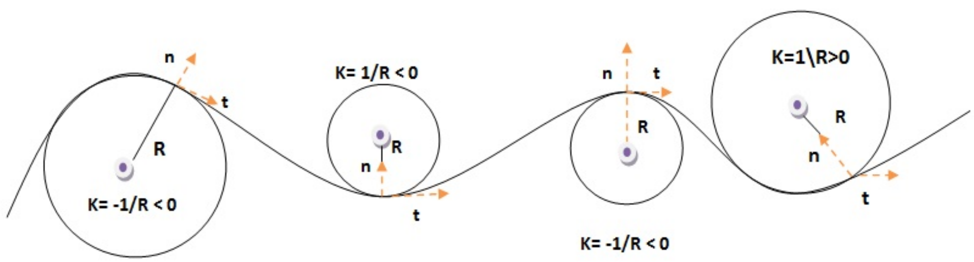


Figure (6): curvature, radius of curvature, normal and tangent vector of a plane curve.

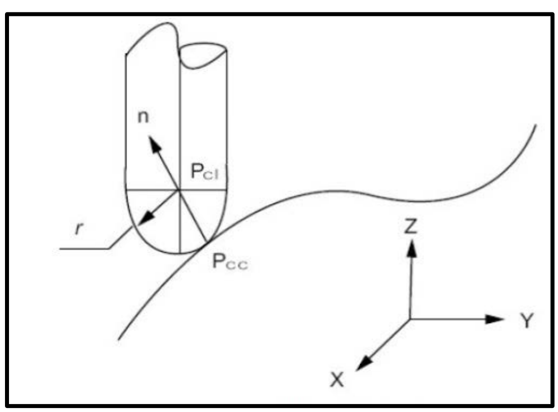


Figure (7): the CC and CL point [Rogers and Adams-1989].

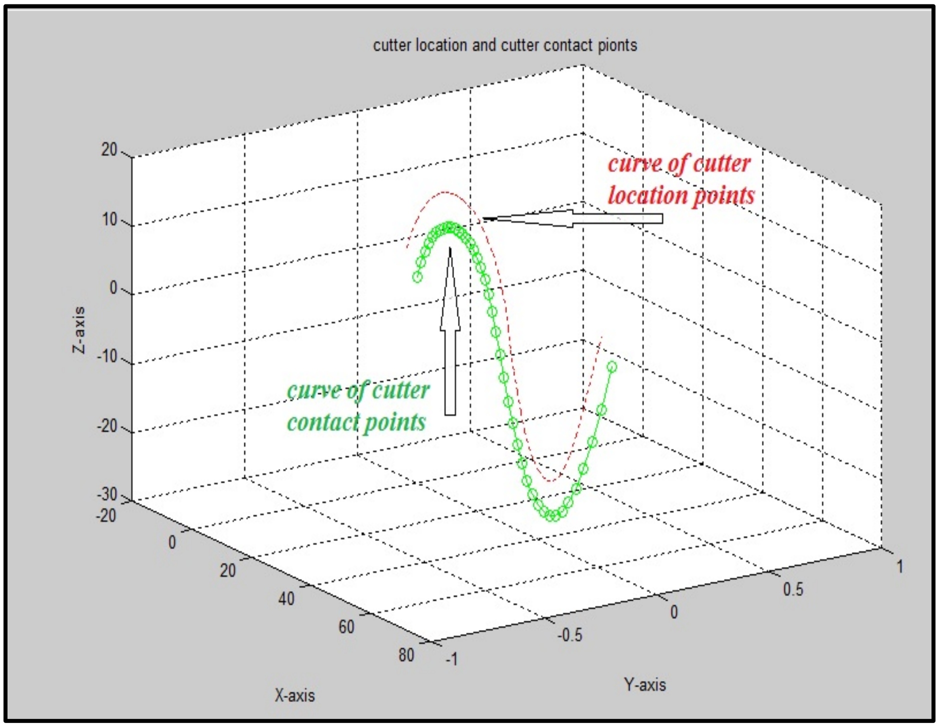


Figure (8): Demonstrate CC and CL detection using MATLAB software for proposed case study.

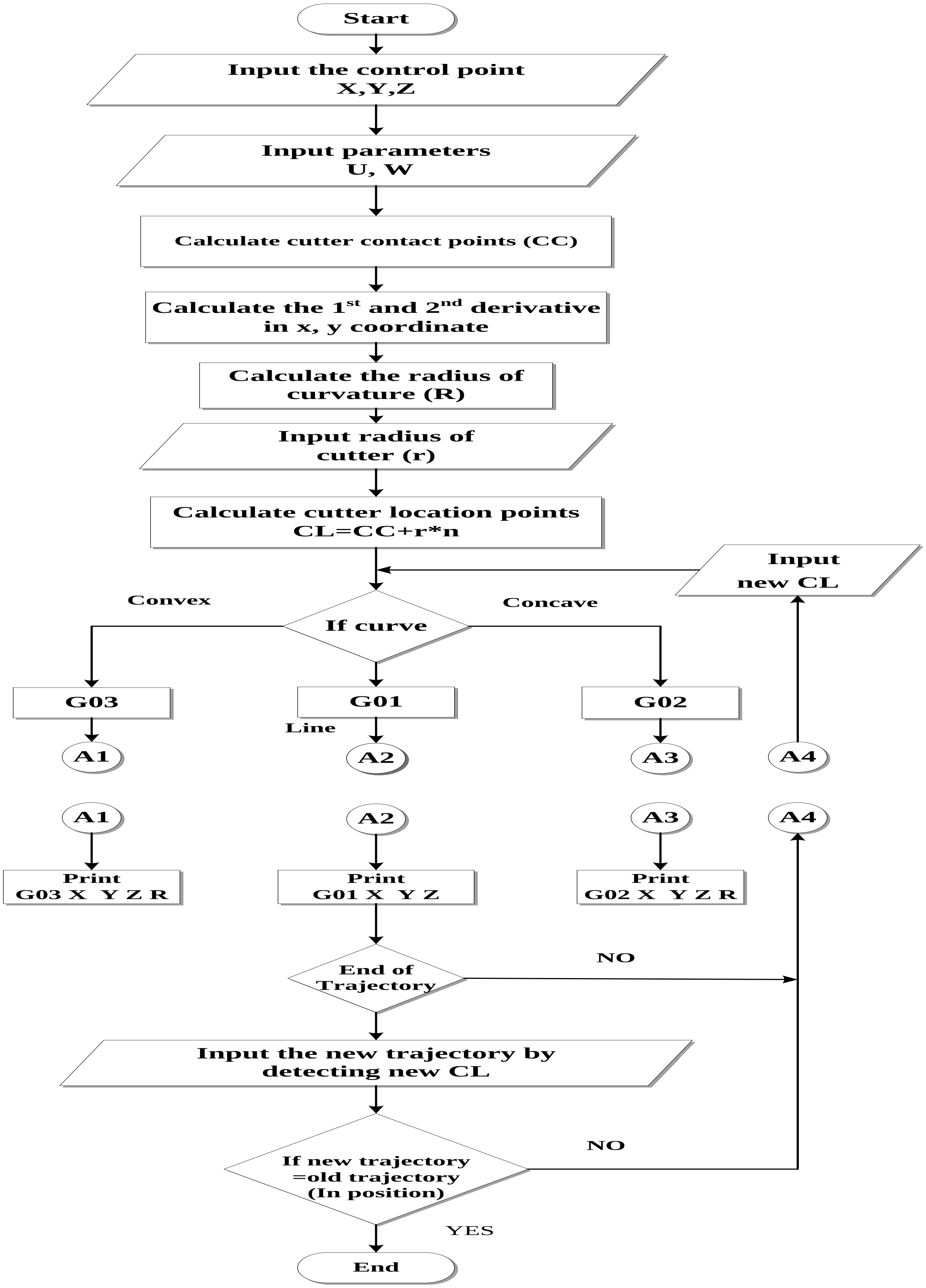
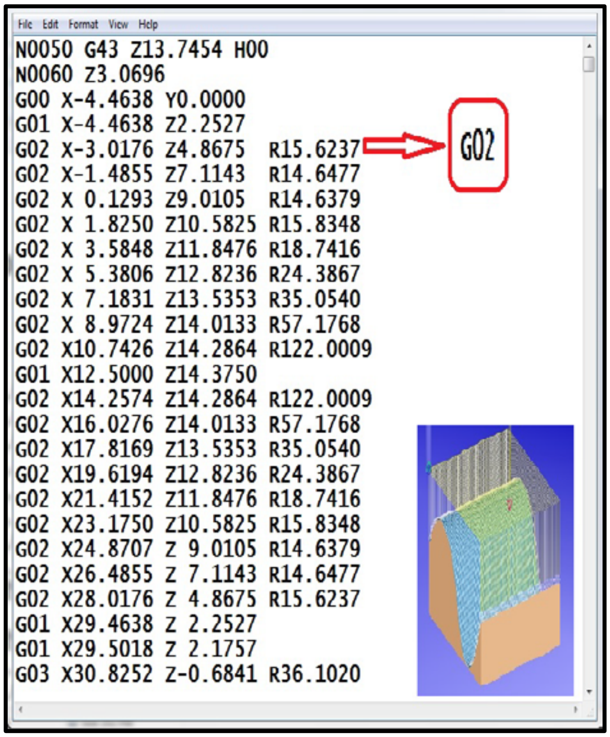


Figure (9): flowchart of circular interpolation algorithm using MATLAB software.



```
N0050 G43 Z13.7454 H00
N0060 Z3.0696
G00 X-4.4638 Y0.0000
G01 X-4.4638 Z2.2527
G02 X-3.0176 Z4.8675  R15.6237
G02 X-1.4855 Z7.1143  R14.6477
G02 X 0.1293 Z9.0105  R14.6379
G02 X 1.8250 Z10.5825 R15.8348
G02 X 3.5848 Z11.8476 R18.7416
G02 X 5.3806 Z12.8236 R24.3867
G02 X 7.1831 Z13.5353 R35.0540
G02 X 8.9724 Z14.0133 R57.1768
G02 X10.7426 Z14.2864 R122.0009
G01 X12.5000 Z14.3750
G02 X14.2574 Z14.2864 R122.0009
G02 X16.0276 Z14.0133 R57.1768
G02 X17.8169 Z13.5353 R35.0540
G02 X19.6194 Z12.8236 R24.3867
G02 X21.4152 Z11.8476 R18.7416
G02 X23.1750 Z10.5825 R15.8348
G02 X24.8707 Z 9.0105 R14.6379
G02 X26.4855 Z 7.1143 R14.6477
G02 X28.0176 Z 4.8675 R15.6237
G01 X29.4638 Z 2.2527
G01 X29.5018 Z 2.1757
G03 X30.8252 Z-0.6841 R36.1020
```


Figure (10): the G-code of the proposed tool path generation

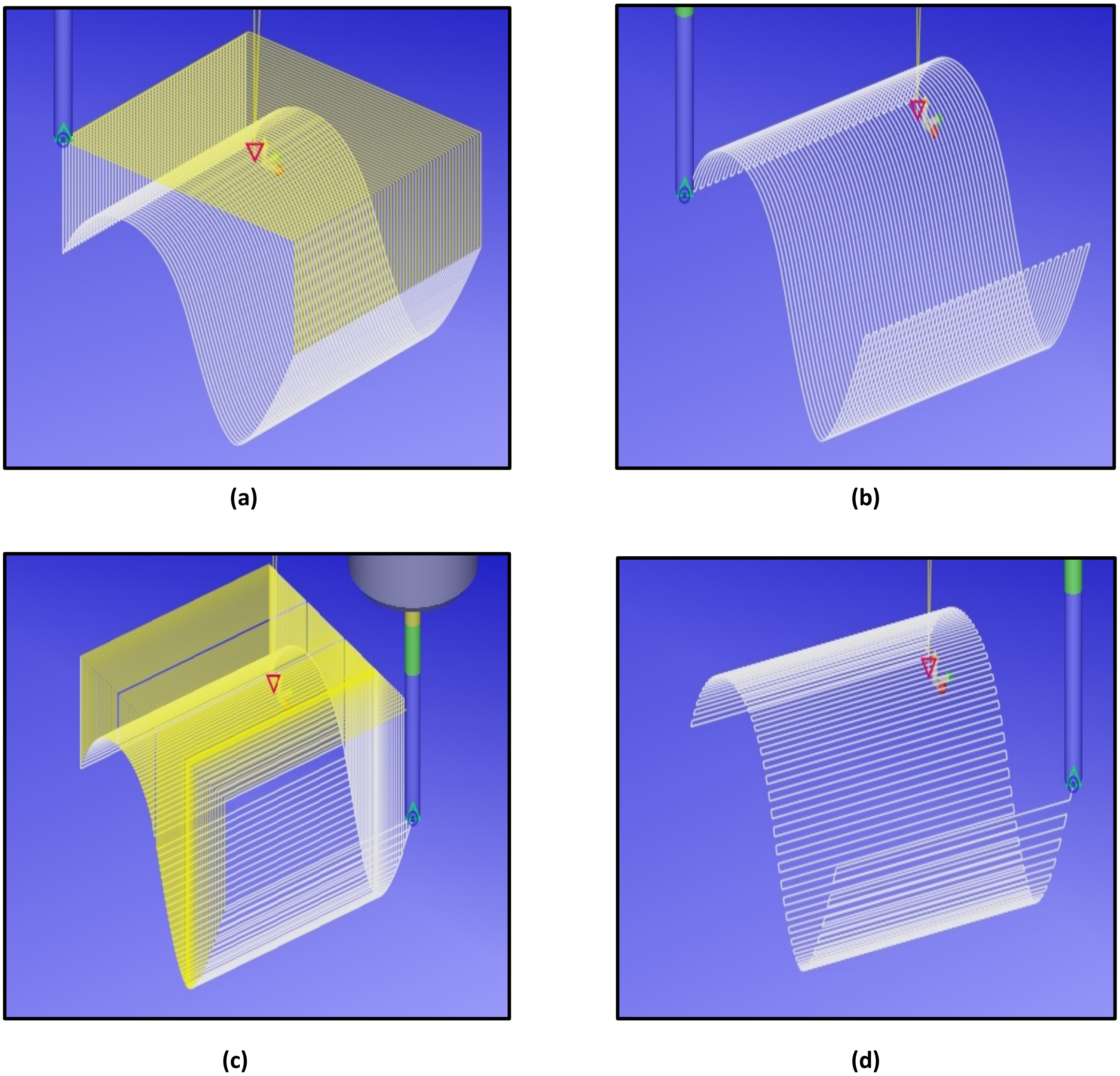


Fig. (11): tool path generation for the sculpture surface using circular interpolation where:

(a)zig tool path type . (b)zig-zag tool path type.

(c)zig in (w) direction tool path type . (d)Zig-Zag in (w) direction tool path type .

(a)

(b)

(c)

(d)

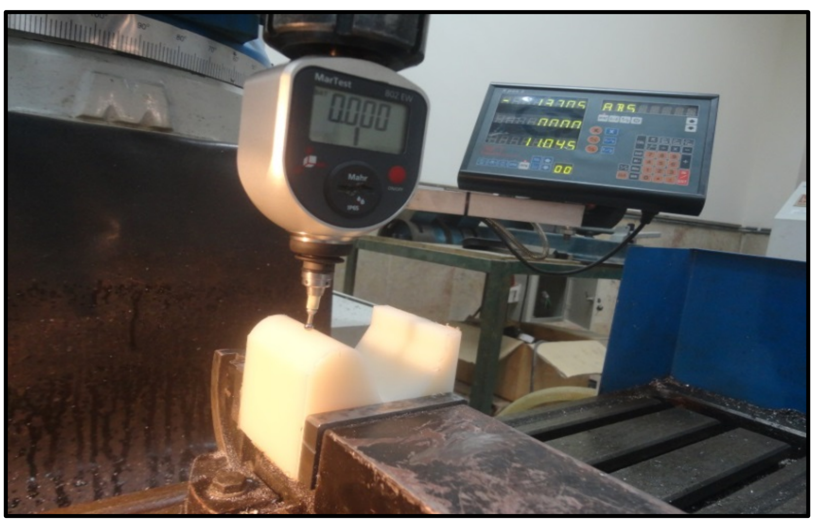


Figure (12): (a) The eight specimens before machining . (b) The specimens that had been implemented with 3-axis milling machine . (c) The eight specimens before machining. (d) The measuring of accuracy for the specimens for the proposed case study.

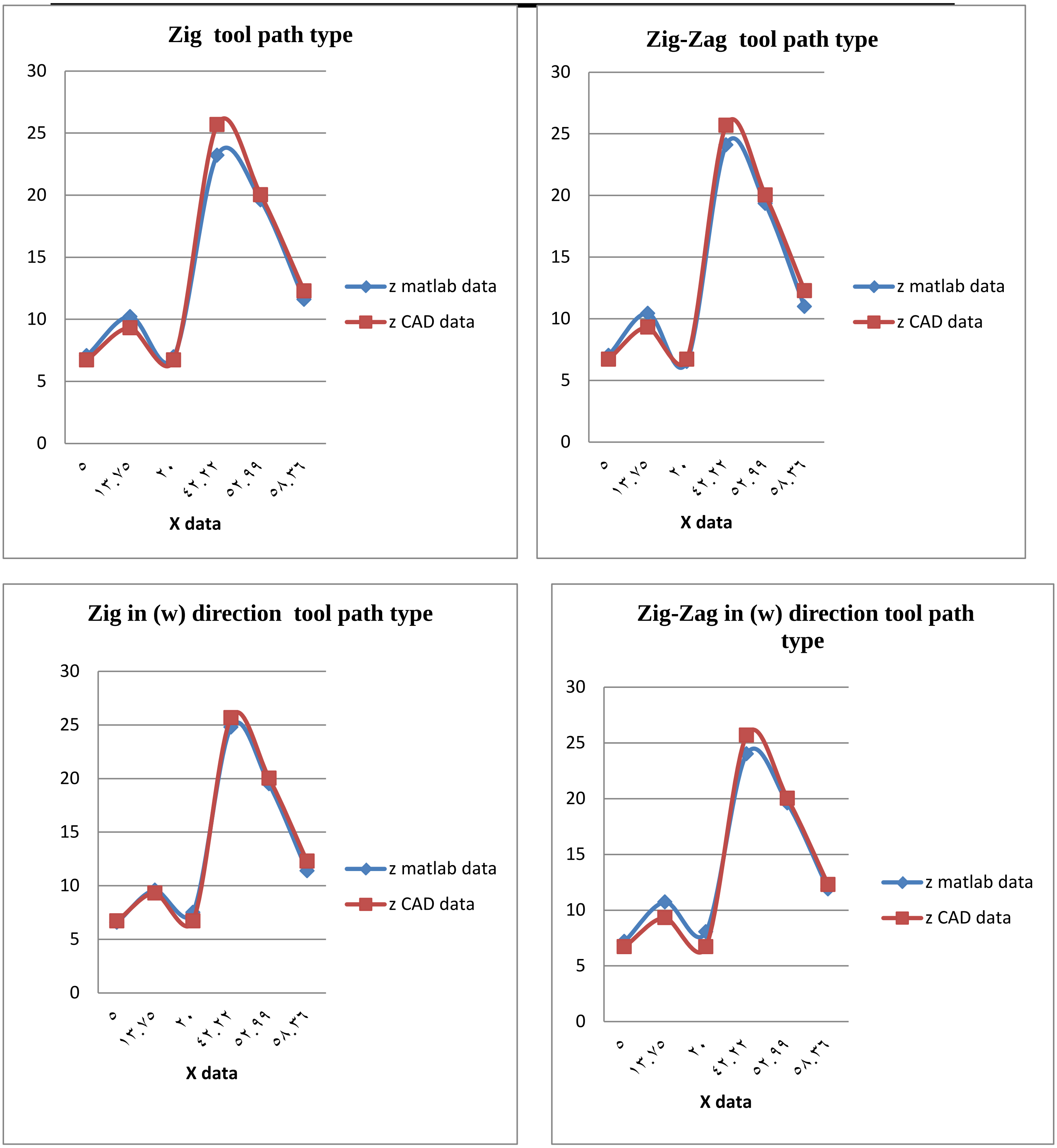


Figure (13): Comparison between CAD actual and MATLAB data tool path types.

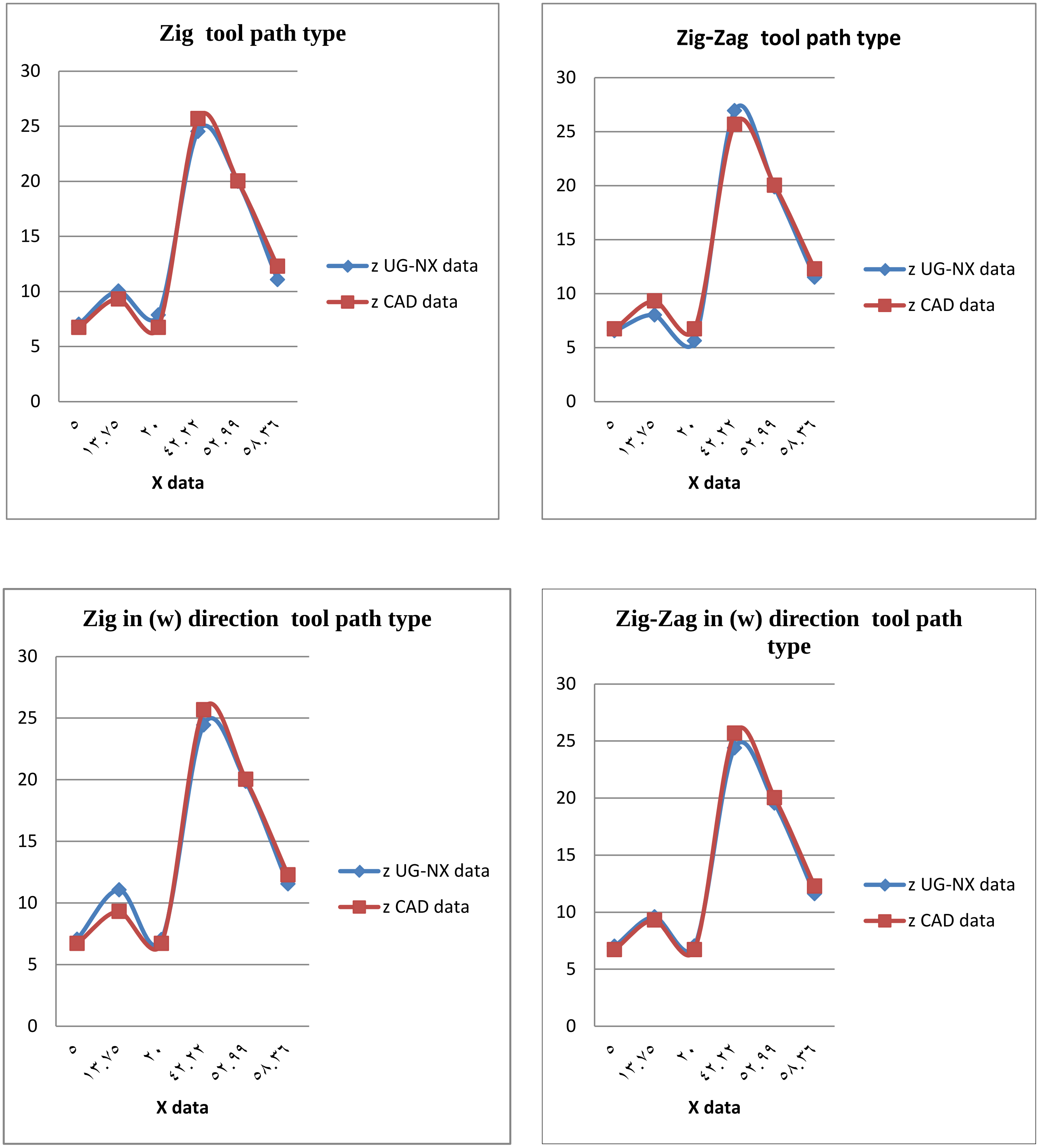


Figure (14): Comparison between CAD actual and UGS data tool path types.

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