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Research on Optimization of Freeform Surface Operation

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Nowadays, many manufacturing companies need to face competition both in domestic and international level. Due to this circumstance, manufacturers recognize that one useful method to enhance their competence is reducing the lead-time of manufacturing.

There are many researchers focused on minimize the time of actual cutting, tool path optimization and energy consumption optimization etc. However, few researchers have investigated the operation optimization of CNC machine that integrating multiple ways to reduce the operation time of freeform surface cutting. For example, integrating tool path calculation optimization and machining parameters optimization together for the sake of providing an optimization solution package to enhance the efficiency of manufacturing.

This master thesis will investigate the main optimization methods of tool path (Iso parametric, Iso planar and Iso scallop), as well as prediction of operation time and energy consumption optimization. Then we will provide several approaches for machining a surface on a metal rectangle to research the effect of different tool paths generation such as Iso parametric and Iso scallop etc. depend on NC code on machining time and quality.

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Preface

Since the industrial revolution, many manufacturers need to enhance their production efficiency in order to increase their competitiveness. Because CNC machine is the Irreplaceable production tool of the manufacturing, so improving the production efficiency of CNC machine is the main way to improve the competitiveness of the entire manufacturing company.

This master thesis will focus on three-axis CNC machine and the research direction is free surface operation. The three-axis machine is widely applied in machining free form surface parts. Many researchers have done several researches on free form surface operation, such as tool path optimization methods, energy consumption optimization, prediction methods etc. In the second part of this master thesis, there will be a detailed research report about three different main types of tool path optimization algorithm, which are iso parametric, iso planar and iso scallop, as well as prediction model and also including the optimization of energy consumption etc. In the case study part, a free form surface will be machined on a metal rectangle to test the effect of different tool path optimization methods.

In the process of making my master thesis, I received lots of help from different people. I would like to say thank you to my supervisor Gabor Sziebig and co-supervisor Sibul Lazar, I appreciate their selfless help and patient.

Dingjun Liu

Abstract

Nowadays, many manufacturing companies need to face competition both in domestic and international level. Due to this circumstance, manufacturers recognize that one useful method to enhance their competence is reducing the lead-time of manufacturing.

There are many researchers focused on minimize the time of actual cutting, tool path optimization and tool change time optimization etc. However, few researchers have investigated the operation optimization of CNC machine that integrating multiple ways to reduce the operation time of freeform surface cutting. For example, integrating tool path calculation optimization, prediction method and machining parameters optimization together for the sake of providing an optimization solution package to enhance the efficiency of manufacturing.

This master thesis will investigate the main optimization methods of tool path (Iso parametric, Iso planar and Iso scallop), as well as prediction of operation time and energy consumption optimization. Then we will provide several approaches for machining a surface on a metal rectangle to research the effect of different tool paths generation such as Iso parametric and Iso scallop etc. depend on NC code on machining time and quality.

1 Introduction

Three-axis machine is widely used in manufacturing parts within the world. The manufacturers are committed to achieve the highest production efficiency so as to enhance their competitiveness. To improve the CNC machines' production efficiency, we need to first know what is CNC machine and understand its working principle.

Today CNC machines have replaced manual machines that all paths and movements can be programed and controlled by computer and codes, which is more convenience than by hand, as well as decrease the total operation time and avoiding human errors [1]. CNC machine can also significantly increase the productivity by integrating Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Numerical Control (NC), which are described in the below Fig.1. Normally, the G code can be generated by CAD/CAM packages automatically from the specific software. However, the parameters such as tool path, feed rate and tool selection are obtained automatically from the program of the software that is not the optimized solution. Due to this circumstance, we will find some place to insert in our optimization program after analysis.



Figure 1 – Manufacturing process: CAD-CAM-PP-CNC

CNC machine (Computer Numerical Control) is a sort of production tool that encompasses different types of machines with variety of shapes, sizes and functions [2]. CNC machines can be divided into two distinct types, which are turning machines and milling machines. A turning machine is generally used to remove materials from the workpiece by spinning the workpiece at a high speed and then use the sharp edge of cutting tool to achieve the desired form [3]. A milling machine is a kind of machine that holds the workpiece with a clamp and then remove the materials to get the need shape with a special high-speed rotation cutting tool to spin and cut in many directions and move in three distinct directions along the x, y and z axis [4].



Figure 2 – Four-axis CNC machine, Three-axis CNC machine and CNC lathe.

Fig.2 shows the 4-axis CNC machine, three moving directions of a real CNC machine (3-axis) and CNC Lathe. The difference between those three types of CNC machine can be seen obviously. 3-axis CNC machine has no function of rotation in any axis. However, cutting tool can move in x, y and z directions to produce the required free-form surface. Three-axis CNC machine is not the most advanced machine nowadays, but it has variety of advantages such as high stability, simple operation etc. so that we decided to focus on 3-axis CNC machine.

Because at present there is an increasing demand of complex parts with aerodynamic shapes. Therefore, this master thesis will mainly focus on researching sculpture free-form surfaces with 3-axis Computer Numerical Control machine. In this master paper, an efficient methodology to calculate tool-moving path in order to minimize the total operation time will be conducted, as well as other methods that can contribute to optimize the operation will be investigated in the main chapter.

This master thesis will be organized as follow: chapter one will brief introduce the CNC machine, as well as the background of the research, which includes three algorithms in machining surface, prediction methods and tool path generation according to energy consumption. These three research fields will be discussed detailed in the chapter two with three distinct sub-chapters. Finally, some of the research content will be utilized in the case study part in the chapter three for the sake of researching the effects of different tool path on surface machining.

1.1 Background

In order to achieve the highest production efficiency, there are plenty of methods that can help manufacturers, such as optimizing the energy consumption, tool path generation methods and prediction of operation cycle time etc. This master thesis will mainly focus on sculpture free form surface machining. These surfaces are usually produced by three-axis CNC machine by using ball-end tools.

In this report we will use the sort of ball-end milling of surface machining and then discuss about plenty of possible methods that can effect the total operation time such as three algorithms (iso

parametric, iso planar and iso scallop) in machining free form surface, optimization of energy consumption and prediction method during the machining process.

1.1.1 Three Algorithms in Machining Surface

There is variety of algorithms for three-axis tool path generation that has been researched, among those methods the three most popular algorithms in machining free form surface adopted in practice are the iso planar algorithm [5-9], the iso parametric algorithm [10-12] and the iso scallop algorithm [13-21]. Each of these algorithms has its own calculation methods and characteristics.

If we discuss about the first two tool path algorithms, the iso parametric algorithm can only be used to parametric surface but the iso planar algorithm has no restriction as iso parametric method. Either of them is able to calculate a tool path that shows the good surface finishing performance. However, overlap always occurs between the machining areas of adjacent CC curves on the surface if applying these two algorithms to generate tool path, sometimes it will lead to cost more machining time when severe on complicated surfaces. Iso scallop algorithm can eliminate the overlap cause it will start from an initial CC curve and then create the CC curves continuously so that any two neighboring CC curves can be maintained. By using this method, the overlap can be reduced dramatically.



Figure 3 – Iso parametric machining path



Figure 4 – Iso planar machining path



Figure 5 – Iso scallop machining path

Fig. 3, 4 and 5 are schematic illustrations of the iso parametric machining path, iso planar machining path and iso scallop machining path. It can be seen from these figures that different machining method has its own features and ways to generate the tool path. Iso parametric method is selecting one of the surface parameters as the forward direction (it is u in Fig. 3) and the initial path will be another parameter v [22], while iso planar method captures the intersection between the free form surface and a parallel vertical planes as the CC paths [23]. The process of generating the tool path with iso scallop method is more complicated than the other two algorithms. The CC path (cutter contact) performs a tangential trajectory of the ball end machining and the free form surface. In the case of 3D surface machining, it is necessary to generate an offsetting surface in the normal direction with a distance equal to the cutter radius so as to get the CL path that is shown in Fig. 5 [24].

In the chapter 2 there will be a more specific explanation of these three tool path generation algorithms with illustration and calculation.

1.1.2 Prediction of Part Machining Times

The purpose of digital engineering is to simulate the operation systems by researching the corresponding mathematical models based on physical principles. This prediction of part machining times model can predict the structural dynamic behaviour of machine tools by finite element and multibody dynamics methods [25]. The interaction between the structure and manufacturing processes is modelled by feeding back the resulting deflections to the process, predicting the process forces and applying them on the machine structure [26]. The process forces and optimal cutting conditions can be predicted in a virtual model of machining part operations ahead of pricy physical trials [27]. All the methods that mentioned above are important in designing better performance machines and manufacturing operations, the actual machining time of the part is essential in designing and selecting cutting tools to machine specific part geometry, specially in the aerospace industry that the physical test are prohibitive because of the high costs of the parts.



Figure 6 – Action order processing in CNC systems

The total operation time of the part in not only decided by the feeds commanded in the NC program but also by the CNC machine cutting tool's ability. The machining cycle times are predicted by the NC programs that are never accurate due to the CAM systems do not consider the rigid body dynamics of the machining tool. In order to obtain the accurate prediction of cycle time, it should be processing the part's NC tool path by the real CNC of the machine or its own simulation model. Despite of these, it is impossible to copy the commercial CNC's interpolation, smoothing, trajectory generation, compensation and control algorithms, which are hidden in the CNC software.

There are several essays about prediction of machining time from NC programs. The travel time of circular and linear paths are estimated by the path lengths [28] and transition directions between them with the deceleration and acceleration constants of the machine [29,30].

The reference [31] has developed a five-axis research of CNC system in real that is used to validate different smooth trajectory generations, interpolation, active vibration damping and high speed tracking control of feed drives. When the physical machine's drives are changed by their closed loop transfer function blocks, the corresponding CNC changes to a Virtual CNC, which can predict the exact cycle time of a part [32].

In chapter 2 of this master thesis the cycle time prediction model, which is mainly determined by the trajectory module of the CNC that can be decided by acceleration, velocity and jerk elements and limits of the machine will be researched. The trajectory profiles can be obtained from the CNC manufacturer or simple linear motion test. The path is treated by the trajectory generation module, which contains kinematic configuration of the cutting tool. The discrete position orders are generated from the trajectory profiler through the path that determines the cycle time.

1.1.3 Tool Path Generation Regard to Energy Consumption

A typical three axis machining process includes three independent parts. In the computer-aided manufacturing (CAM), a tool path can be generated on different strategies in the workpiece coordinate system (WCS), which can setup virtually aligned and fixed on the operation table. Then at the computer numerical control (CNC) part, the tool path can be transformed into the machine coordinate system (MCS) by inverse kinematics transformation (IKT) and obtains a part program such as G code part program, in which the feedrate is adjusted per the machine's kinematic capacity by the controller. At the final stage, the cutting stage, the part program is conducted and the energy is consumed.

In this paragraph, the energy consumption and related works will be introduced. In order to improve the energy efficiency for a given machining process, the investigation of relationship between the energy consumption and machining parameters. It is important to realize the main contributors to the energy among all the relevant parameters. In reference [33] has made an overall review of existing energy consumption models and found that the cutting process contributes the main energy consumption, which is highly related to the cutting parameters and material removal rate. Reference [34] made a complete evaluation for various machine tools and made a conclusion that the idle power can take about 50% of the total power, which consumes more energy than needed. Reference [35] suggested an empirical way to calibrate the energy consumption model according to their models and they found that material removal rate (MRR) will result in a significant energy saving and cutting in a dry condition is more efficient than in a wet condition. Reference [36] established a model efficiency and specific energy as a unary intention of various parameters and they found that a given set of parameters could decide the specific energy. Energy reduction was researched by [37], with the power pattern for the X, Y and Z axis that is got to be linearly to the feedrate in a certain proportion. In mention to the feedrate, reference [38] has compared the average energy consumption between distinct feedrate and they found that either small or large feedrate could cause high total energy consumption.

Finally, they suggested a medium feedrate that can save about 25% of the total energy cost. Furthermore, such as [39] focused on optimizing different machining parameters by using distinct cutting tool for the sake of reducing energy consumption. Reference [40] also introduced a prediction model that can provide more accurate result of energy consumption by analysing the effect of the feedrate, spindle speed and cutting depth. The connection between the particular power, cutting width and cutting height is studied in [41]. In order to reduce the plunging energy, the relationship between particular cutting energy and cutter swept angle is investigated in reference [42]. Recently, a research for the purpose of minimizing the energy consumption was conduct in [43]. Other investigations such as [44] and [45] have done various production planning methods for the sake of making the control process more efficient.

In the chapter 2 of this master thesis, more details about energy consumption optimization will be introduced in the third sub chapter and it will be organized as follows. Firstly, an energy potential field on the specific surface will be researched, and then an energy consumption model will be build in order to obtain the quotient of energy consumption over the swept area. Sequentially, two essential parameters that used to determine the amount of total energy consumption will be calculated as well. Finally, the optimal feed direction and principle curve generation will be mentioned for the sake of optimize the whole machining process.

2 Research of Optimization Methods

In this chapter, three parts such as tool path algorithm optimization, prediction of operation cycle time and minimizing of energy consumption that related to optimize the machining would be researched for the sake of better balancing between the surface operation performance and machining time. This second chapter is including three axis and five axis CNC machine with ball end and flat end cutting tool in order to cover all the processing situation as much as possible in this not long master thesis.

The three tool path algorithms focus on optimizing the tool path by calculation in mathematical way and try to obtain a theoretical value that can be executed in the real operation, which will be conduct in the case study part as well. The methods in this master thesis have some limit in the real application due to the optimization method is based on the G code. In the G code optimization process, we can only adjust the cutting spacing, which will be calculate by using distinct algorithms. Furthermore, the surface in the real operation at CNC machine is a plane rather than a free form surface. The part that this master thesis did not contain will be accomplished in the future.

The prediction of machining cycle time is the method to predict the total operation time of the part with action order processing steps that has been mentioned in Fig.6. The prediction model will utilize the trajectory generation and corner smoothing models to provide a high accuracy result. In this part, the trajectory generation profiles will be introduced as the key function of the CNC and 3-axis corner smoothing will be mentioned in this part as well.

The third part is about the energy consumption model to find out the most efficient energy cost way, which can also be a part of optimization solution for machining. It should be mentioned that this part research is based on 5 axis CNC machine with the flat end cutter in order to cover a more comprehensive range of research. This part will contain a detailed and exhaustive explanation such as pre determination of tool orientation, establishment of energy consumption model, optimization of feed direction, principle curve generation and expansion algorithm based on Iso-scallop height. At the end of this part there will be a brief conclusion of this method.

The tool path algorithm optimization including iso parametric, iso planar and iso scallop will be the main part of utilization in the real operation. The prediction part should be a theoretical tool for the purpose of predicting the total operation cycle time and the tool path generation regards to energy consumption optimization will be used as a theoretical basis in future research work.

2.1 Tool Path Algorithm Optimization

Producing a part with free form surface is one of the most important technologies that are widely utilized in CAD/CAM software. In order to cut the free form surfaces, ball end cutting tool is the most popular type of tool that is utilized in three axis CNC milling machines. In the current approach, the CAM software response for scheduling the CC (cutter contact) path over the free form surface, and then calculate out their offset curves, which is the CL (cutter location) path [46, 47]. Fig.7 shows the differences between CC (cutter contact) path and CL (cutter location) path, as well as the location and direction of normal vector, which will be introduced in the following part. As Fig.7 described, the CC

path represents the contact or intersection point between the cutter edge and the free form surface, while the CL path denotes the path that made up by a mount of consecutive linear sectors of the centre of the ball end cutter.



Figure 7 – Illustration of CC path, CL path, Tool axis vector and Normal vector.

Table.1 is the nomenclature of calculation in the following section. It should be noted that some of the parameters in the table.1 are illustrated in Fig.7 as well for the sake of better understanding of the parameters.

Table 1 - Nomenclature

В	Unit vector in the side-step or path-interval direction
С	Cutter-contact path
h	Scallop-height limit
L	Cutter-location path
М	Unit normal vector to the planes in iso-planar machining
N	Unit normal vector to the surface
r	Radius of the ball-end cutter
S	Parametric surface
Т	Unit tangent vector in the CC path direction
t	Spatial parameter along the CC path

U	u–v curve in the parametric domain
и, v	Surface parameters
V	Feedrate along the CC path
Δl	Distance of the side step
Δm	Step distance of the planes in iso-planar machining
ρ	Radius of surface curvature in the side-step direction
τ	Sampling period

In order to generate the tool path, it needs to first define the free form surface, and then choose the algorithm to generate the parametric curve. After which the cutting tool will be offsite depends on the surface geometry and the cutting tool's radius. Finally the CC path will be calculated by three different algorithms, which are iso parametric, iso planar and iso scallop. The following sections will describe all the steps in a more detailed way.

2.1.1 Definition of the free form surface

In this master thesis, the free form surface will be machined in the case of ball end milling that can be defined as:

$$S = S(u, v), \tag{1}$$

Where u and v are the surface parameters that are shown in Fig.8, notice that the scope of the u and v domain $(u_{min} \le u \le u_{max} \text{ and } v_{min} \le v \le v_{max})$.



Figure 8 – Iso parametric machining paths

2.1.2 CC path scheduling algorithm and cutting tool offsetting

The algorithm for the CC path interpolation and the cutting tool offsetting will be explained in this section and it should be mentioned that these algorithms are essentially derived from the current methods [48].

2.1.2.1 CC path scheduling algorithm

The CNC system has the sampling rate function that can create a sequence of CC dots in order to follow the CC path at a specific CC velocity and feedrate. At present there are many algorithms about the parametric curve generation have been researched. One of these researched algorithms will be used [49]. Before the calculation of CC path interpolation, a C(t), where t is the spatial parameter that denotes CC path on the free form surface should be introduced. It should be noted that t = u or v for iso parametric machining. Then let t_{i+1} and t_i to be the amounts of the path parameter t at two continuous sampling instants, $(i + 1)\tau$ and $i\tau$, where τ is the sampling time. Then:

$$t_{i+1} = \emptyset t_{i+1}^* + (1 - \emptyset) t_i , \qquad (2)$$

Where,

$$t_{i+1}^* = 2.5t_i - 2t_{i-1} + 0.5t_{i-2},$$
(3)

$$\phi = \frac{\tau V}{|C(t_{i+1}^*) - C(t_i)|},\tag{4}$$

where V is the specific CC velocity or feedrate. It should be mentioned that at the beginning of the CC path, t_{-1} and t_{-2} need to be calculated by:

$$t_{-1} = t_0 - \frac{\tau V}{|dC/dt|_{t=t_o}}, t_{-2} = t_{-1} - \frac{\tau V}{|dC/dt|_{t=t_{-1}}}$$
(5)

Then parameter t can be calculated by using Eqs. (2)-(5), recursively, at each sampling rate in order to get the CC point.

2.1.2.2 Tool offsetting

The cutting tool's radius and the surface geometry can decide the cutter offsetting. L is defined as the centre of the ball end cutter at the location of cutter.

$$L = C + r \cdot N \cdot sign(N_z) , \qquad (6)$$

where r is the radius of the cutting tool, N is the unit normal vector at point C to the surface, N_z is the component of N at z axis and $sign(N_z)$ is the sign function that can keep the tool offsetting on the top side of the free form surface all the time. Then unit normal of the free form surface can be calculated by:

$$N = \frac{\frac{\partial S}{\partial u} \times \frac{\partial S}{\partial v}}{\left|\frac{\partial S}{\partial u} \times \frac{\partial S}{\partial v}\right|},\tag{7}$$

2.1.3 Three algorithms of CC path scheduling

In this part the three different algorithms of CC path scheduling, which are iso parametric, iso planar and iso scallop machining methods, respectively will be discussed and then find out the best proposal for machining free form surface.

2.1.3.1 Iso parametric machining

In the previous section, Fig.8 has described the iso parametric path and introduced the values that should be used in the calculation. In this part, attending to select one of the surface parameters u as the forward direction, therefore another boundary curves, which is $v = v_{min}$ will be the initial CC path. Let kth CC path can be expressed by $C_k(u) = S(u, v_k)$. It should be noted that the curve $v = v_k$ in the domain that constitute by u and v according to the CC path C_k in the x-y-z domain (Cartesian domain). The value of the side parameter can be decided one by one,

i.e.,
$$v_{k+1} = v_k + \Delta v_k$$
,

where Δv_k (the parametric side interval between two neighboring CC paths) can be determined depends on the scallop height limit, *h* (generally from 0.001 mm to 0.01 mm).

In the general case, the CC path of iso parametric algorithm does not correspond to a constant scallop height *h* and Δv_k . For this reason, the maximum scallop height on the CC path will not exceed *h*.

The calculation of Δv_k can be executed on line the generation of the *k*th CC path. During this generation process, every sampled point, which is $C_{i,k} = C_k(u_i)$, are evaluated in order to get a corresponding value, $\Delta v_{i,k} = \Delta v_k(u_i)$. At the final point of the *k*th CC path, the minimum value of these corresponding values has chosen, i.e., $\Delta v_k = min(\Delta v_{i,k}'s)$. According to the $v_{k+1} = v_k + \Delta v_k$, the next CC path can be settled consequently. The formulas that can calculate the corresponding value, $\Delta v_{i,k}$, are shown as follows.

Given a sample point on the parametric surface $C_{i,k} = S(u_i, v_k)$, the radius of curvature in the side direction ρ need to find first, which can be calculated by [50]:

$$\rho = \frac{e\alpha^2 + 2f\alpha + g}{a\alpha^2 + 2b\alpha + c},\tag{8}$$

Where,

$$\alpha = \frac{\frac{\partial S}{\partial v}T}{\frac{\partial S}{\partial u}T}, e = \frac{\partial S}{\partial u} \cdot \frac{\partial S}{\partial u}, f = \frac{\partial S}{\partial u} \cdot \frac{\partial S}{\partial v}, g = \frac{\partial S}{\partial v} \cdot \frac{\partial S}{\partial v}, a = \frac{\partial^2 S}{\partial u^2} \cdot N, b = \frac{\partial^2 S}{\partial u \partial v} \cdot N, c = \frac{\partial^2 S}{\partial v^2} \cdot N,$$

where N is the unit normal vector to the parametric surface and T is the unit tangent vector on the CC path direction. Then T will be obtained since the tool path is used in the u direction:

$$T = \frac{\partial S}{\partial u} / \left| \frac{\partial S}{\partial u} \right|$$

then, side step distance Δl can be calculated for each evaluated point [51]:

$$\Delta l = \sqrt{\frac{8\rho rh}{\rho \pm r}},\tag{9}$$

where h is the scallop height that has introduced in the previous description, r is the cutting tool radius, the plus minus sign depends on the case of the surface shape is convex or concave that is illustrated in Fig.9.





It should be noted that the CC path direction (*T*) and the surface normal (*N*) are orthogonal to the side step direction. Since Δl is in mm unit distance and it is generally not in the *v* direction, a transformation from Δl to the parametric side Δv is necessary.



Figure 10 – Side step distance Δl and parametric side interval Δv

This transformation process is described in Fig.10. Depends on the geometrical relationship that illustrate in Fig.10,

$$\Delta l = B \cdot (\frac{\partial S}{\partial v}) \Delta v ,$$

where,

$$B = N \times T$$
,

where B is a unit vector in the side direction. In the end part, the corresponding path interval $\Delta v_{i,k}$ for the *i*th sampled point on the *k*th path can be obtained by:

$$\Delta v_{i,k} = \frac{\Delta l}{(N \times T \cdot \frac{\partial S}{\partial v})},\tag{10}$$

By using the CC path scheduling algorithm and tool offsetting that have described above, as well as the iso parametric algorithm presented in the above section, the iso parametric algorithm can be implemented in a CNC machine tool. More details and the process of calculation are shown in appendix.

2.1.3.2 Iso scallop machining

The iso scallop machining path is shown in a schematic illustration in Fig.11. The scallop height is produced by two neighboring CC path that equal to the assigned limit h. It can be seen from the figure

below that each CC path C(t) has a corresponding specific curve U(t) in the domain made up by u and v. In the general case, the curve does not follow a constant u and v.



Figure 11 – Iso scallop machining path

There is a existing method that generate the (k + 1)th CL or CC path based on the curve fitting of the increment points $x_{k+1}, y_{k+1}, z_{k+1}$ from a set of chosen points x_k, y_k, z_k on the *k*th path. The 3D curve is fitting [51]:

$$L(t) = (x(t), y(t), z(t)),$$

where t is the time consuming of the path parameter. Furthermore, in order to obtain sufficient position accuracy, a lot of points need to be evaluated, as well as several spine segments to fit a machining path. Therefore a proposed method is suggested that makes the machining path by 2D curve U(t) = (u(t), v(t)) in the parameter domain. It is obvious that the 2D curve fitting for U(t) is uncomplicated for calculation compares with L(t). Fig.12 compares the existing and the proposed methods for the machining path generation.



Figure 12 – A comparison of the existing and the proposed methods

In addition, the proposed method does not need tolerance or allowable error to fit U(t). The reasons of this are:

- (1) Even though an inaccurate value is applied into the surface function, the CC point is still located on the surface because of 2D curve.
- (2) The parameter error can only result in the deviation in the scallop height, which is extremely less than the path interval.

As same as the iso parametric method, the surface parameter u is chosen as the forward machining direction. Therefore another boundary curves, which is $v = v_{min}$ will be the initial CC path and the initial curve is $U_0(t_0) = (u(t_0), v_{min})$ in the domain that consist of u and v. In order to explain it in a more simplicity way, the initial path parameter need to be defined as $t_0 = u$, which can also represented as $U_0(t_0) = U_0(u)$. So that $U_k(t_k) = (u_k(t_k), v_k(t_k))$ means the *k*th curve in the u - v domain and the two components $u_k(t_k)$ and $v_k(t_k)$ express t_k through curve fitting as polynomials. Then in consequent, the *k*th CC path becomes to $C_k(t_k) = S_k(U_k(t_k))$ and a cubic spline is used to fit U(t) for a exact CC path because a tight curve fitting for U(t) is not required.

As mentioned in the above section and the illustration in Fig.12 (b), $U_{k+1}(t_{k+1})$ is obtained based on $U_k(t_k)$. In the existing method, four set of (U_{k+1}, t_{k+1}) should be calculated to fit the curve U_{k+1} . While the proposed method will finish this process by generating the *k*th and the (k + 1)th CC path. In addition, the four sets path parameter are selected as:

$$t_k = t_k^s + j(t_k^e - t_k^s)/3, (j=0,1,2,3),$$

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where t_k^e and t_k^s are the end and the start of the path parameter for U_k . For each of the four sets, they have:

$$U_{k+1} = U_k + \Delta U_k,$$

where $\Delta U_k = (\Delta u_k, \Delta v_k)$.

Let $t_{k+1} = t_k$ to define the path parameter for the subsequent path. Then the key issues can be focused to calculated in order to determine an iso scallop machining path, which are the increment of the surface parameters ($\Delta u_k, \Delta v_k$), as well as the end and the start of the path parameter t_k^e and t_k^s .

After the explaination, the proposed algorithm can be started. Given a set of (U_k, t_k) , the first step is to calculate N (the unit surface normal) and T (the tangent vector). N can be obtained by using Eq. (7) and T can be calculated by:

$$T = \frac{\frac{dS}{dt}}{\left|\frac{dS}{dt}\right|} = \frac{\frac{\partial S}{\partial u}\frac{du}{dt} + \frac{\partial S}{\partial v}\frac{dv}{dt}}{\left|\frac{\partial S}{\partial u}\frac{du}{dt} + \frac{\partial S}{\partial v}\frac{dv}{dt}\right|},\tag{11}$$

Then Δl (the side step distance) can be calculated by utilizing a given scallop height *h* based on Eqs. (8) and (9). The transformation from Δl to the increment of the surface parameters ($\Delta u_k, \Delta v_k$) can be obtained by:

$$\Delta lB = \frac{\partial S}{\partial u} \Delta u_k + \frac{\partial S}{\partial v} \Delta v_k , \qquad (12)$$

where $B = N \times T$ is the unit vector in the side step direction.

In the calculation process, the end and the start path parameter t_k^e and t_k^s for U_k are correlating to the intersections of the curve U_k and $u = u_{min}$, $u = u_{max}$, $v = v_{min}$ and/or $v = v_{max}$ (the boundaries of the parametric domain). There are some numerical methods that have been researched to have these intersection points [52]. In this master thesis, a more advance and fast algorithm will be researched for determining t_k^e and t_k^s and the proposed algorithm is introduced in the following.



Figure 13 – Schematic description for determining t_k^s

Fig.13 is the schematic description for determining t_k^s . As the explanations above, $U_k(t_k)$ is an isoscallop increment curve that is obtained from $U_{k-1}(t_{k-1})$. The initial parameter set $U_{k-1}(t_{k-1}^s)$ is defined that has a corresponding increment parameter set (u_k^*, v_k^*) . As shown in the Fig.13 (a), t_k^s is corresponding to the intersection of U_k and $u = u_{min}$. Therefore, (u_k^*, v_k^*) and (u_{min}, v_k^s) are two adjacent point on U_k . Then t_k^s can be calculated by:

$$t_{k}^{s} = t_{k}^{*} - \frac{u_{k}^{*} - u_{min}}{\frac{du_{k}}{dt_{k}}(t_{k} = t_{k}^{*})},$$
(13)

where $t_k^* = t_{k-1}^s$. Eq. (13) gives us a good method to find approximation value for t_k^s , it can be approached to the real solution additionally by changing t_k^* by the presently calculated t_k^s and repeating the calculation through Eq. (13). It should be mentioned that Fig.13 (b) illustrate the value t_k^s may be corresponding to the junction of U_k and $v = v_{max}$. In this circumstance, Eq. (13) should be changed by:

$$t_{k}^{s} = t_{k}^{*} - \frac{v_{k}^{*} - v_{min}}{\frac{dv_{k}}{dt_{k}}(t_{k} = t_{k}^{*})},$$
(14)

The algorithm for obtaining the end of the path parameter t_k^e is as same as t_k^s .

By using the CC path scheduling algorithm and tool offsetting that have described above, as well as the iso scallop algorithm presented in the above section, the iso scallop algorithm can be implemented in a CNC machine tool. More details and the process of calculation are shown in appendix.

2.1.3.3 Iso planar machining

The iso planar machining path is shown in a schematic illustration in Fig.14. It can be seen from the figure that the CC path are obtained form the intersections of a series of parallel vertical planes and the parametric surface.



Figure 14 – Iso planar machining paths

In this master report, the unit normal vector perpendicular to the vertical planes that can be denoted by $M = (m_x, m_y, 0)$, and the distance between two close parallel planes is represented by Δm as shown in Fig.14 as well. The proposed algorithm for the iso planar is as same as the iso scallop method, which can be seen from Fig.10 and Fig.14 that each CC path C (t) corresponds to a unique curve U(t) in the parametric domain. For instance, C(t) = S(U(t)).

In the processing, U(t) can be obtained recursively by :

$$U_{k+1} = U_k + \Delta U_k,$$

where $\Delta U_k = (\Delta u_k, \Delta v_k)$.

The main difference between the iso scallop approach and iso planar algorithm is the method to calculate the parameter increment, which is $(\Delta u_k, \Delta v_k)$.

The kth curve is defined as $U_k(t_k)$, and then the iso planar increment curve can be obtained:

$$U_{k+1}(t_{k+1})$$
,
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where $t_{k+1} = t_k$.

For two adjacent points on U_k and U_{k+1} , the related CC points $C_k = S(U_k)$ and $C_{k+1} = S(U_{k+1})$ are both placed on the surface. The different vector between these two points, which is $(C_{k+1} - C_k)$ can be obtained approximately by:

$$\frac{\partial S}{\partial u}\Delta u_k + \frac{\partial S}{\partial v}\Delta v_k ,$$

In the geometrical consideration, this distinction vector is placed on a cross section that is developed by the side vector M and the tool axis vector Z. Therefore,

$$\frac{\partial S}{\partial u}\Delta u_k + \frac{\partial S}{\partial v}\Delta v_k = \Delta mM + \Delta zZ , \qquad (15)$$

Depends on the components x and y, Δu_k and Δv_k can be solved, and then $U_{k+1} = (u_k + \Delta u_k, v_k + \Delta v_k)$ can be obtained.

The same as the above section and the illustration in Fig.12 (b), $U_{k+1}(t_{k+1})$ is obtained based on $U_k(t_k)$. In the existing method, four set of (U_{k+1}, t_{k+1}) need to be calculated to fit the curve U_{k+1} . While the proposed method will finish this process by generating the *k*th and the (k + 1) th CC path. In addition, the four sets path parameter are selected as:

$$t_k = t_k^s + j(t_k^e - t_k^s)/3, (j=0,1,2,3),$$

where t_k^e and t_k^s are the end and the start of the path parameter for U_k . For each of the four sets, they have:

$$U_{k+1} = U_k + \Delta U_k,$$

where $\Delta U_k = (\Delta u_k, \Delta v_k)$.

An initial curve U_0 should be created first in the case of this value does not correspond to a boundary of the u - v domain for the iso planar scheduling. There is an uncomplicated method that can get U_0 . Lets say there exist four representative points on four directions from the left bottom corner (u_{min}, v_{min}) on U_0 , and the four directions are 0^o , 30^o , 60^o and 90^o , respectively. The original CC path, $C_0 = S(U_0)$, is placed on a vertical plane and deviate from the surface corner $S(u_{min}, v_{min})$ by the distance of $\Delta m M$. Correspondingly, all the points on $U_0 = (u_0, v_0)$ should satisfy:

$$\left[\frac{\partial S}{\partial u}(u_0 - u_{min}) + \frac{\partial S}{\partial v}(v_0 - v_{min})\right] \cdot M = \Delta m,$$
(16)

Therefore, $(u_0, v_0) = (\lambda, 0)$, $[(\sqrt{3}/2)\lambda, (1/2)\lambda]$, $[(1/2)\lambda, (\sqrt{3}/2)\lambda]$ and $(0, \lambda)$ can be inserted into Eq. (16) in order to obtain the four solutions.

By using the CC path scheduling algorithm and tool offsetting that have described above, as well as the iso planar algorithm presented in the above section, the iso planar algorithm can be implemented in a CNC machine tool. More details and the process of calculation are shown in appendix.

2.2 Prediction of Part Machining Times

The prediction model is introduced in this sub chapter based on researching of trajectory generation profiles and corner smoothing algorithm, which can determine the total cycle time. The trajectory module will be divided into acceleration, velocity and jerk in order to better explain the influence of these parameters. This prediction model will give us the theoretical basis of prediction field in the future utilization.

2.2.1 Trajectory Generation

The action order processing in a CNC system is mentioned before in Fig.6. The G code, which is the main optimization part in this master thesis that belongs to the NC program, can be parsed into linear, circular and spline path section. The total travel distance L for every path section can be calculated and divided into acceleration, constant feed and deceleration area that are shown in Fig. 15. The discrete displacement will be calculated through the path, which is a function of the trajectory profile at continuous interpolation time intervals T_{int} and then dissolve the constant interpolation time intervals into axis position orders. The function is implemented by the interpolator functions and sent the information to drive servo controllers over the cutting tool's inverse kinematic module.



Figure 15 – Jerk continuous trajectory command generation profile

There is a replacement of a fifth order polynomial function of time when the CNC system attend to maintain the continuous velocity, acceleration and jerk profiles that is shown in Fig. 15. The less proportion content can be obtained is the acceleration and jerk are smooth and this will decrease the vibrations during high-speed contour operation [31].

The most CNC machine system has a double exponential feed profile that is illustrated in Fig.16. The three time zones including acceleration, constant feedrate and deceleration can be expressed in the mathematical way as following:

$$\frac{f_{s} - f_{c}}{T_{1} - T_{2}} (T_{1}e^{-(t/T_{1})} - T_{2}e^{-(t/T_{2})}) + f_{c}, \qquad t \in [0, t_{1})$$

$$f(t) = f_{c}, \qquad t \in [t_{1}, t_{1} + t_{2})$$

$$\frac{f_{c} - f_{e}}{T_{1} - T_{2}} (T_{1}e^{-((t-t_{1}-t_{2})/T_{1})} - T_{2}e^{-((t-t_{1}-t_{2})/T_{2})}) + f_{e}, \qquad t \in [t_{1} + t_{2}, t_{1} + t_{2} + t_{3}]$$
(17)

where $t = kT_{int}$, k = 1, 2, ..., N and T_1, T_2 are specified time constants.



Figure 16 – Exponential feed generation profile

 T_1, T_2 are specified time constants that obtained from a series of linear travel commands, which are conducted on each drive, as well as the real velocities are obtained and measured by using the CNC's internal data storage part over the application of programming interface.

The time constants are determined by a non-linear least squared identification method in this research. So that the corresponding travel length l(t) can be obtained by integrating the feed from Eq. (17) along the path.

$$\frac{f_{s}-f_{c}}{T_{1}-T_{2}} \{T_{1}^{2}(1-e^{-(t/T_{1})}) - T_{2}^{2}(1-e^{-(t/T_{2})})\} + f_{c}t + l(0), \quad t \in [0,t_{1})$$

$$l(t) = f_{c}(t-t_{1}) + l(t_{1}), \quad t \in [t_{1},t_{1}+t_{2})$$

$$\frac{f_{c}-f_{e}}{T_{1}-T_{2}} \Big(T_{1}^{2} - T_{2}^{2} - T_{1}^{2}e^{-((t-t_{1}-t_{2})/T_{1}} + T_{2}^{2}e^{-\left(\frac{t-t_{1}-t_{2}}{T_{2}}\right)}\Big)$$

$$+f_{e}(t-t_{1}-t_{2}) + l(t_{1}+t_{2}), \quad t \in [t_{1}+t_{2},t_{1}+t_{2}+t_{3}]$$
(18)

It should be mentioned that the time t is discretised as $t = kT_{int}$ at the interpolation interval time T_{int} . The part machining cycle time can be predicted by the machining time if assuming each path segment length is finished, for instance $L = l(t_1 + t_2 + t_3)$.

The CNC systems have several trajectory generation modules, they are infinite and constant profiles, as well as continuous and exponential jerk profiles as shown in Fig. 15 and Fig. 16.

In order to evaluate the machining time, the main influencing factors should be known first. From reference [31] and [53] the operation time is influenced by the feed speed transitions between the smoothing feed and NC blocks to avoid high frequency jitters that may causes inertial vibrations. Nonetheless, the trajectory generation profile and corner smoothing calculations are the main factors that affect the machining time.

Fig. 17 is the three-axis corner smooth algorithm in order to increase the accuracy of prediction. The initial path has a sharp corner regarding to a tool tip coordinate of p_2 for a three-axis machining application. For the sake of avoiding the dimensional rightness, the corner path can be adjusted. In another hand, the CNC can be adjusted as well to stop at the end of each action so as to achieve zero error. A five order micro spline can be fitted by locating 7 points, which are $P_0, P_1, P_2, P_3 \dots, P_6$ through the path sectors when maintaining the part tolerance ε_{pos} at the corner that can be seen in Fig. 17.

The tool path through the corner spline can be calculated by the following equations:

$$P(u) = P_0 \sum_{n=0}^{5} C_{0n} u^n + \dots P_5 \sum_{n=5}^{5} C_{5n} u^n + P_6 \cdot 0, \qquad 0 \le u \le 0.5$$

$$P_0 \cdot 0 + P_5 \sum_{n=1}^5 D_{5n} u^n + \dots P_6 \sum_{n=1}^5 D_{6n} u^n + P_6, \qquad 0.5 \le u \le 1$$

where u = 0.5 according to the corner point.

In order to make sure the jerk and acceleration continuity at the union points $P_0(u = 0)$ and $P_6(u = 1)$, the parameters of the spline and the locations of the control points should be defined.



Figure 17 – 3-axis corner smoothing of sharp corner

It should be mentioned that some of the CNC systems start executing the next block earlier than while the machine reaches at the corner. It will be explained in the following example:

The example NC Program is:

N010 G01 X4 F1000

N020 X2 F500

N030 X8 F2000

N040 X-4 F1000

The Fig. 18 [60] is the commanded feedrate in four subsequent NC blocks. The next NC block will start moving when the previous block is finished.



Figure 18 – Four subsequent NC blocks [60]

The time shifting of action blocks of CNC can be obtained and it can be seen from Fig. 19 that when the linear command begin to decelerate, the next NC block, for instance linear motion command, is shifted advanced of its schedule time.



Figure 19 – Time shifting of motion blocks [60]

This scheme mixes the sharp corners in a smooth way but the disadvantage of this is ignoring the constraint of the path error with the tolerance of the machining part. The block shifting strategy can be executed in the virtual CNC by mixing the block transitions that is shown in Fig. 20.



Figure 20 – Fixed feed profiles for continuous block transitions [60]

In this part of study, the two main factors have been researched that can affect the total machining cycle time in three-axis CNC system, which is not the limitation of the virtual CNC system. More descriptions are in the appendix. The virtual CNC system cannot only simulate three-axis tool path but also all range systems from one to five axis. All the servo states can be simulated including torque, position and acceleration etc., as well as total machining time and contouring errors. Despite that, the two main factors that have been studied still affect the total cycle time most.

2.3 Tool Path Generation Consider to Energy Consumption

This part of research is based on a five-axis CNC system for the purpose of making this master thesis study a wider range of coverage, then some useful part will be researched to utilize in the case study part. The case study part will only focus on three-axis surface machining optimization and the five-axis machining will be researched in the future work.

Table 2 is the nomenclature for the calculation in this section. The factors are listed according to the sequence of appearance.

Table 2 - Nomenclature

α	Lead angle (rad)
β	Tilt angle (rad)

r_{f}	Surface radius of curvature through feed direction (mm)
r _e	Effective cutting radius of a flat-end mill (mm)
r _k	Surface radius of curvature that perpendicular to feed direction (mm)
f	Feedrate (mm/min)
S	Spindle speed (rad/s)
P _{idle}	Idle power (W)
P _T	Cutting power (W)
P _D	Driving power (W)
J_k	Inertia of each axis
F _k	Viscosity friction coefficient of each axis
μ_k	Friction coefficient of each axis
ν	Axis velocity
а	Axis acceleration
E _T	Energy consumption due to cutting power (J)
E _D	Energy consumption due to driving power (J)
Wi	Effective cutting width (mm)
A _i	Swept area (mm ²)
U	Specific energy (J/mm^2)
d_f	Forward step (mm)
ds	Side step (mm)

The five-axis milling is widely used in machining complicated surfaces with high accuracy needs. It is implemented in many industries such as aerospace and shipbuilding etc. This part will study the optimization method regarding to energy consumption by the following sectors:

- 1. Build an energy potential field on the known surface that includes the distinct power demand through any feed directions at random cutter contact point.
 - a. Determinate the tool orientation before establishing the energy consumption model
 - b. Make a energy consumption model to find out the parameters that can determine the energy consumption
- 2. Find an optimal tool path generation that fits to the minimum directions of the field and meet the maximum scallop height needs at the same time.

2.3.1 Energy Potential Field

2.3.1.1 Determination of tool orientation

Generally, in a five-axis machining, a tool path is consisting of cutter location curve (CL), which is the trajectory of the tool tip and a tool orientation T. Sequentially, the surface normal n can be used and feed direction f, as well as the cross product k corresponding to n and f to determine a local reference frame.

Where, $k = f \times n$.

It is obvious to see in the Fig. 21 that the tool orientation T can be defined by two angles α (lead angle) and β (tilt angle).

In this part, the flat-end cutter will be considered to use because it has close tool surface contact and large cutting width. Furthermore, the flat-end cutter is intrinsically related to orientation of the tool and the work of analysis will be complex, specially considering the side and rear gouging that is illustrated in Fig. 22.



Figure 21 – Parameters define the local frame

If CC point p is given, the lead angle α should be positive so as to protect the rear gouging when the surface radius of curvature r_f through the feed direction f is negative. The relationship of these parameters is shown in Fig. 22 as well.
The lead angle α should be:



Figure 22 – Side and rear gouging considering a flat-end cutter

The real cutting profile of a flat-end cutter is a kind of ellipse and its effective cutting radius r_e (as shown in schematic figure 23) can be calculated refer to reference [54]:

$$r_e = t^2 r^2 \left(\frac{1 + tan^2\theta}{t^2 + r^2 tan^2\theta}\right)^{3/2},$$
(21)

where $t = rsin\alpha \cdot cos\beta = \theta = tan^{-1}(tan\alpha \cdot sin\beta)$.



Figure 23 – The effective cutting shape (ellipse)

In order to meet the side gouging free needs, the lead angle α and the tilt angle β need to be optimized by the following equation:

$$r_e(\alpha,\beta) = \frac{1}{Max(-\frac{1}{r_k},0)},$$
(22)

where r_k is the radius of curvature on the surface at point p through k.

Then the concave case can be known, in which the lead angle α is positive when r_k is negative in order to protect the local gouging. On the contrary, the lead angle α can be infinitely closed to 0 for the sake of having the largest cutting width.

In the case that the global collision has been maintained, the tilt angle β is set to 0 so as to have a more regular cutting strip. Then the pre-determined the tool orientation can be implemented by using the following equation:

$$(\alpha,\beta) = (Max(0,sin^{-1}(\frac{r}{-r_f}),sin^{-1}(\frac{r}{-r_k})),0),$$
(23)

In the workpiece coordinate system, the tool orientation can be expressed as:

$$T_i = (a_i, b_i, c_i) = n \cos \alpha + f \sin \alpha \cos \beta - k \sin \alpha \sin \beta, \qquad (24)$$

The tool orientation can be a unary function of feed direction f because of the different feed directions can cause the changing of r_f and r_k , which means the known CC curve can define a unique tool orientation of the flat-end cutter.

If we consider the ball-end tool that will be utilized for our case study, Eq. (24) will be simplified if a positive and fixed lead angle α has been take care as invariant when the tilt angle β becomes to zero.

2.3.1.2 The model of energy consumption

We know that the feedrate is the tool tip's speed when the tool moves through the tool path. This speed is usually changed in process by the controller of the machine so as to avoid from exceeding the machine's kinematic or dynamic constraints when transforms the tool tip's speed to the speed of the machine's axis.

In order to make such similar system, a reference constant feedrate f should be assigned to simulate the machine in verse kinematic and then the machine axis's velocity and acceleration can be calculated in advance to ensure whether the given feedrate is conservative, and then decrease it if the virtual numerical controller is unaccepted. When the above work is finished, the energy consumption model can be build with both the feedrate and tool orientation specified.

In general, there are three main contributing factors to the power demand that are power demand P_{idle} , cutter power demand P_T and driving power demand P_D , respectively according to reference [38] and [55].

If assuming the tool moves an infinitesimal distance from CC point P_i to P_{i+1} by the specified feedrate f, then the total consumed energy of the cutting movement can be calculated:

$$E = (P_{idle} + P_T + P_D) * \frac{||p_{i+1} - P_i||}{f},$$
(25)

where $\frac{||p_{i+1} - P_i||}{f}$ is the time consuming between P_i and P_{i+1} , to be denoted as Δt .

Each machine tools have their own intrinsic characteristic that can be calibrated. For example the inertia of each axis J_k , the idle running power P_{idle} and the viscosity friction coefficient μ_k . The energy requirement according to cutting power demand P_T for compensating the cutting force is:

$$E = P_T * \frac{||p_{i+1} - P_i||}{f} = \int_0^{\Delta t} \int_0^{h_0} (F_t(h, t)rS) dh dt,$$
(26)

where $F_t(h, t)$ is the intensity of the tangential force at a given height *h* and a given time *t*. S is the spindle speed and *r* is the tool radius. Therefore, the part $\int_0^{h_0} (F_t(h, t)rS) dh$ of the equation is the cutting power at time *t*.

Each axis's power demand P_D should be independent to each other, so other variable power demand in the machine coordinate system needs to be investigated. The internal friction force and the torque in the machine coordinate system require extra energy for acceleration. Therefore, the velocity v_k and acceleration a_k should be calculated of each axis at the first step. Suppose that the chord error e is known, and then the two adjacent CC points can be found out due to the feed direction f.

Fig. 24 is the illustration of the parameters that are needed to the calculation. Assume that the cutter posture at point p_i in the workpiece coordinate system can be expressed as:

$$(x_i, y_i, z_i, a_i, b_i, c_i),$$

where $T_i = (a_i, b_i, c_i)$ is the tool orientation that determined previously.



Figure 24 – Three adjacent cutter postures with the chord error

Then the cutter postures p_{i-1} , p_i and p_{i+1} can be converted into their corresponding machine coordinates by utilizing the inverse kinematics transformation:

$$(m_{i,1}, m_{i,2}, m_{i,3}, m_{i,4}, m_{i,5}) = IKT(x_i, y_i, z_i, a_i, b_i, c_i),$$
(27)

For more information about IKT is given in the appendix. Then the velocity v_k and acceleration a_k of each axis can be calculated by following:

$$v_k = (m_{i+1,k} - m_{i,k}) / \Delta t , \qquad (28)$$

$$a_k = (m_{i+1,k} - 2m_{i,k} + m_{i-1,k})/\Delta t^2, \qquad k = 1,2,3,4,5,$$
 (29)

According to the Eq. (28) and Eq. (29), the total energy cost of the driving power demand can be obtained by:

$$E_{D} = P_{D}\Delta t$$

$$= \sum_{k=1}^{5} (\mu_{k}J_{k}v_{k}\Delta t + F_{k}v_{k}^{2}\Delta t + \{\frac{1}{2}J_{k}((v_{k} + a_{k}\Delta t)^{2} - v_{k}^{2}), if a_{k} > 0$$

$$0, if a_{k} \leq 0\})$$
(30)

It should be mentioned that the part kinetic energy demand $\frac{1}{2}J_k((v_k + a_k\Delta t)^2 - v_k^2)$ is 0 for any axis when $a_k \leq 0$ is following the laws of energy conservation. In the contrary, the motor has to provide more energy to accelerate the whole inertia that related with the axis.

Until now the three main factors of energy consumption have been calculated. In order to obtain the infinitesimal energy consumption of any neighboring two CC points, the three main factors, which are Eq. (25), Eq. (26) and Eq. (30) can be simply summed up as follows:

$$E = P_{idle}\Delta t + E_T + E_D , \qquad (31)$$

There is a new factor named the area swept A_i by the cutter from p_i to p_{i+1} that is used to better evaluate the energy efficiency. The area swept value A_i can be determined by the equation as following:

$$A_{i} = \frac{1}{2}(w_{i} + w_{i+1})||p_{i+1} - p_{i}||, \qquad (32)$$

where w_i is the effective cutting width on the surface at point p_i that is determined by the length of the effective cutting chip from the nominal surface S to the tolerance surface S'. Fig. 25 illustrates the two distinct cases according to the effective cutting width.



Figure 25 - The two different cases considering of effective cutting width of flat-end milling

It is obvious to distinguish the difference between the concave and convex considering of the effective cutting width of flat-end milling. The distance of cutting width of concave case is defined between the two intersection points from the ellipse shape to the local arc of the tolerance surface S' that can be determined by solving the two parameters θ and φ of the following equations:

$$r_k - (r_k - h)cos\theta = rsin\alpha - rsin\alpha cos\varphi$$
,
 $r_k sin\theta = rsin\varphi$, (33)

The effective cutting width w_i of the concave case can be simply calculate as follows and the illustration of the relationship between r and φ can be seen in appendix:

$$w_i = 2rsin\varphi , \tag{34}$$

Similarly, it is obvious to see from the Fig. 25 that the distance of cutting width of convex case is degenerated into the cord length between the nominal surface *S* and the tolerance surface *S'*. Then the effective cutting width w_i of the convex case can be calculated by the following formula:

$$w_i = \min(2r, \sqrt{8r_k h}), \tag{35}$$

After determination of the effective cutting width w_i , the specific energy can be obtained at a random CC point and through any feed direction is then the quotient of the energy consumption over the swept area:

$$U = E/A = \frac{P_{idle}\Delta t + E_T + E_D}{\frac{1}{2}(w_i + w_{i+1})p_{i+1} - p_i},$$
(36)

2.3.1.3 Energy consumption based on tool path generation

In a five-axis machining, the tool path is composed of a series of discrete CL curves that dominate the tool tip position and the relevant tool orientation in the workpiece coordinate system. In general, the CC curves are composed of groups of discrete CC points. Usually, the CC curves are decided at first on the nominal surface, and then a tool orientation is decided subsequently, and then calculates the CL curves according to the CC curves, the corresponding tool orientation and the nominal surface.

According to the requirements of machining accuracy, two important constraints should be defined while planning a tool path:

- 1. The maximum value of scallop height should be keeping below a threshold.
- 2. The chord error *e* of any two neighboring CC points cannot exceed a known tolerance.

Fig. 26 shows the definition of the side step and forward step. There are two important factors d_s and d_f in this figure require to explain: the side step d_s is the distance between any two adjacent CC points and the forward step d_f is the maximum distance between any two subsequent CC points. Both the side step d_s and the forward step d_f are depending on the local surface curvature. In Eq. (35) the effective cutting width w_i is being the side step when calculating d_s . The forward step d_f can be calculated by the following formula [56]:

$$d_f = min(\sqrt{8e|r_f| - 4e^2}, d_{f0}),$$
(37)

where r_f is the curvature radius of the surface along the feed direction and d_{f0} is a constant that can be set to bound the forward step in the situation r_f is infinite.

As mentions and explanations above, the feed direction, which is the direction orthogonal to the CC curve at the CC point, can determine the tool orientation at any CC point. The target of this sub chapter is not only satisfying d_s and d_f at each CC point, but also attend to optimize the total energy consumption according to the Eq. (36). The final solution should be the iteration of the principle curve generation and iso scallop height that will be introduced in the next part.

2.3.1.4 Feed direction optimization

The specific energy term is a pure quantity which changes continuously versus different feed directions, this means a vector field about the energy cost efficiency embedded on the entire surface, which is extremely dependent on the machine's configuration. It can be called as the machine based energy potential field. There is a distinct feed direction f_i through the specific energy cost is the lowest between all the others for each CC point p_i . Furthermore, this feed direction can be named as the optimal specific energy direction.

There are two properties of the potential field that is described as below:

- 1. For any point on the surface, it has two opposite optimal directions. However, if the specific energy U in Eq. (36) for arbitrary point on the surface is a constant, there is an exception for the case of flat surface.
- 2. The flow lines on the surface are continuous and will never interact to itself.

When the potential field is defined, the tool path should be defined in a way that the feed directions are as close as possible to the individual optimal directional flow lines of the machine based energy potential field in order to minimize the energy consumption. There is some of the research such as reference [57] and [58] that attended to fit a tool path into a known vector field. A better way to balance between the best fitting to the machine based energy potential field and the demand regular patterns of CC curves can be found.

If a free-form surface is defined as:

$$S(u, v) = (X(u, v), Y(u, v), Z(u, v),$$

a discrete $N \times N$ grid of the machine based energy potential field is created upon the parametric uv domain $[0,1] \times [0,1]$ of the surface.

For each point $\mu_{ij} = (u, v)$ on the grid, the specific energy U that is calculated in Eq. (36) at point S(u, v) can be obtained for every k radian of feed direction from 0 to 2π , where

$$k=\frac{\pi}{180},$$

this can be recorded as a value of vector U_{ij} that is shown in Fig. 26.

the machine based energy potential field is required to constantly calculate at an random S(u, v) in the process of computation of CC curves. This is better than directly calculating it for the case of a grid point μ_{ij} . To be more clear, for an arbitrary node:

$$p=S(u,v)\,,$$

then let:

$$U_i$$
, $i = 1,2,3,4$,

which is the machine based energy potential field of the four neighboring grid nodes of (u, v). Then the machine based energy potential field vector u of S(u, v) can be calculated by:

$$u = \frac{1}{\sum_{i=1}^{4} \frac{1}{||p - \mu_i||^2}} \sum_{i=1}^{4} \frac{U_i}{||p - \mu_i||^2},$$
(38)



Figure 26 – Discrete the machine based energy potential field in the uv domain

The optimal feed direction f at the arbitrary S(u, v) is directly obtained if using the minimum of the $2\pi/k$ values once u is calculated. By using this method, a principle CC curve can be obtained, which will be introduced in the next part.

2.3.1.5 Principle curve generation

Generally, the principle cutter contact curve is planned foremost to direct the general tendency of the subsequent cutter contact curve, which is expanded based on the distinct criteria that have been introduced in the sub-chapter 2.1 such as iso-parametric, iso-planar and iso-scallop.

The original principle curve is generated in the parametric uv domain of the known surface on which the machine based energy potential field is embedded. It can be started with a random initial point p_i , which related vector u_i and the optimal feed direction f_i of the machine based energy potential field on the sampled $N \times N$ grid are already known if this node can be obtained by Eq. (38). By continuous the steps from f_i with a forward step d_f in the workpiece coordinate system, the following CC point p_{i+1} can be calculated as shown:

$$p_{i+1} = p_i + \frac{d_f}{E(f_i \cdot \vec{u})^2 + 2F(f_i \cdot \vec{u})(f_i \cdot \vec{v}) + G(f_i \cdot \vec{v})^2} f_i ,$$
(39)

where \vec{u} and \vec{v} are the fundamental unit vectors of the uv domain, as well as E, F, G are the modulus of the first basic form in differential geometry [59].

The principle curve can be generated in the forward step until reach the uv domain's boundary. Then it can be started the similar process from p_i to generate the backward step through the opposite direction of f_i . Finally, the whole principle curve can be fully generated by cascading the forward and backward part.

2.3.1.6 Expansion algorithm according to Iso-scallop height

After generating the principle curve, cutter contact curves can be expanded to its both sides in order to filling the whole surface. According to the iso-scallop height needs, the side step between the neighboring CC curves should be enlarged as more as possible, as much as possible the maximum scallop height.

If the tangent direction determines with the optimal feed direction at each CC point on the principle curve, the expansion of the CC curve is impossible. Fig. 27 shows how to generate the first expanded curve according to the traditional iso-scallop height expansion rules: shift a side step $d_s = w_i$ that perpendicular to the feed direction f_i for each CC point p_i on the principle curve.

Reference [56] provides the equation for the sake of calculating p_i as shown below:

$$|p_i p_i'| = w_i , (40)$$

$$(p_i - p'_i)(\frac{\partial S}{\partial u}\frac{du}{dt} + \frac{\partial S}{\partial v}\frac{dv}{dt}) = 0,$$
(41)

where the differential form $\frac{\partial S}{\partial u}\frac{du}{dt} + \frac{\partial S}{\partial v}\frac{dv}{dt}$ is the feed direction f_i at p_i in theoretically.

The Taylor expansion can eliminate higher order terms of the value p'_i :

$$p_i' = p_i + \frac{\partial S}{\partial u} \Delta u + \frac{\partial S}{\partial v} \Delta v , \qquad (42)$$



Figure 27 – The way to generate the first expanded curve according to the traditional iso-scallop height expansion rules

By utilization of the Eqs. (40)-(42), the parametric increment of p'_i can be calculated in order to match the key equations:

$$\Delta u = \frac{\pm w_i (F \frac{du}{dt} + G \frac{dv}{dt})}{\sqrt{(EG - F^2)(E(\frac{du}{dt})^2 + 2F \frac{du}{dt} \frac{dv}{dt} + G(\frac{dv}{dt})^2)}},$$
(43)

$$\Delta v = \frac{\pm w_i (E \frac{du}{dt} + F \frac{dv}{dt})}{\sqrt{(EG - F^2)(E(\frac{du}{dt})^2 + 2F \frac{du}{dt} \frac{dv}{dt} + G(\frac{dv}{dt})^2)}},$$
(44)

where $E = \frac{\partial S}{\partial u} \cdot \frac{\partial S}{\partial u}$, $F = \frac{\partial S}{\partial u} \cdot \frac{\partial S}{\partial v}$ and $G = \frac{\partial S}{\partial v} \cdot \frac{\partial S}{\partial v}$ are the factors of the first basic form in differential geometry.



Figure 28 – Three expansion groups of cutter contact curves that mantle the whole surface domain

The bias between the optimal feed direction and the tangent direction of the expand curve will be extremely large if the expansion step have been finished and have the certain expanded curves. Then a concept of quality evaluation should be introduced, which will terminated the expansion when the deviation is exceeding a threshold that is expressed as the ratio:

$$\frac{\sum u_i - \sum u_{i0}}{\sum u_i}$$

where $\sum u_i$ is the sum of the machine based energy potential field value through the real feed direction at all the cutter contact points on the expanded curve, as well as $\sum u_{i0}$ is the sum of the optimal machine based energy potential field value at each CC point on the curve. It should be noted that the ratio should be 0 for a principle curve.

As Fig. 28 shown, three expansion groups with the principle curve coloured in blue can cover the entire surface domain. This sub-chapter has introduced a path generation considering the energy consumption, which will be selective utilized to the case study and the rest will be used to future work of research.

3 Case Study

The purpose of the case study section is that to find the most optimized solution of the target shape by researching and adjusting the G codes of the machining. Generally, the machining simulation software such as EdgeCAM will generate a default tool path that can process the target shape according to the blueprint. However, the default solution cannot meet our specific requirements in instance, for example surface smoothness requirements and machining time optimization needs etc.. In this master thesis, we will choose a surface shape that is shown in Fig. 29, which is chosen for the sake of easier observing and comparing intuitively.



Figure 29 – The four views of the target stock and surface

We use EdgeCAM to plan the tool path, simulate and generate the G codes in this thesis. The G codes of all the methods and approaches are attached in the appendix part at the end of this paper. The illustration and investigation of the G codes will be conduct by the diagrammatic sketch in order to explain the codes in a simple and intuitive way.

In this chapter, we will first generate different types of tool path approaches and compare with them in the simulation software, and then the solution will be obtained by combining the optimized machining method. At the end of this chapter the final optimized solution will be conduct in the CNC machine and will be compared with the default case depends on the operation time and smoothness of working surface.

3.1 Analysis of Default Generation Path Based on G codes

As the above description, the tool path of the default solution can be read in the G code file and illustrated in the Fig. 30. The main tool path of the default one is moving in the y-axis direction (top figure of Fig. 30) and cutting layer by layer through the z-axis.



Figure 30 – The tool path illustration of default solution from EdgeCAM

Fig. 31 shows the tool path simulation by G code simulation software. The general shape of the target surface can be seen in this figure by the route of tool movement. The machining time is about 16 minutes and the surface is rough, which cannot meet our requirements in both smoothness and operation time. Therefore, the optimized solutions and approaches are proposed in the following sub chapters.



Figure 31 – Tool path simulation figure of the default case

3.2 Approaches to the Case Based on G codes (simulation)

It is obvious that the default solution mentioned above is not a satisfactory program. Therefore, several approaches in this section will be mentioned to optimize the surface machining. It should be mentioned that this section's research and comparison of the different approaches are based on the simulation software in order to save time and money, as well as comparison of different tool path's processing performance. There are four optimization approaches that will be investigate by analysing the G codes, which are attached in the appendix part and in the attachment as well.

In this thesis, we will propose a module method to optimize the tool path movement. The main module can be divided into two different machining ways:

- 1. Linear tool path movement module
- 2. 3D tool path movement module

Then we will optimize each module to produce the optimized module, and then combine the optimized module together to provide the final proposal of tool path optimization, which will be execute in the CNC machine.

3.2.1 Surface Machining Optimization Method 1: Linear Path only

Fig. 32 and Fig 33 show the tool path illustration by investigating of the G codes. The Rough milling will be the first step to mill the target stock in the x-axis, afterwards the profile milling will be conducted in order to fulfil the smoothness requirements.



Figure 32 – Rough milling illustration of linear path only optimization solution (RM module)



Figure 33 – Profile milling illustration of linear path only optimization solution (PM module)

It should be mentioned that Fig. 32 and Fig. 33 are described the tool path movement in the top view of the stock. The interval between the adjacent tool paths can be seen from the G codes and illustrated in the Fig. 32 as well. However, in the profile milling stage, the neighboring tool paths are not in the same axis. In another word, each tool path is in the distinct depth, which is illustrated in the Fig. 34 (left view of the stock). The principle of the machining of surface is: through iterations of several small processing paths in the x-axis direction, the target surface will be formed by an infinite approximation of the shape of the surface.



Figure 34 – Machining illustration of linear path only optimization solution based on left view of the stock

Fig. 35 is generated from the same G code simulation software. It can be seen from this figure that the surface smoothness is better than the default case. Nonetheless, the machining time is longer than the default case. We will compare the operation time of all the simulation approaches in the comparison section.



Figure 35 – Tool path simulation figure of the linear only optimization case

Method 1 is the original method to conduct the surface machining in linear way as we introduced in the previous section. In the next section we will propose a 3D machining method that has different tool path compare to the linear operation.

3.2.2 Surface Machining Optimization Method 2: Iso Scallop Method

This section will experiment the feasibility of the 3D machining method. Fig. 36 is the tool path illustration of the iso scallop method. The tool path is through the y-axis direction if we consider the tool route in the top view of the stock. The actual path is increment in the z-axis direction and moved in the y-axis, which is the reason we use the short line on the arrow to indicate the incremental change on the other axis.



Figure 36 – Tool path illustration of iso scallop optimization solution (CM module)



Figure 37 – Tool path simulation figure of the scallop optimization case

There is a serious problem in the machining of iso scallop method. We can read the start point of the tool path through the G codes. The path is from the bottom to the top of the surface. However, the vertical distance of the surface is 30mm, which is longer than the tool length. Moreover, the ball-end cutting tool cannot be perpendicular to the target plane in the real machining. Therefore, we need to

purpose an optimization solution of this 3D machining method, which will be carried out in the next section.

3.2.3 Surface Machining Optimization: Optimization of Method 2

Due to the tool crash problem that has mentioned in the above section, we will add a rough milling step in the front of the method 2 in order to avoid tool damage.



Figure 38 – Tool path illustration of combination of RM module & CM module (iso scallop)

Fig. 38 describes the tool movement of iso scallop method. It needs the rough milling before iso scallop machining. Like a double-edged sword, the iso scallop method provides better smoothness while also consuming more processing time due to the small step over in our simple surface case. The iso scallop method might has a better balance performance in the processing time and processing accuracy in the more complex cases. Due to this reason, we will make a more complex surface to test the different algorithms on five-axis CNC machine in the future works.



Figure 39 – Tool path simulation figure of combination of RM module & CM module (iso scallop) case

It can be seen in Fig.39 that the optimization of method 2 is avoiding the damage to the cutting tool and increasing the accuracy of processing at the same time, which means the 3D machining method is an optimized solution that can be considered in the real CNC machining (adjusting of the parameters such as feedrate and spindle speed will be conducted in the real processing in the following chapter).

3.2.4 Surface Machining Optimization: Optimization of Method 1

Method 1 is an approach that makes the tool travel in a linear way in x-axis direction. As the illustration Fig. 32 shown, the cutting tool needs to travel back to the previous x-axis coordinates so as to start the new cutting step. This travel time will probably waste the energy and total machining time. In order to optimize the linear method, the best solution is to make the tool path moving without the travelling time.

Fig. 40 shows the tool path of the optimization of method 1. The main difference between the optimized one and the origin one is the rough milling's tool path. The following machining can be profile milling or small step over rough milling so as to achieve the surface as close as possible to the final surface we want to process.



Figure 40 – Tool path illustration of optimization of method 1 (rough milling module optimization)

We can see from the Fig. 41 that the tool path is changed in the rough milling step. It should be mentioned that he path interval is not small enough in both the linear cutting and 3D cutting simulations. All the simulations are using the same parameters such as feedrate, path interval, cutting depth etc. to make the reasonable comparison, which will be made in the next section.

In the next part, the comparison through machining time, tool distance and program line will be made according to the four optimized approaches and the default case. Then the two real program proposals will be proposed so as to test the result of optimization method.



Figure 41 – Tool path simulation figure of optimized method 1 case

3.3 Comparison of the Different Approaches & Final Proposal

The data of Table 3 from left to right is arranged in the order in which they appear in the previous section and the resources of these data are attached in the appendix part.

	DEFAULT CASE	LINEAR CASE	3D CASE	LINEAR+3D	OPT. LINEAR
MACHING TIME	16m00s	24m07s	07m01s	18m12s	20m53s
PATH DISTANCE	18561.22	32474.83	12619.95	25449.27	28749.98
FEEDRATE	1000	1000	1000	1000	1000
SPEED (RPM)	5730	6366	6366	6366	6366
PROGRAM LINE	1288	710	2262	2382	588
MACHINING TECHNOLOGY	Rough	Smooth	Tool Damage	Smooth	Smooth

Table 3 – Comparison of the five simulations

There are four methods from the chart that can be considered to the comparison such as default case, linear case, linear + 3D case and optimized linear case except the tool damage approach (3D case). Then we ruled out rough case for machined faces (default case) and the most time consuming case

(linear case). At the final stage, we have two optimized options (blue column) that need to implement in the real CNC machining so as to test the performance of this two methods.

As the comparison chart shows to us, although the simulation above is the most resource saving method and the results of the simulation can help us to choose what kind of program should be implement in the real case, but its limitations are obvious, that is, it can not be intuitive to reflect the specific performance of specific program. In order to make our research more practical, the experiment of comparing these two methods will be conducted in the next section. It should be noted that the machining parameters would be modified for the sake of achieving the highest performance of each method.

3.4 Experimental Results & Conclusion

3.4.1 Experimental Process & Results

Fig. 42 is the linear method surface, which will be the reference material compare with the linear + 3D method. In order to increase the contrast, our linear processing program is only used in the simulation part of the selected processing methods, which means the specific parameters are not optimized. The total operation time is about 22 minutes and the surface quality of this method is not satisfactory as shown in the figure.



Figure 42 – Linear method surface

Then we plan to machine the surface by using linear + 3D approach. As we mentioned before, this method is using the iso scallop method (the path interval is 0.4mm) for the profile milling step and the parameters such as feedrate and spindle speed are calculated by following:

$$N = \frac{V_c}{\pi \cdot D},\tag{45}$$

where N is the spindle speed, V_c is the specific speed that is selected depends on different materials and D is the diameter of the cutting tool.

$$f_r = N \cdot n \cdot f_z , \qquad (46)$$

where f_r is the feedrate of each machining, n is the number of teeth and f_z is the ERC feed depends on different materials.

We also need the formula to calculate the material removal rate so as to compare the performance of distinct machining:

$$MRR = a_e \cdot a_p \cdot f_r \,, \tag{47}$$

where a_e is the width of cut and a_p is the depth of cut.

Then we can utilize Eq. (45) and Eq. (46) to calculate the parameters for our specific milling method (linear + 3D machining).

For the machining of first rough milling by using 12mm Flute End Mill:

$$N = \frac{V_c}{\pi \cdot D} = \frac{350}{\pi \cdot 0.012} = 9288RPM$$
$$f_r = N \cdot n \cdot f_z = 9288 \cdot 3 \cdot 0.1 = 2786 \ mm/min$$

For the machining of second rough milling by using 12mm Flute End Mill:

$$f_r = N \cdot n \cdot f_z = 9288 \cdot 3 \cdot 0.14 = 3900 \ mm/min$$

where f_z for each step is adjusted by different correction factor depends on distinct a_e .

For the machining of profile milling by using 10mm Ball Nose End Mill:

$$N = \frac{V_c}{\pi \cdot D} = \frac{440}{\pi \cdot 0.01} = 14012RPM$$

$$f_r = N \cdot n \cdot f_z = 14012 \cdot 2 \cdot 0.057 = 1597 \ mm/min$$



Figure 43 – Linear +3D method surface

After calculation of the specific parameters, we execute the machining by using these numbers. Then we obtain a smoother surface than the contrast surface as shown in Fig. 43 and the total machining time is about 30 minutes.

		LINEAR CASE	LINEAR + 3D CASE
MACHING TIME		22m	30m
FIRST STEP ROUGH	Feedrate (mm/min)	2250	2786
	Spindle Speed (RPM)	8000	9288
	MRR (mm ³ /min)	32400	25074
SECOND STEP PROFILE	Feedrate (mm/min)	995	3900
	Spindle Speed (RPM)	9550	9288
	MRR (mm ³ /min)	746	2808
THIRD STEP FINISH	Feedrate (mm/min)	N/A	1597
	Spindle Speed (RPM)	N/A	14012
	MRR (mm ³ /min)	N/A	638

It is obvious that the optimized linear + 3D method can process more smoother surface without consuming too much time. More comparison of the two methods can be seen in table 4.

Figure 44 – Three different NC programs

However, the surface is not smooth enough in the horizontal direction cause the output method of NC program. There are three types of NC program that we can select for the surface machining and these three programs are shown in Fig. 44. In the end we chose the none type NC program, which is the linear moving of the cutting tool. The chosen surface is not made with a circular radius so that it cannot be implemented as a linear arc NC program, as well as the spline NC program cannot be used causes limitation of the CNC machine.

3.4.2 Conclusion

According to the experimental results, the optimized method (linear + 3D solution) can get more than the previous surface several times the smoothness, while with only an increase of 36% of the processing time. Thus, through the whole research in the previous chapters and the case study, we can draw the following conclusions:

- 1. Only the path optimization tool path method that combines the machining parameters with the optimized calculation can achieve maximum optimization performance.
- 2. 3D machining methods such as iso parametric, iso scallop and iso planar methods might cost more processing time than the linear methods, but they can achieve a higher degree of smoothness. So in the surface processing methods, 3D processing methods have better overall performance than linear ones.
- 3. For the 3D machining step, the type of spline NC program should have the best performance and smoothness than the other two options.

According to the research previously, in the 3D machining methods, iso scallop might have the best performance in machining more complex free form surface. In the future work, we will investigate the application of iso scallop method in five axis CNC machine for machining more complicated free form surface compare with other optimization methods. Moreover, the future work will be an increased optimization level. We will focus on the overall energy consumption of the machining that is mentioned in the before chapter, to optimize the energy consumption of the entire process so as to achieve the ultimate goal of the optimization.

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Appendix: Notes of Iso-Parametric Machining



Appendix: Notes of Iso-Planar Machining



Appendix: Notes of Iso-Scallop Machining

Appendix: Notes of Prediction model page 1



Appendix: Notes of Prediction model page 2



Appendix: Notes of Tool path generation regard to energy consumption page 1

2.1 Pre-determinention of tool mentarism Conclusion woril page 3 : According to Fig 1, 2, 3, lead angle a stand be positive if the is negative. or - 1. - + - 1. - as small as 0 to architere largert cutty woth Two orlentootim Ti = (a:, b:, c:) = n condet f sind cosp - le sind sing ? 2.2. Everyy insumption model reference unstant feed rate f. idle power willy power driving power demand demand although If calibrated Eq: = PT + II Pin-Pill = Sis (Ft (h, t))rS)dhidt speed cred/s) F tain height the Time t contain heyert tangential Ford Intensity-50500028 AE - type filting table with only two retains ares. (Appendix) (mi,1 , mi,2 , mi,6 , mi,4 , mi,5) = IRT (x: 1; , 2: , a: , b: , c;) huseheuts VK= (Mi+1, k - mi, k) at at at a contract (Mi+1, k - 2mi, k + mi-1, k) 4

Appendix: Notes of Tool path generation regard to energy consumption page 2


Price to backing according, two customing:
(1) The wapisour scale bright on the finish surface would they been
a threshold BA.
(2) The chord error e of any two adjacent cc paints would not exceed
a gran taleman.
(3: Fig.2 W: swin(2t, IPTAN))
Uf: Fig.3 of swin (IF strp) - using a would be wreat FBAD + 2PBADAFAN.
(4: Fig.3 of swin (IF strp) - using a would be along the feed direction.
(5. Surface radius of curvature along the feed direction.
(5. Surface radius of curvature along the feed direction.
(5. Surface for and minimize radial energy encomption to Target
(1) optimal field direction

$$u = \frac{1}{\sum_{i=1}^{N}} \frac{\sum_{i=1}^{N} \frac{U_i}{|I| - P_i|I|}}{\sum_{i=1}^{N} \frac{U_i}{|I| - P_i|I|}}$$
(3. Principle curve generation
Next as point from .
Phile Fit of the fit of start to be direction
BDI at the TRE of the along and adjacenter
(F: -P_i') (for df - and the context of the fit of the f

By Taylor expansion : Pi' = Pi + 25 ou + 25 ou calculate as , or miny equation (24-622) Mensurement reation _ Zu: - I did , which shadd be a on priniple curve. not larger than u.2 on expanded curve. selen forminated because ratio > 0.2 new cc curre incorrected only inside uncover portion No.le 3. DBSFs in Five-aver maching. Direction - Based Scalar Fields 3.1. The mudifiel cutting strip width - Fig. 2 (10)- odxq(0) - dxq(0)- odxq(0) 3.2 The workpiecte fact race LAUGISE bimmettic transformation 1 Fig.4. PW.Tw - O Msetup - Eq.8 - IKT Eg.8. (WCS) (Tes) (MCS) 1 1 4 knowpiece coastinge Table condition Magine Condinate \$ ystem system. system £

Cutting force of
$$E$$
-over flat end willing.
Cutting edge with a constant hosis angle:
 $I = P_{L} = (X_{L}, q_{L}, z_{L}) = (Rining), Riceq. 2)$ = in the trul
undiverse upseen
CTCS =
 $q = q_{L} = \frac{R}{R}$ ten to
return angle of the cutting point
 $V = \frac{R}{R}$ ten to
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 $V = \frac{R}{R}$ ten to

$$[G_{i}, f_{i}, C_{i}, 1]^{T} = P_{c}t_{i} (\partial_{w} - M_{i}f_{i}) \cdot P_{c}t_{i} (X_{w} - M_{i}, 0) \cdot [D, 0, 0, 1]^{T}$$

$$\int Bepaul to$$

$$\binom{G_{i}}{b_{1}} = \binom{(sin(M_{i}, i_{i}) + sin(M_{i}, 0))}{(sin(M_{i}, 0) + (sin(M_{i}, 0))}$$
When the two intertial coordinates obtained, the translational wavement (M_{i}, M_{i}, M_{i}) of the TCS in terms of a notated frame in the gapsesed as:

$$[M_{i}(1, M_{i}), M_{i}(3, M_{i}), (1]^{T} = P_{c}t_{i} (X_{w}, M_{i}, w) \cdot P_{c}t_{i} (\partial_{w}, M_{i}, s) \cdot [X_{i}, y_{i}, E_{i}, 1]^{T}$$
Frackly the Let solution (M_{i}, M_{i}), M_{i}(3, M

Appendix: G codes simple definition page 1



Appendix: G codes simple definition page 2



Appendix: G codes simple definition page 3

Note that some of the above G-codes are not standard. Specific control features, such as laser power control, enable those optional codes. M codes simple definition M00 Unconditional stop M01 Conditional stop M02 End of program M03 Spindle clockwise M04 Spindle counterclockwise M05 Spindle stop M06 Tool change (see Note below) M19 Spindle orientation M20 Start oscillation (configured by G35) M21 End oscillation M30 End of program M40 Automatic spindle gear range selection M41 Spindle gear transmission step 1 M42 Spindle gear transmission step 2 M43 Spindle gear transmission step 3 M44 Spindle gear transmission step 4 M45 Spindle gear transmission step 5 M46 Spindle gear transmission step 6 M70 Spline definition, beginning and end curve 0 M71 Spline definition, beginning tangential, end curve 0 M72 Spline definition, beginning curve 0, end tangential M73 Spline definition, beginning and end tangential M80 Delete rest of distance using probe function, from axis measuring input M81 Drive On application block (resynchronize axis position via PLC signal during the block) M101-M108 Turn off fast output byte bit 1 (to 8) M109 Turn off all (8) bits in the fast output byte M111-M118 Turn on fast output byte bit 1 (to 8) M121-M128 Pulsate (on/off) fast output byte bit 1 (to 8) M140 Distance regulation "on" (configured by G265) M141 Distance regulation "off" M150 Delete rest of distance using probe function, for a probe input (one of 16, M151-M168) M151-M158 Digital input byte 1 bit 1 (to bit 8) is the active probe input M159 PLC cannot define the bit mask for the probe inputs M160 PLC can define the bit mask for the probe inputs (up to 16) M161-M168 Digital input byte 2 bit 1 (to bit 8) is the active probe input

Appendix: G codes of default solution page 1



Appendix: G codes of default solution page 2

Y1.0015	11.5	11,9943	1-1-3	11.005	8-4.5	11.3815	61 2-12.5
60.15	G1 2-3.5	60 25	61 2-6.5	60 15	61 2-9.5	00.05	x97,5 114.1336
395.5 136.0724	322.5 126.0733	8120,5008 127,54	5 847,5000 127.51	181 X145.5 12	1,2009 834,5 811,20	N30_5 Y21_2555	11.9938
61 p-3.4	60.05	87 t - 5	11,8000	61.0-5.5	62 13	1-4.5	907 85 31200 8804 324 1222
387.5 136.0725	325.5 134.0731	#112,5000 127,541	J 850,5005 127.55	142 3137.5 12	1.2405 875.5 121.25	#1 #2.501 121.2157	1-7.5
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60.15	01 2-3.5	60.45	63 2-6.5	60 15	01 1-9.5	x549.9942 V-0.0088	R\$2.5 Y26.3334
300.5 134.0725	317.5 124.0731	8115,5008 127,54	3 342,5008 927,50	110 3140.5 12	1.2407 887,5 815.25	ED #050.0003 VD.0043	93.,9837
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43, 1-2.5	60.15	61.1-6.5	00.15	61.1-9.5	00.15	8547,499 916,8353	395,5001 V16,1332
872.5	828.5 124.0193	197,5001 127.5404	835,5008 127,50	175 A122.5 12	1,2193 882,5 121,25	VD., 9950	2-7.5
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321.3 138.0131	2-1-5	X52.5001 Y27.558	121.2009	R14.9 A11	L1941 835-5 ¥21-25	07 11., 994	8-7.5
68.15	63 2-6.5	11,370,7	61.2-9.5		11 Page 2	x005,5000 V14,1379	01 2-12.5
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$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8125 11.1.1.1.1 11.1.1.1.1 11.1.1.1.1 11.1.1.1.1 11.1.1.1.1.1 11.1.1.1.1.1 11.1.1.1.1.1.1.1.1.1.1.1.1.1.1.1.1.1.1.1	8006 V11.7394 45 9 (51,739) 8 (51,739) 43 43 43 43 43 45 45 45 45 45 45 45 45 45 45 45 45 45	Note: 512.1725 124.5.3 512.1725 124.5.4 512.1725 124.5.4 512.1725 124.6 512.1725 124.6 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7275 124.7 512.7276 124.7 512.7276 124.7 512.7264	11.4994 01.55 12.4754 24.13.50 14.45.50 14.45.50 1	$\begin{array}{c} z=1.5, \\ z=1, z=5, \\ z=1, z=1, \\ z=$	11,4917 61,35 143,500 17,8715 243,500 17,8715 243,500 17,8715 243,500 17,8715 243,500 17,4715 243,500 17,4715 244,500 17,4715 245,4705 17,4715 247,500 17,4705 247,500 17,500 17,500 247,500 17,500 17,500 247,500 1	Y1,2458 Y4,4054 Y4,4054 Y4,4057 Y4,4051 Y4,4051 Y4,405
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$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8125 11.1.1.1.	8006 V11.7394 45 5064 V11.7399 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5 5	Mail. 3026 1131175 2-43.5 40 2-15.5 201 2-15.5 2	11.4994 01.55 12.2934 21.3.3 01.4.3.000 01.400 0	1-12.5 61 P. (-16.5 877, -1019 F. (-17.13 81, -18.12 910, -18.17, -17.13 910, -16.15	11,4917 61,35 135,560 17,8717 24,3,3 47,961 7,4715 17,4935 61,360 17,4715 17,4935 61,35 14,	Y1,243.8 Y1,243.4 Y1,252, Y1,427 Y1,427 Y1,427 Y1,427 Y1,427 Y1,428 Y1,448 Y1,458 Y1,458 Y1,458 Y1,458 Y1,458 Y1,459 Y1,429 Y1,4
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8122 16.0 2 8105 8105 8105 8105 8105 8105 8105 8105	8000 V21.7294 K5 804 V21.7290 305 V21.7290 42 805 V21.7290 82 85 85 85 85 85 85 85 85 85 85	X008.3002 Y12.17275 2-84.5 3 X012.3004 Y12.1725 Y12.8001 Y12.1726	12-4924 42 33 17.2934 42.394 42.394 42.394 42.394 42.394 42.394 42.394 42.394 42.395 42.39	$\begin{array}{c} 1{-}13.5\\ 61 \\ -2{-}16.5\\ 82 \\ -2{-}16.$	11,4917 G1 25 21,5,5 2 21,5,5 2	Y1.063 Y4.054 Y4.057 Y4.027 Y4.027 Y4.027 Y4.027 Y4.020 Y4.000 Y4.
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	822 100-2 10	80.0 127300 42 50 50 50 50 50 50 50 50 50 50	Mail. 3004 112.1275 2-42.5 40 2-15.5 701.2010 121.7373 701.2010 121.7373 701.2010 121.7373 701.2010 121.7375 701.2.5 701.5 701.5 701.5 701.5 701.5 701.5 701.5 701.5 701.5 701.5 701.5	1. 1994 0. 15 1. 2754 2.12,3 0.12,5 0.12,	$\begin{array}{c} 5+15.5\\ 61 > (24.5)\\ 817, 1018 \\ 11, $	11.4917 61.35 12.500 17.8717 2-1.35 6.500 17.8717 2-1.35 6.500 17.8717 1.4055 61.995 1.4055 61.9717 2.4059	Y1,4818 Y1,4944 Y1,4947 Y1,4927 Y1,4927 Y1,4928 Y1,4928 Y1,4928 Y1,4928 Y1,4928 Y1,4928 Y1,4929 Y1,
69 15 20, 20 10, 20	8122 15.0.0	NODE VII. 7394 HS NODE VII. 7394 A NODE VII. 7396 A A NODE VII. 7399 HS	NUENUEL_TITL 1-44.5. 0.8 1-51.5. 0.8 1-51.5. 0.8 1-51.5. 0.8 1-51.5. 0.8 1-51.5. 0.8 1-51.5. 0.8 1-51.5. 0.8 1-51.5. 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.8 1-51.7.175 0.9 1-51.7.176 0.9 1-51.7.176 0.9 1-51.7.176 0.9 1-51.7.176	11.4994 12.394 13.3954 14.3954 14.3954 14.395 14	$\begin{array}{c} 1{+}1{-}5\\ 81{-}1{-}1{+}5\\ 81{-}1{-}1{+}5\\ 81{-}1{-}1{-}15\\ 81{-}1{-}1{-}15\\ 81{-}1{-}1{-}1{-}15\\ 81{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}$	11,4917 61,23 12,5,52 14,555 14,555 15,55	Y1.4535 Y4.4535 Y4.4535 Y4.452 Y4.452 Y4.4535 Y4.4545 X4.4545 Y4.454 X4.454 X4.454 Y4.454 Y4.454 Y4.455 Y4.455 Y4.457 Y4.457 Y4.455 Y
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	822 101-10 10-10	884, 121, 7294 45 50 50 50 50 50 50 50 50 50 5	$\begin{array}{l} \mbox{Xid}, \mbox{Xid}, \mbox{Yid}, \mbox{Yid}, \mbox{Yid}, \mbox{Yid}, \mbox{Yid}, \mbox{Yid}, \mbox{Xid}, \mbox{Xid}, \mbox{Xid}, \mbox{Yid}, \mbox{Yid},$	1. 1994 10 15 17. 2794 2.12.3 4.12.3 4.12.5 17. 2994 17. 2995 17. 29	$\begin{array}{c} 1{-}13.5\\ 61 \\ +10.5\\ 81 \\ +10.5\\ +$	11.4917 61.35 125.500 17.8717 1-1.35 64.96 64.96 17.8735 65.965 7.8755 65.965 7.875 7.8755	Y1,2434 Y2,2505 Y1,487 Y1,4
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8122 15.9.9 15.9.9 16.9.2 16.9.2 17.9.2	8005 V11.7394 H5 V11.7394 H5 V11.7399 V1 V11.7399 V1	Note: 5121725 5-455 60 61 5-155 716801 60 62 5-155 716801 60 62 5-155 716801 60 62 5-155 716801 7517373 726802 7517373 736804 7517373 746804 7517374 746804 7517374 746804 7517374 746804 7517374 746804 7517374 74681 7517374 74681 7517374 74681 7517374 74681 7517374 74681 7517374 7479 7479 7479 7479 7479 7479 7479 7479 7479 7479 7479 7479 7479 7479	11.4994 01.55 11.3754 12.3754 12.3754 12.3754 12.3754 12.3754 12.3754 12.3754 12.3754 12.3754 12.37555 12.37555 12.37555 12.37555 12.37555 12.37555 12.37555 12.3755555 12.3	$\begin{array}{c} z=1.5, \\ z=1.0, \\ z=1.0$	TL, 4917 G1 23 R1, 500 87, 8713 P1, 30 R1, 500 87, 8713 P1, 300 87, 8714 P1, 300 87, 74, 7433 P1, 483 97, 74, 7433 P1, 500 88 P1, 300 87, 74, 7433 P1, 493 97, 74, 7433	Y1, 9438 Y4, 4044 Y4, 4044 Y3, 8020 Y4, 4021 Y4, 4021 Y4, 4021 Y4, 4021 Y4, 4021 Y4, 4021 Y4, 4021 Y4, 4023 Y4, 4023 Y4, 4023 Y4, 4023 Y4, 4023 Y4, 4024 Y4, 4025 Y4, 4
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8.22 1. 1. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2.	825, 721, 7294 K5 505 (711, 7296 3 505 (711, 7296 42 505 (711, 7398 42 505 (711, 7398 42 505 (711, 7398 505 (711, 7398) 505 (711, 7398 505 (711, 7398) 505 (711, 7398	X008.3002 Y12.47275 2-84.5 3 X02.3004 Y12.4725 Y1.6803 00 Y2.6514 112.7572 Y2.65143 112.7572 Y2.75143 11	12.4994 62.33 17.354 18.254 18.2554 18.2556 18.2556 18.2556 18.2556 18.2556 18.2556 18.2556 18.2556 19.25566 19.25566 19.25566 19.25566 19.	$\begin{array}{l} 1{-}13.5\\ 61 \\ -101.5\\ 812, -101.5\\ 812, -101.5\\ 812, -101.5\\ 812, -101.5\\ 812, -101.5\\ 812, -101.5\\ 812, -101.5\\ 812, -101.5\\ 812, -101.5\\ 812, -101.5\\ 813, -101.5\\ 8$	11, 1917 G1 25 21, 5, 5, 5 21,	Y1.4628 Y1.4024 Y2.4027 Y2.4027 Y2.4027 Y2.4027 Y2.4027 Y2.4027 Y2.4027 Y2.4027 Y2.4027 Y2.4027 Y2.402 Y2
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	800 100 21 100 2	Anda 121,7204 42 43 45 45 45 45 45 45 45 45 45 45	Not. 3002 Y12., Y175 2-42.5 G 01 2-15.5 Y1., P693 G 92 2-15.5 92 2-15.5 92 2-15.5 92 2-15.5 92 2-15.5 92 2-15.5 92 2-15.5 92 2-15.5 92 2-15.7 92 2-15.7 92 2-15.7 92 2-15.7 92 2-15.7 93 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177 94 10.177	11.4994 01.55 12.2954 21.3.3 12.4.3.500 11.495 12.4.3.500 11.495 12.4.3.500 11.495 12.4.3.500 11.495 12.4.500 11.495 12.4.500 12.4.	$ \begin{array}{l} z + 1.5 \\ z + 1.5 \\ z + 7, z + 10.5 \\ z + 7, z + 10.5 \\ z + 1, z + 10.5 \\ z $	11,4917 01,35 143,500 17,8713 143,500 17,8713 143,500 17,8713 143,500 17,8713 043,500 17,8713 043,500 17,8714 043,500 17,8714 043,500 17,8714 043,500 17,8714 043,500 17,8713 044,500 17,8713 045,500 17,8713 05,500 17,500 1	Y1,2418 Y1,2418 Y1,242 Y1,422 Y1,4
00 15 20.5 10 116.1214 20.5 20 116.1214 20.5 20.5 20.5 20.5 20.5 20.5 20.5 20.5	8122 15.0-10 15.0-1	8006 V21.7204 K5 806 V21.7206 3 5 807 V21.7209 808 V21.7209 808 V21.7209 808 V21.7201 808 V21.7201 808 V21.7201 808 V21.7200 808 V2	$\begin{array}{l} \mbox{X00.} \ \mbox{X00.} \ \ \mbox{X00.} \ \ \ \mbox{X00.} \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \ \$	12.4994 02.15 13.2954 14.42.5961 14.42.5961 14.42.5961 14.45	$\begin{array}{c} 1{-}1{-}5{-}5\\ 61{-}1{-}1{-}1{-}5\\ 82{-}1{-}1{-}1{-}5\\ 82{-}1{-}1{-}1{-}5\\ 82{-}1{-}1{-}1{-}5\\ 82{-}1{-}5\\ 82{-$	11, 1917 61 25 21, 5, 5, 5 21, 5	Y1.4635 Y4.4034 Y4.4034 Y4.4027 Y4.4027 Y4.4027 Y4.4027 Y4.403 Y4
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	822 1962 - 1965	845 121.7204 45 55 55 55 55 55 55 55 55 5	$\begin{array}{l} \mbox{Xid}, \mbox{Xid}, \mbox{Yid}, \mbox{Yid}, \mbox{Yid}, \mbox{Yid}, \mbox{Yid}, \mbox{Yid}, \mbox{Xid}, \mbox{Xid}, \mbox{Xid}, \mbox{Xid}, \mbox{Yid}, \mbox{Yid},$	11.4994 10.15 11.4994 11.43 11.45	$\begin{array}{c} 1{-}13.5\\ 61\ ({-}101.5\\ 81\ ({-}101.5\ $	11.4817 01.35 125.502 17.8717 2-1.35 2-1.3	Y1,2413 Y1,2413 Y1,2427 Y1,4227 Y1,4227 Y1,4227 Y1,4227 Y1,4227 Y1,4227 Y1,4227 Y1,4229 Y1,
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8122 15.0.0	8005 V21.7394 H5 S06 V21.7396 b b c s06 V21.7396 b c c s06 V21.7396 b c c c s06 V21.7396 b c c c c c c c c c c c c c c c c c c	Note. 50005 Y12., Y275 1-46.5 G 05 1-51.5 06 1-51.5 07 1-66.5 08 1-51.5 08 1-51.5 08 1-51.5 08 1-51.5 08 1-51.5 08 1-51.5 08 1-51.5 08 1-51.5 08 1-51.5 08 1-51.5 08 1-51.5 09 1-51.5 09 1-51.5 010 1-51.5 0111 1-51.5 0111 1-51.5 0111 1-51.5 0111 1-51.5 0111 1-51.7 0111 1-51.7 0111 1-51.7 0111 1-51.7 0111 1-51.7 0111 1-51.7 0111 1-51.7 0111 1-51.7 0111 1-51.7	12-5924 02-55 12,2754 12,3754 12,3754 12,3755 12,375 12	$\begin{array}{c} 1\!$	11,4917 61,33 12,5,692 17,8715 15,592 17,8715 15,592 17,8715 10,595 1	Y1,9438 Y4,404 Y4,404 Y1,927 Y1,402 Y1,402 Y1,403 Y1,403 Y1,404 X2,500 Y1,404 X2,500 Y1,404 X3,500 Y1,404 X1,404 Y1,404 X1,500 Y1,403 Y1,40
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8.22 1. 1. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2.	8245 723.7294 K5 504 753.7296 3 505 753.7398 42 505 753.7398 43 505 753.7398 43 505 753.7395 505 753.7395 505 753.7395 505 555 505 753.7395 505 555 505 753.7395 505 555 505 753.7395 505 555 505 555	X000001 Y121725 2-84.5 3 X12504 Y121715 Y1601 Y121715 Y1602 Y121715 Y1602 Y121715 Y1602 Y121715 Y1602 Y121715 Y1602 Y121715 Y1603 Y121715 Y1604 Y121715 Y1605 Y121716 Y1791 Y121716 Y1791 Y121716 Y1791 Y121716 Y1791 Y121716 Y1791 Y121716 Y1791 Y121716 Y17916 Y121716	12.4994 02.03 17.3954 18.42,390 17.4954 18.42,390 17.4955 18.42,390 17.4955 18.42,390 17.4955 18.42,390 17.4955 19.43,300 17.4955 19.43,400 17.4955 19.43,400 17.4955 19.43,400 17.4955 19.43,400 17.4955 19.43,400 19	$\begin{array}{c} 1{-}13.5\\ 61 \\ 1{-}101.5\\ 81 \\ 81 \\ 81 \\ 81 \\ 81 \\ 81 \\ 81 \\ 81$	31, 4937 60 35 31, 51, 53 31, 51, 51 51, 53 41, 55, 53 51, 598, 55 51, 598, 57 51, 598, 57 51, 558, 57, 578, 58 51, 598, 57 51, 598, 57 51, 598, 57 51, 558, 57, 578, 58 51, 558, 57 51, 558, 57 51, 558, 57 51, 558, 578, 578, 58 51, 558, 563, 59 51, 558, 563 51, 558, 563 51, 558, 563 51, 558, 563 51, 558 51, 558 51, 558 52, 558, 578, 578, 578 51, 558, 563 51, 558	Y1.4628 Y1.4627 Y1.4627 Y1.4627 Y1.4627 Y1.4627 Y1.4628 Y1.4628 Y1.4628 Y1.4628 Y1.462 Y1.46
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8122 15.9.9	8005 V11.7394 H5 V11.7394 H5 V11.7394 V1 V11.7394 V11.739	Note	11.4994 12.37544 12.375	$\begin{array}{c} z=1.5,5\\ z=r_{1},0,0\\ z=r_{1},0,0\\ z=r_{2},0,0\\ z=$	TL, 4917 G1 23 R1, 500 87, 8713 P1, 30 R1, 500 87, 8713 P1, 300 87, 8714 P1, 300 87, 8714 P1, 300 87, 97, 4713 P1, 473 97, 97, 9713 P1, 473 97, 97, 9714 P2, 473 97, 97, 9715 P2, 473 97, 97, 9714 P3, 97, 9714 P3, 97, 97, 9715 P3, 97, 97, 9715 P3, 97, 97, 9714 P3, 97, 97, 9714 P3, 97, 97, 9714 P3, 97, 97, 9749 P3, 97, 97, 9749 P3, 97, 97, 9749 P3, 97, 9749 P4, 4505 P4, 4505 P4, 4508 P4, 4509 P4, 4509 P4, 4509 P4, 4509 P4, 4	Y1, 9618 Y1, 1014 Y1, 1027 Y1, 6020 Y1, 60
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8,22 1, 10 1,	8888 923.7294 K5 804 923.7298 3 204 923.7298 4 2 8 2 8 2 8 2 8 2 8 2 8 2 8 2 8	X008.3002 Y12Y275 2-84.5 3 X12.3004 Y12Y775 Y12.8007 Y12.807 Y12.8007 Y12.907 Y12.8007 Y12.907 Y12.8007 Y12.907 Y12.8007 Y12.907	12-4994 02-35 14-25-55 14-25-56	$\begin{array}{c} 1{-}13.5\\ 61 \\ -213.5\\ 8$	11,4917 G1 23 21,5,5 2 21,5,5 2 21,5 2	Y1.4635 Y1.4034 Y2.5550 Y2.4027 Y2.4027 Y2.4027 Y2.4027 Y2.402 Y2.403
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	822 1962 - 1962	844 121.7204 45 55 56 55 55 55 55 55 55 55 5		11.4994 10.15 11.435	$\begin{array}{c} 1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}1{-}13.5\\ 0{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1$	11,4917 01,35 125,502 17,8713 141,503 17,8713 141,503 17,8713 141,503 17,8713 141,503 17,8713 141,50	Y1, 2414 Y1, 244 Y1, 255 Y1, 255 Y1
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8,222 15,0,0 16,0,0,0 16,0,0,0 16,0,0,0 16,0,0,0 16,0,0,0 16,0,0,0 16,0,0,0,0 16,0,0,0,0 16,0,0,0,0 16,0,0,0,0,0,0 16,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0	8886 V21.7294 K5 S06 V21.7294 S06 V21.7294 S S06 V21.7294 S S S S S S S S S S S S S S S S S S S	Note	12-5924 02-35 14-25-35 14-25-3501 17-255 14-25-350 17-255 14-25-350 17-255 14-25-350 17-255 14-25-350 17-255 14-25-350 17-255 14-25-350 14-25-35	1-13.5 81 - 2-13.5 82 - 2018, 93 - 94 - 95 96 - 2018 (* - 2018) 96 - 2018 (* - 2018) 96 - 2018 (* - 2018) 97 - 201	11,4917 61,35 81,55,97	Y1.49438 Y4.4943 Y4.4947 Y1.4927 Y1.4927 Y1.4927 Y1.4927 Y1.4928 Y1.4928 Y1.494 Y1.494 Y1.494 Y1.494 Y1.494 Y1.494 Y1.494 Y1.495
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8.22 1. 1. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2. 2.	825, 721, 7294 15 50 50 50 50 50 50 50 50 50 5	Mail. 3001 V12Y275 2-84.5 5 2-84.5 5 3-8.5 5	12.4994 02.35 17.4994 17.4994 17.4995 17.49	$\begin{array}{c} 1{-}13.5\\ 0{-}1{-}14.5\\ 0{-}1{-}14.5\\ 0{-}1{-}14.5\\ 0{-}1{-}14.5\\ 0{-}1{-}1{-}14.5\\ 0{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1$	11, 1987 01 35 21, 5, 53 21, 5, 53 21, 53 21, 53 21, 54 21, 54 21, 54 21, 54 21, 54 21, 54 21, 54 21, 54 21, 54 21, 55 21, 55	Y1.4628 Y1.4627 Y1.4627 Y1.4627 Y1.4627 Y1.4627 Y1.4628 Y1.
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8122 15.0.0	8005 VII. 7394 HS S006 VII. 7396 A A S006 VII. 7396 A A S005 VII. 7396 A A A A A A A A A A A A A A A A A A A	$\begin{array}{l} \mbox{Note:} $ $ $ $ $ $ $ $ $ $ $ $ $ $ $ $ $ $ $$	11.4994 01.5 11.3754 12.37545 12.37545 12.37545 12.37545 12.37545 12.37545	$\begin{array}{c} 1+1.5\\ 8+1.5,8\\ 8+1.6,8$	11,4917 01,33 21,502 21,57 21,502 21,57 21,57 21,502 21,57 21,502 21,57 21,	Y1, 9438 Y1, 943 Y1, 932 Y1, 932 Y1, 932 Y1, 932 Y1, 933 Y1, 935 Y1, 945 X2, 505 Y1, 945 X2, 505 Y1, 945 X1, 945 Y1, 945 Y1
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8.22 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1. 1	8848 723.7294 K5 804 753.7298 3 205 753.7398 4 2 8 2 8 2 8 2 8 2 8 2 8 2 8 2 8	X00000 Y121725 2.450 Y 2.450 Y X12000 Y121725 Y14.807 Y121726	12.4994 02.13 14.2553 14.2553 14.25539 14.25599 14.25599 14.25599 14.25599 14.25599 14.2559	$\begin{array}{c} 1{-}1{-}5,5\\ 0,1,2{-}10,5\\ 0,2,3{-}10,3{-}10,3{-}10,5\\ 0,2,3{-}10,3{-}10,3{-}10,5\\ 0,2,3{-}10,3{-}10,3{-}10,3{-}10,5\\ 0,2,3{-}10$	11,4937 G1 23 23,5,53 24,55 24,55 24,55 24,56 24,56 24,56 24,56 24,56 25,56 24,56 25,566 25,567 25,5	Y1.4638 Y1.4634 Y1.4027 Y1.4027 Y1.4027 Y1.4027 Y1.4027 Y1.4028 Y1.4028 Y1.4028 Y1.4028 Y1.4028 Y1.403 Y1.4
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	822 1942 1942 1942 1942 1942 1942 1942 19	844, 121, 7294 45 54 55 55 55 55 55 55 55 5	Mail. 3001 913.1.7275 2-84.3 5 2-84.5 5 3-8.2.804 91.2.1973 71.602 92.3.1973 71.602 92.3.1973 71.602 92.3.1973 74.602 92.3.1973 74.602 92.3.1973 74.602 92.4.1973 74.603 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1973 74.604 92.4.1974 74.604 92.4.1974 74.604 92.4.1974 74.604 92.4.1974 74.705 92.4.1974 7	11.4994 12.13.3 12.13.5 13.13.5 13.13.5 13.13.5 13.13.5 13.13.5 13.13.5 13.13.5 13.13.5 13.13.5 13.13.5 13.13.5 13.13.5 14.	$\begin{array}{c} 1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}1{-}1{-}13.5\\ 0{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1$	11,4917 01,35 12,500 12	Y1, 2614 Y1, 2614 Y1, 2627 Y1, 4623 Y1, 4623 Y1, 4623 Y1, 4623 Y1, 4624 Y1, 4624 Y1, 4624 Y1, 4624 Y1, 4625 Y1, 4625 Y1, 4627 Y1, 46
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8,22 1,5,0 1,5	NUME VII. 7394 K5 S04 VII. 7394 A S04 VII. 7394 A S04 VII. 7394 S S S S S S S S S S S S S S S S S S S	Note, Note: Y12, -7275 2-84.5 3 G. 12, -13 3 Y1, -1975 Y12, -1775 Y1, -1975 Y12, -1775 Y2, -14, -1 3 Y1, -1975 Y12, -1775 Y1, -1975 Y11, -1775 Y11, -1775 Y11, -177	12-5924 02-35 14-25-55	1-13-5 81 - 2-13-5 82 - 2-13-5 82 - 2-13-5 84 - 2-13-	11, 4937 61 35 23, 5, 5, 5, 7, 8713 24, 5, 5, 5, 7, 8713 25, 5, 5, 7, 8715 26, 1, 465 27, 4715 26, 5, 5, 5, 5, 7, 1, 7, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1,	Y1.49438 Y1.4943 Y1.4927 Y1.4927 Y1.4927 Y1.4927 Y1.4927 Y1.4927 Y1.4927 Y1.4928 Y1.492 Y1.
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	4 4 4 4 4 4 4 4 4 4 4 4 4 4	0.04.0 Y2.1. 72.04 1.5 Sole 0.5 Sole 0.6 Y2.1. 72.04 0.7 Sole 0.8 Y2.1. 72.04 0.9 Y2.1. 72.04	Mail. 3001 912.1725 2.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.3. 5 3.4.4.5. 5 3.4.5.3. 5 3.4.5.3. 5 3.4.5.3. 5 3.4.5.3. 5 3.4.5.3. 5 3.4.5.3. 5 3.4.5.3. 5 3.4.5.3. 5 3.4.5.3.5. 5 3.4.5.3.5.5. 5 3.4.5.5.5.5. 5 3.4.5.5.5.5.5. 5 3.4.5.5.5.5.5.5.5.5.5.5.5.5.5.5.5.5.5.5.	12.4994 02.33 17.4594 17.4595 17.45	$\begin{array}{c} 1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}1{-}13.5\\ 0{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1$	31, 4937 G1 35 21, 5, 53 21, 55, 54 21, 56, 56 21, 56, 57 21, 58, 58 21, 58, 58 21, 58, 58 21, 58, 58 21, 58, 58 21, 58, 58 21, 58, 58 21, 58, 58 21, 58, 58 21, 58, 58 21, 58 21, 58 21, 58 21, 58, 58 21, 58 21, 58 21, 58 22, 58 23, 58 24, 58 24, 58 25, 58 26, 58 26, 58 27, 58 28, 58 28, 58 29, 58 21, 58 21, 58 21, 58 21, 58 21, 58 21, 58 21, 58 21, 58 21, 58 21, 58 21, 58 21, 58 <t< td=""><td>Y1.4628 Y1.4625 Y1.4627 Y1.4627 Y1.4627 Y1.4627 Y1.4627 Y1.4628 Y1.</td></t<>	Y1.4628 Y1.4625 Y1.4627 Y1.4627 Y1.4627 Y1.4627 Y1.4627 Y1.4628 Y1.
$\begin{array}{c} 09 & 15 \\ 3,0,0,0\\ 3,0,0,0\\ 3,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0\\$	4 1 1 1 1 1 1 1 1 1 1 1 1 1	8005 V21.7394 H5 S06 V21.7396 b b c s06 V21.7396 b c c s06 V21.7396 b c c s06 V21.7396 b c	Note	12.4994 02.45 12.3754 12.3754 12.3754 12.3754 12.375 12	$\begin{array}{c} 1+1.5\\ 8+1.5\\ 81-2+1.5\\ 81-2+1.5\\ 81-2+1.5\\ 81-2-$	11,4917 01,33 21,5,502 21,5,502 21,5,502 21,5,502 21,5,502 21,5,502 21,5,502 21,5,502 21,5,502 21,5,503	Y1, 9438 Y4, 943 Y4, 404 Y4, 932 Y4, 643 Y4, 945 Y4, 945 Y4
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	1 1-11.5. 1 1-11.5.	825, 723, 7294 43 50 50 50 50 50 50 50 50 50 50	X00000 Y121725 2.4.5. 3 X12500 Y121725 Y14.801 Y121726 Y14.901 Y121726	12.4994 02.13 17.2953 16.1-14.5 16.1-14.	1-13.5 61 p-14.5 82 p-14.5 92 p-14.5 93 p-14.5 94 p-14.5 94 p-15 94 p-	71, 4937 GI 23 23, 5, 5, 5 31, 5, 5, 5 41, 5, 49, 17, 47, 13 7, 5, 5, 5, 5, 17, 47, 13 7, 5, 5, 5, 5, 17, 47, 14 7, 5, 5, 5, 5, 17, 47, 14 7, 5, 5, 5, 5, 7, 47, 15 7, 5, 5, 5, 7, 7, 7, 15 7, 5, 5, 5, 7, 7, 7, 15 7, 5, 5, 7, 7, 7, 7, 7, 15 7, 5, 5, 7, 7, 7, 7, 15 7, 5, 5, 7, 7, 7, 7, 15 7, 5, 5, 7, 7, 7, 7, 7, 15 7, 5, 5, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7, 7,	Y1.4628 Y1.4024 Y1.4027 Y1.4027 Y1.4027 Y1.4027 Y1.4027 Y1.4027 Y1.4027 Y1.4028 Y1.4028 Y1.4028 Y1.4028 Y1.4028 Y1.402 Y1.4028 Y1.402 Y1.4028 Y1.40
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8,22 1,0,2,4 1,0,2,4 1,0,2,4 1,0,2,4 1,0,2,4 1,0,2,4 1,0,2,4 1,0,2,4 1,0,2,4 1,0,4,4,4 1,0,4,4,4 1,0,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,	Basis Y237398 ASS Y337398 ASS Y337398 ASS Y337398	Mail. 3001 912.17275 2-84.3 5 3-84.3 5 3-84.3 5 3-84.3 5 3-84.3 5 3-84.3 5 3-84.3 5 3-84.3 5 3-801 51.1973 2-45.3 5 3-801 51.1973 2-45.4 5 3-804 53.8 3-804 63.8 3-904 63.8 3-904 63.8 3-904 63.8 3-904 63.8 3-904 70.8 3-904 70.8 3-904 70.8 3-904 71.7 3-904 71.7 3-904 71.7 3-904 71.7 3-904 71.7 3-904 71.7 3-904 71.7 3-904 71.7 3-905 71.7 3-906 71.7	11.4994 12.374 12.37545 12.37545 12.37545 12.37545 12.37545 12.3754	$\begin{array}{c} 1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}1{-}13.5\\ 0{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1$	11,4917 01,35 12,5,502 12,5,502 12,55 12,55 12,55 12,55 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12,557 12	Y1, 9414 Y1, 1014 Y1, 1027 Y1, 4027 Y1, 4027 Y1, 4027 Y1, 4027 Y1, 4028 Y1, 4028 Y1, 4028 Y1, 4028 Y1, 4028 Y1, 4029 Y1, 40
69 15 3.0.5 17.5	1 1-1-1.1. 1 1-1.1. 1 1-1.1.1. 1 1-1.1. 1 1-1.1.	8000 V21.7204 K5 S000 V21.7204 S000 V21.7209 S000 V21.7209 S000 V21.7209 S000 V21.7209 S000 V21.7209 S000 V21.7209 S000 V21.7300	Note, Note: Y12, -7275 2-84.5 -3 G 1.5 G 1.5 Y1, -1975 Y1, -1975 Y1, -1975	12-5924 02-35 14-25-35 14-25-352 14-25-3	1-13.5 61 - 2-13.5 82 - 2-13.5 82 - 2-13.5 92 - 2-13.5	71, 4937 G1 25 23, 5, 5, 5, 7, 8717 G1 25 G1 25	Y1,49438 Y1,4943 Y1,4927 Y1,4927 Y1,4927 Y1,4927 Y1,4927 Y1,4927 Y1,4927 Y1,4928 Y1
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	4 1 1 1 1 1 1 1 1 1 1 1 1 1	848, 721, 7294 15 85 85 85 85 85 85 85 85 85 8	Mail. 3001 912.1725 2-84.5 5 2-84.5 5 3-2.504 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1723 91.605 912.1724 91.605 912.1724 91.605 912.1724 91.605 912.1724 91.605 912.1724 91.605 912.1724 91.605 912.1724 91.605 912.1724 91.605 912.172	12.4994 02.35 17.4594 17.4595 17.45	$\begin{array}{c} 1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}1{-}13.5\\ 0{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1$	31, 4937 G1 35 245, 53 31, 54, 53 31, 54, 54 31, 54, 54 31, 54, 54 31, 54, 54 31, 54, 54 31, 54, 54 31, 54, 54 31, 54, 54 31, 55, 54 31, 55, 55 31, 55, 56 31, 55, 56 31, 55, 56 31, 55, 56 31, 55, 56 31, 55, 56 31, 55, 56 31, 56, 56 31, 55, 56 31, 55, 56 31, 56, 56 31, 55, 56 31, 56, 57 32, 56 31, 56 31, 57, 572 31, 57, 572 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57 31, 58, 57	Y1, 4624 Y1, 464 Y1, 404 Y1, 402 Y1, 402 Y1
$\begin{array}{c} 09 & 15 \\ 3,0,0,0\\ 3,0,0,0\\ 3,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0,0\\ 4,0,0\\$	1 1-11.5. 1 1-11.5.	Basis 12.1.7398 Amin 12.1.7398 Amin 12.1.7398 Amin 2.1.7398 Amin	Note	12-5994 02-55 12,2754 12,3754 12,3754 12,3754 12,37555 12,375555 12,37555 12,37555 12,37555 12,37555 12,3755	$\begin{array}{c} 1+1.5\\ 8+1.5\\ 81-10$	11,4937 01,35 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,593 12,5,593 12,5,593 12,5,593 12,5,593 12,5,593 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595	Y1, 9438 Y1, 943 Y1, 932 Y1, 932 Y1
$\begin{array}{c} 00 & 15 \\ 30.5, 50 \\ 30.5, 50 \\ 10.5, 10.$	1 1-11.4. 1 1-11.4.	825, 723, 7294 15 15 15 15 15 15 15 15 15 15	X00000 Y127275 2-8.3 3 X12500 Y127755 2-8.4 3 X12500 Y127755 2-8.4 Y127755 2-8.4 Y127755 2-8.4 Y127755 2-8.4 Y127755 2-8.4 Y127755 2-8.4 Y127757 2-8.5 Y127757 Y12895 Y127958 Y12895 Y127958 Y12895 Y127958 Y13995 Y127958 Y145 Y127958 Y146 Y127958 Y145 Y127958 Y146 Y127958 Y146 Y127958 Y146 Y127958	12.4994 02.13 14.2553 14.2553 14.25539 14.25599 14.25599 14.25599 14.25599 14.25599 14.25599 14.25599 14.259	1-13.5 61 p.14.5 82 p.14.5 92 p.14.5 94 p.14.5 94 p.15 94 p.15	71, 4937 GI 23 23, 5, 5, 5 31, 5, 5, 5 41, 5, 49, 17, 47, 13 31, 5, 5, 5 31, 5, 49, 17, 47, 13 31, 5, 5, 5, 5, 17, 47, 14 31, 5, 5, 5, 5, 17, 47, 14 31, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5, 5,	Y1.4525 Y1.4527 Y1.4527 Y1.4527 Y1.4527 Y1.4527 Y1.4527 Y1.4528 Y1.4528 Y1.4528 Y1.4528 Y1.4528 Y1.4528 Y1.4528 Y1.4529 Y1.
$\begin{array}{c} 00 & 0.7 \\ 20.5 & 0.7 \\ $	8,22 1,0,2,4 1,0,2,4 1,0,2,4 1,0,2,4 1,0,2,4 1,0,4,4,4 1,0,4,4,4 1,0,4,4,4 1,0,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,	844 12.7394 45 54 55 55 55 55 55 55 55 5	Mail. 3001 912.17275 2-84.3 3 302.3084 912.1723 71.602 92.1723 71.602 92.1723 71.602 92.1723 71.602 92.1723 72.613 92.1723 72.623 92.1723 72.623 92.1723 72.623 92.1723 72.623 92.1723 72.623 92.1723 72.623 92.1723 72.623 92.1723 72.623 92.1723 72.623 92.1723 72.623 92.1723 72.623 92.1723 72.7243 92.1723 72.7243 92.1723 72.7243 92.1723 72.7243 92.1723 72.7243 92.1724 72.7243 92.1724 72.7243 92.1724 72.7243 92.1724 72.7243 92.1724 72.7244 92.1724 72.7244 92.1724	1. 4994 0. 15 1. 3.754 1. 3.754 1. 3.754 1. 3.754 1. 3.754 1. 3.754 1. 3.754 1. 3.754 1. 3.755 1. 3.7555 1. 3.75555 1. 3.75555 1. 3.75555 1. 3.755555 1. 3.755555 1. 3.755555 1. 3.755555555555555	$\begin{array}{c} 1-13,5\\ 0,1-13,5\\ 0$	11,4917 01,35 12,5,502 12,5,503 12,5,503 12,5,503 12,5,503 12,5,503 12,5,503 12,5,503 12,5,503 12	Y1, 9414 Y1, 9417 Y1, 9427 Y1, 94
09 15 3.0.5 17.5	1 1-11.5 1 1-11	888, 723, 7294 K5 504 703, 7299 504 703, 7299 505 703, 7399 505 703, 7399 505 703, 7399 505 703, 7390 506 703, 7390 506 703, 7390 507 703, 7390 505 700, 7300 505 700, 700, 7000 505 700, 7000 505 700, 70	$ \begin{array}{l} \mbox{X00}, \mbox{X00}, \mbox{Y01}, \mbox{Y01}$	12-5924 02-53 14-52-554 14-52-554 14-52-554 14-52-554 14-52-554 14-52-554 14-52-554 14-52-554 14-52-554 14-52-554 14-52-554 14-52-554 14-55555 14-55555 14-55555 14-55	1-13.5 61 - p-16.5 82 - 2013, 2013, 2013 93 - 2013, 2013, 2013 94 - 2013 94	11.4937 01.35 21.5.52 21.5.53 21.5.54 21.5.55 21.5.55 21.5.55 21.5.55 21.5.55 21.5.55 21.5.55 21.5.55 21.5.55 21.5.55 2	Y1,49438 Y1,4944 Y1,404 Y1,402 Y1,
$\begin{array}{c} 00 & 17 \\ 32.5, 30 \\ 32.5, 30 \\ 42.5, 32.5, 30 \\$	1 1-1-1. A (1) (1) (1) (1) (1) (1) (1) (1) (1) (1)	8.84, 127204 13 8.9 8.9 9.5	Mail. 3001 913.17275 2-84.5 5 3-84.5 5 3-84.5 5 3-84.5 5 3-84.5 5 3-84.5 5 3-84.5 5 3-84.5 5 3-801 50.1 3-81.5 5	12.4994 02.03 11.254 12.254	$\begin{array}{c} 1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}13.5\\ 0{-}1{-}1{-}13.5\\ 0{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1{-}1$	31, 4937 GL 35, 493 GL 353, 493 GL 354, 494 GL 354, 494 <td>Y1.4524 Y1.4525 Y1.4527 Y1.4527 Y1.4527 Y1.4527 Y1.452 Y1.455 Y</td>	Y1.4524 Y1.4525 Y1.4527 Y1.4527 Y1.4527 Y1.4527 Y1.452 Y1.455 Y
$\begin{array}{c} 09 & 15 \\ 3,0,5,29 \\ 3,0,5,29 \\ 3,0,5,29 \\ 4,0,10 \\ 4,0,1$	1 1-11.4. 1 1-11.4.	Basis 12.1.7394 Amin 12.1.7394 Amin 12.1.7394 Amin 2.1.7394 Amin	Note	12-5994 02-55 14-25-55	1-13-5 81 - 2-13-5 82 - 2-13-5 84 - 2-13-5 85 - 2-13-5 86 - 2-13-5 86 - 2-13-5 87 - 2-13-	11.4937 01.35 21.5.52 2	Y1,49438 Y1,4943 Y1,4927 Y1,4927 Y1,4927 Y1,4927 Y1,4927 Y1,4927 Y1,4927 Y1,4928 Y1,492 Y1,
$\begin{array}{c} 00 & 17 \\ 32.5, 32.5, 30 \\ 32.5, 32.5, 30 \\ 32.5, 32.5, 30 \\ 32.5, 32.5, 30 \\ 32.5, 32.5, 30 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32.5, 32.5, 32 \\ 32$	1 1-1-1.5 1 1-1-1.5	825, 723, 7294 15 50 50 50 50 50 50 50 50 50 5	X00000 Y121725 2.4.3. 3 X12500 Y121725 Y14.801 Y121726	12.4994 02.35 13.2953 14.21.500 17.2953 14.21.500 17.4955 14.21.500 17.4955 14.21.500 17.4955 14.21.500 17.4955 14.25.500 17.4755 14.25.500 17.4755 1	1-13.5 61 p.14.5 82 p.14.5 92 p.14.5 94 p.14.5	71, 4937 GI 25 GI 25 GI 25 GI 25 GI 26 GI	Y1.4523 Y1.4523 Y1.4527 Y1.4527 Y1.4527 Y1.4527 Y1.4527 Y1.4527 Y1.4528 Y1.
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	8,22 1,0,2,4 1,0,2,4 1,0,2,4 1,0,2,4 1,0,4,4,4 1,0,4,4,4 1,0,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,4,	840 121.7304 550 121.7304 5.53 121.7394 5.53 121.7394 5.53 121.7394 5.53 121.7394 5.53 121.7394 5.53 121.7394 5.54 121.7394 5.55 121	Mail. 3001 913.1.7275 2-84.3 3 3.3.2.808 912.1.973 71.402 912.1.973 71.402 912.1.973 71.402 912.1.973 74.402 912.1.973 74.402 912.1.973 74.402 912.1.973 74.402 912.1.973 74.403 912.1.973 74.403 912.1.973 74.404 913.1.973 74.404 913.1.973 74.405 913.1.973 74.405 913.1.973 74.405 913.1.973 74.405 913.1.974 74.405 913.1.974 74.405 913.1.974 74.405 913.1.974 74.405 913.1.974 74.405 913.1.974 74.405 913.1.974 74.405 913.1.974 74.405 913.1.974 74.405 913.1.974 74.405 913.1.974 74.405 914.1.974	1. 4994 0. 15 1. 3,3754 1. 3,37545 1. 3,37545 1. 3,37545 1. 3,375545 1. 3,375545	$\begin{array}{c} 1-13,5\\ 0,1-13,5\\ 0$	11,4937 01,35 12,5,502 12,502 12,502 12,502 12,502 12,502 12,502 12,502	Y1, 9414 Y1, 942 Y1, 942 Y1, 942 Y1, 942 Y1, 942 Y1, 945 Y1, 945 Y1
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$\begin{array}{c} 00 & 0.1 \\ x > 0.4 \\ x > $	1 1941. 1 1	No.0 VILL. 7200 AND VILL. 7200 S.S. S.S. 7200 S.S. 7200 S.S. 7200 S.S. 7200 S.S. 7200 S.S. 7200 S.S. 7200 S.S. 7200	Mail. 3001 112.17275 2-84.3 3 3.1.2004 122.1723 12.601 122.1723 12.602 122.1723 2-84.5 3 3.1.2004 122.1723 2-64.5 3 3.1.2004 122.1723 2-64.5 3 3.1.2004 122.1723 2-64.5 3 3.1.2004 122.1723 2-64.5 3 3.1.2004 122.1723 2.1.2.3 122.1724 3.1.2.3004 123.17304 3.1.2004 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304 3.1.2.3005 123.17304	12.5994 02.55 12.3754 12.3754 12.3754 12.3754 12.37555 12.37555 12.35555 12.35555 12.35555 12.35555 12.35555 12.35555 12.35555 12.35555 12.3555555 12.35555 12.35555 12.35555 12.35555 12.355	$\begin{array}{c} 1-13,5\\ 0,1-13,5\\ 0$	11,4937 01,35 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,592 12,5,593 12,5,593 12,5,593 12,5,593 12,5,593 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,5,594 12,595 12,594 12,594 12,594 12,594 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 12,595 <t< td=""><td>Y1, 494.58 Y1, 494.5 Y1, 402.4 Y1, 402.4 Y1, 402.7 <t< td=""></t<></td></t<>	Y1, 494.58 Y1, 494.5 Y1, 402.4 Y1, 402.4 Y1, 402.7 Y1, 402.7 <t< td=""></t<>
$\begin{array}{c} 00 & 15 \\ 30.5, 3$	1 1-11.5. 1 1-11.5.	NAGE VILL. 7204 KS VILL. 7208 A SUB SUB SUB SUB <td< td=""><td>X00000 Y12Y275 2-84.5 3 X12S00 Y12Y175 Y14S01 Y12Y175</td><td>12.4994 12.2954 14.25566 14.2556 14.2556 14.2556 14.255666 14.255666 14.255666 14.255666 14.25</td><td>1-13.5 61 p-13.5 82 p-13.5 93 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 95 p-13.5</td><td>71, 4937 G1 30 215, 513 2</td><td>Y1, 9428 Y1, 9427 Y1, 927 Y1, 927 Y1, 927 Y1, 927 Y1, 927 Y1, 928 Y1, 927 Y1, 928 Y1, 927 Y1, 928 Y1, 929 Y1, 929 Y</td></td<>	X00000 Y12Y275 2-84.5 3 X12S00 Y12Y175 Y14S01 Y12Y175	12.4994 12.2954 14.25566 14.2556 14.2556 14.2556 14.255666 14.255666 14.255666 14.255666 14.25	1-13.5 61 p-13.5 82 p-13.5 93 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 94 p-13.5 95 p-13.5	71, 4937 G1 30 215, 513 2	Y1, 9428 Y1, 9427 Y1, 927 Y1, 927 Y1, 927 Y1, 927 Y1, 927 Y1, 928 Y1, 927 Y1, 928 Y1, 927 Y1, 928 Y1, 929 Y1, 929 Y
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Sanftue optivization L only SPATH=/ N WKS DIR/ N WPD D-codes instruction to the GRE Machine Tool : DMJ 40 eVo - Sienens 840D sl plotoplotler that networkly include the Part1 master thesis Part1 master thesis.2 Part Namo Sequence letter "P". Programmed By Date 117-P Continuous well 4 - 4 Cycletime represent opertures or positions on the phytoclotter's T0 = 10.0 mm Ball Nose Hill 010.0 CYCLESSOOD & Metric dimension date input, also for fundence F (Involid) Wheel (10-199) t is the constand that "chem" trues. NO T="10.0 mm Ball Nose Hill" [00] -> more to the x-y location specifical with the 20153 12-0.11 [00] T="10.0 mm Ball Nose Hill" ; NEXT TOOL PO2"; more to the X-y location . Chutter open . specifical with the churiler closed 054 / Tep CYCLEB00(5,"DHG",0,57,0,0,0,0,0,0,0,0,0,1) CYCLEB00() 054 / S5730 M3 G0 X0 Y0 3- safe Z30 the centre of the are x2.6941 ¥35.311 z4.5001 24,5 394 03 X2.0319 Y34.0230 1-1.9 (-AC(4,4909) J-AC(33.5729) TURN-5 F1145.92 617 103 X2.0319 Y34.0230 1-AC(4.4909) J-AC(33.5729) X148.0097 Ъъ G0 25 X1.9904 20 21.5 G1 2-3.5 x1.9908 x29.0324) liner motion Ц 65 G0 Z5 X1.9905 Y32.0324 34.0344 -21.5 G1 2-3.5 X1.9912 Y24.0324 X148.0097 The, 24mots . -1.03-4 26 1324 bistome. 32474.83 60 25 x1.9909 Y27.0324 Feed: 1000 z1.5 G1 z-3.5 X1.9915 Y19.0324 X148.0097 G0 25 Speed : 6366.00 PPM X ÷. Program 1'dat : 710 1.9124 148.0317 X1.9913 Y22.0324 21.5 G1 2-3.5 X1.9919 Y14.0324 ANI 2 comis-X148.0097 GO 25 x1.9917 y17.0324 21.5 34.28. . G1 z=3.5 X1.9923 Y9.0324 X148.0097 1 Frechere 4 GARS 00000000000 G0 25 0000000 9 X1.9921 Y12.0324 21.5 G1 2-3.5 X1.9927 <u>¥4.0334</u> X150.0097 138.0782 x149.719 Y38.0718 x0 x-0.0099 Y38.0734 x-0.0097 Y0.0101 19 1 3 1.5p26 Ö



X-0.0096 Y23.256 X-0.0097 Y0.0101 G3 XD.0051 Y-0.0086 CR=0.0206 G1 X149.9942 Y-0.0088 G3 X150.0093 Y0.0063 CR=0.0208 G1 Y4.1272 X149.9093 G0 75 1.1 8 x149.9093 G0 25 z2.0143 Y13.9662 z-7.7972 G3 X2.0281 Y14.056 z-12.5 z-AC(4.4916) J=AC(13.6299) TURM=2 G17 G3 X2.0383 Y14.1107 I=AC(4.4916) J=AC(13.6299) G1 X2.0281 Y14.056 X1.991 Y14.0624 Y148.004.0624 X148.0094 G0 25 X1.991 2-7.5 G1 Z-12.5 X1.9918 Y9.0634 X148.0094 X148.0094 G0 X5 X1.9913 Y12.0434 Z=7.5 G1 Z=12.5 X1.9926 Y4.0644 X150.0093 X150.0093 X150.0094 Y18.1354 X0 Y18.1302 X-0.0096 Y18.131 X-0.0097 Y0.0101 X=0.0097 Y0.0101 G3 X0.0051 Y=0.0086 CR=0.0206 G1 X149.9942 Y=0.0088 G3 X150.0093 Y0.0063 CR=0.0208 G1 Y4.0444 X149.9093 GO 25 X1.9921 Y9.2738 A1.9921 (9.2738) 2-10.7972 G3 X1.9951 Y9.364(1-01.1) I=AC(4.4918) J=AC(9.2353) TURM=2 G17 G3 X1.9951 Y9.3646 I=AC(4.4918) J=AC(9.2353) G1 X1.9951 Y9.3648 X148.0094 GO 25 X1.9913 Z-10.5 G1 2-15.5 X1.9923 Y4.3668 X150.0093 X150.0094 Y13.7403 X0 Y13.7356 X-0.0097 Y13.7363 X=0.0001 Y=0.0101 G3 X0.0051 Y=0.0086 CR=0.0206 G1 X149.9942 Y=0.0088 G1 X149.0993 Y0.0063 CR=0.0208 G1 Y4.3668 X149.9093 G 75 G0 Z5 X2.5065 Y6.8899 X2.5065 Y6.8899 <u>2-13.7972</u> GJ X2.563 Y6.961 <u>2-11.5</u> I=AC(4.4921) J=AC(5.3709) TUBN=2 GI 7 GJ X2.6358 Y7.0454 I=AC(4.4921) J=AC(5.3709) GI X2.5967 Y7.0036 X1.967 Y6.961 X1.991 Y7.4325 X148.0094 C0 Y6 . . G0 Z5 X1.991 - 4 X1.991 Z-13.5 G1 2-18.5 X1.9925 Y2.4345 X150.0093 X150.0094 Y9.8756 x0 Y9.8713 X-0.0097 Y9.8721 X=0.0091 19.0721 Y0.0101 G3 X0.0051 Y=0.0086 CR=0.0206 G1 X149.9942 Y=0.0088 G3 X150.0093 Y0.0043 CR=0.0208 G1 12.4345



GD IS X155,7803 X40.3961 24.5 G3 10 F1782.54 G3 110 Y44.469 CR=5 F1336.91 G1 X149.6019 Y44.4 F1782.54 X0 G3 X-5 Y39,4 CR=5 F1336.91 G0 25 X155,7795 Y38.0521 X150,775 128.0021 24 5 61 128 F1782.54 63 X150 Y42.126 CR*5 F1336.91 61 X149,6019 Y42.0571 F1782.54 . . . X0 G3 X-5 Y37,0571 CR+5 F1336.91 GO 25 X155,6359 Y35.7494 1 1 24.5 G1 23 E1782.54 G3 X150 Y40.0199 CR+5 F1336.91 G1 X149.6019 Y39.965 F1782.54 300 G3 X-5 Y34,965 CR+5 F1336.91 GD 25 X155,6219 Y33.937 24.5 G1 1-1-5 F1782.54 G3 X150 Y38.2259 CR+5 F1336.91 G1 X149.6019 Y38.1723 F1782.54 300 G3 X-5 Y33.1723 CR+5 F1336.91 G0 25 X155.5793 Y32.1291 and the second s G1 C14.5 G1 C14.5 G1 C14.5 G1 C14.5 G1 X150 Y36.4732 CR=5 F1336.91 G1 X149,6019 Y36.4237 F1782.54 () fedrete 30 G3 X-5 Y31.4237 CR=5 F1336.91 00 25 X155,5172 Y30.5408 C1 24 4 C1 24 4 C1 24 4 C3 2150 734.9635 CR=5 F1336.91 C1 2149.6019 734.9196 F1782.54 204:3 300 G3 X-5 Y29.9196 CR+5 F1336.91 G0 25 X155,5172 Y29.1034 đ A150,5172 125,1034 24 5 63 x150 733,5261 CR+5 F1336.91 61 x149,6019 Y33,4823 F1782.54 4 0433 10 G3 X-5 Y28,4823 CR+5 F1336.91 G0 25 x155.5186 y27.6697 X150,5100 127.0097 24.5 G1 11, F1782.54 G3 X150 Y32.0908 CR*5 F1336.91 G1 X149,6019 Y32.0468 F1782.54 305 G3 X-5 Y27,0468 CR+5 F1336.91 GD 25 X155.4612 Y26.3665 A1353.4012 126.3005 24.5 G1 P1782.54 G3 X150 Y30.8583 CR+5 F1336.91 G1 X149.6019 Y30.8195 F1782.54 300 G3 X-5 Y25.8195 CR+5 F1336.91 60 25 x155.4435 x25.1509 24.5 G1 244 F1782.54 G3 x150 Y29.664 CR+5 F1336.91 G1 x149.6019 Y29.6268 F1782.54 300 G3 X-5 Y24,6268 CR+5 F1336.91 G0 25

X155.4435 Y23.9586 24.5 24.5 G1 3 F1782.54 G3 X150 Y28.4717 CR=5 F1336.91 G1 X149.6019 Y28.4345 F1782.54 G3 X-5 Y23.4345 CR+5 F1336.91 G0 25 60 Z5 x155,318 Y13,5352 X155.4072 Y22.7877 24.5 G1 2-12.5 F1702.54 24-5 G1 -7.5 F1782.54 G3 X150 Y27.3443 CR=5 F1336.91 G1 X149.6019 Y27.3103 F1782.54 G3 X-5 Y22.3103 CR=5 F1336.91 GD 25 X155.318 Y12.7717 G0 25 X155.39 ¥21.7322 24.5 G1 2-8 F1782.54 G3 X150 Y26.3091 CR=5 F1336.91 G1 X149.6019 Y26.2766 F1782.54 G3 X-5 Y21.2766 CR=5 F1336.91 00 25 X155.318 Y12.0085 G0 25 X155.3907 Y20.7209 24.5 G1 2-8.5 F1782.54 G3 X150 Y25,297 CR=5 F1336,91 G1 X149.6019 Y25.2644 F1782.54 G3 X-5 Y20.2644 CH#5 F1336.91 G0 25 X155.3079 Y11.2353 X155,3904 V19,7087 24 5 G1 - A F1782.54 G3 X150 Y24.2851 CR=5 F1336.91 G1 X149.6019 Y24.2526 F1782.54 G3 X-5 Y19.2526 CR=5 F1336.91 03 25 x155,3168 y10,5084 X155.3741 Y18.7187 G1 2-9.5 F1782.54 G1 2-3.5 F1782.54 G3 X150 Y23.3142 CR=5 F1336.91 G1 X149.6019 Y23.2831 F1782.54 300 G3 X-5 Y18,2831 CR=5 F1336,91 G0 25 X155.293 Y9.7896 G0 25 X155.3493 Y17.7866 24.5 G1 210 F1782.54 G3 X150 Y22.411 CR=5 F1336.91 G1 X149.6019 Y22.382 F1782.54 G3 X-5 Y17.382 CR=5 F1336.91 G0 Z5 X155.293 Y9.1159 X155.3493 Y16.913 24.5 G1 2-15.5 F1782.54 Z4.5 G1 -10.5 F1782.54 G3 X150 Y21.5374 CR=5 F1336.91 G1 X149.6019 Y21.5085 F1782.54 G3 X-5 Y16.5085 CR=5 F1336.91 03 25 x155.293 Y8.4421 X155,3498 Y16,0401 Z4.5 G1 2-1 F1782.54 G3 X150 Y20.6639 CR=5 F1336.91 G1 X149,6019 Y20,6349 F1782,54 10 G3 X-5 Y15.6349 CR=5 F1336.91 G0 Z5 G9 25 X155.2934 ¥7.7688 x155.3376 ¥15.1592 Z4 5 G1 2-11.# F1782.54 G3 X150 Y19.7971 CR=5 F1336.91 G1 X149.6019 Y19.7692 F1782.54 G3 X-5 Y14.7692 CR=5 F1336.91 G0 25 X155,3396 Y14,3249

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G1 2-17 F1702.54 G3 X155 Y11.7903 CR=5 F1336.91 G1 X149.6019 Y11.7669 F1702.54 G3 X-5 Y6.7669 CR=5 F1336.91 x155.2932 ¥6.4543 24.5 G1 -17.5 F1702.54 G3 X150 Y11.1428 CR=5 F1336.91 G1 X149.6019 Y11.1106 Y1702.54 G3 X-5 Y6.1186 CR=5 F1336.91 GO 25 X155.2739 Y5.8205 Z4 5 G1 2-18 F1782.54 G3 X150 Y10.5306 CR=5 F1336.91 G1 X149.6019 Y10.5082 F1782.54 G3 X-5 Y5.5082 CR+5 F1336.91 G0 25 X155.2736 Y5.2209 24.5 01 2-18.5 F1782.54 G3 X150 Y9.9315 CR=5 F1336.91 G1 X149.6019 Y9.909 F1782.54 G3 X-5 Y4.909 CR=5 F1336.91 G0 25 x155.2736 Y4.6215 24.5 G1 2-13 F1782.54 G3 X150 Y9.3321 CR=5 F1336.91 G1 X149.6019 Y9.3097 #1782.54 X0 G3 X-5 Y4.3097 CR=5 F1336.91 G0 25 x155.2735 ¥4.0223 24 G1 2-19.5 F1782.54 G3 X150 Y8.7329 CR-5 F1336.91 G1 X149.6019 Y8.7105 F1782.54 G3 X-5 Y3.7105 CR-5 F1336.91 G0 25 X155.2735 Y3.423 24.5 G1 2-24 F1782.54 G3 X150 Y8.1337 CR-5 F1336.91 G1 X149.6019 Y8.1112 F1782.54 G3 X-5 Y3.1112 CR=5 F1336.91 G0 25 x155.2652 ¥2.0373 24.5 G12-20.5 F1702.54 G3 X150 Y7.5572 CR=5 F1336.91 G1 X149.6019 Y7.5355 F1702.54 G3 X-5 Y2.5355 CR-5 F1336.91 GD 25 X155.2683 Y2.2726 Z4 5 G1 2-21 F1782.54 G3 X150 Y6.9891 CR=5 F1336.91 G1 X149.6019 Y6.9671 F1782.54 G3 X-5 Y1.9671 CR-5 F1336.91 60 25 X155.2576 Y1.7235 24.5 G1 2-21.5 F1702.54 G3 X150 Y6.4519 CR=5 F1336.91 G3 X150 76.4519 CR-5 71336.91 G1 X149.6019 Y6.4308 F1782.54 X0 G3 X-5 Y1.4308 CR=5 71336.91 G0 25 x155.2576 ¥1.1874 24 5 G1 2-23 F1782.54

G3 X150 Y5.9157 CR+5 F1336.91 G1 X149.6019 Y5.8946 F1782.54 G3 X-5 Y0.8946 CR+5 F1336.91 00 25

X155.2576 Y0.6511 24,5 G1 7-37,5 F1782.54 G3 X150 Y5.3794 CR-5 F1336.91 24,5

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24,5 G1 1-1 F1782.54 G3 X150 Y4.8433 CR=5 F1336.91 G1 X149.6019 Y4.8222 F1782.54 10

G3 X-5 Y-0.1778 CR+5 F1336.91 GD 24,9983 X155,2576 Y-0.4214

24,5 G1 1-23,5 F1782.54 G3 X150 Y4.307 CR*5 F1336.91 G1 X149,6019 Y4.2859 F1782.54

G3 X-5 Y-0.7141 CR=5 F1336.91 GD 24.9738 X155.2425 Y-0.9589

24,5 G1 7-74 F1782.54 G3 X150 Y3.7862 (G3 X150 Y3.7862 CR+5 F1336.91 G1 X149.6019 Y3.7664 F1782.54 G3 X-5 Y-1.2336 CR+5 F1336.91

GD 24.9227 X155.249 Y-1.4504 24,5 G1 1-24,5 F1782.54 G3 X150 Y3.2876 CR=5 F1336.91 G1 X149.6019 Y3.2672 F1782.54

G3 X-5 Y-1.7328 CR+5 F1336.91 GO 24,8474 X155,2447 Y-1.9468

24,5 G1 7-11 F1782.54 G3 X150 Y2.7958 CR+5 F1336.91 G1 X149.6019 Y2.7758 F1782.54

G3 X-5 Y-2.2242 CR+5 F1336.91 GO 24.7478 X155.2445 Y-2.4293

24.5 G1 2-25.5 F1782.54 G3 X150 Y2.3136 CR+5 F1336.91 G1 X149.6019 Y2.2936 F1782.54

G3 X-5 Y-2.7064 CR+5 F1336.91 GD 24,6248 X155.2443 Y-2.9116

F1782.54 G1 2-24 F1782.54 G3 X150 Y1.8315 CR-5 F1336.91 G1 X149.6019 Y1.8115 F1782.54 20 G3 X-5 Y-3.1885 CR+5 F1336.91

G0 24.5 X155.2441 Y-3.3938 G1 2214.5 F1782.54 G3 X150 Y1.3493 CN=5 F1336.91 G1 X149.6019 Y1.3293 F1782.54 G3 X-5 Y-3,6707 CR-5 F1336.91

60 24.5 60 24.5 X155,2446 Y=3.8755 G1 --- 7 F1782.54 G3 X150 Y0.8673 CR=5 F1336.91 G1 X149.6019 Y0.8473 F1782.54 G3 X-5 Y-4,1527 CR+5 F1336,91 G0 24,5 X155,2468 Y-4,3549 G1 2-77.5 F1782,54 G3 X150 Y0.3855 CR+5 F1336,91 G1 X149,6019 Y0.3653 F1782,54 X0 G3 X=6 -1 G3 X-5 Y-4.6347 CR+5 F1336.91 G0 24.5 230 <u>x-0.2301</u> <u>x-0.7809</u> <u>G64</u> TRAFOOF ROT TRANS CICLE800 () M6

Appendix: G codes of iso scallop crash page 1



Appendix: G codes of iso scallop crash page 2





Appendix: G codes of linear path + iso scallop page 1



Appendix: G codes of linear path + iso scallop page 2

	10 10 10 10 10 10												
$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	108.000 01.000 01.1-27.000 10	$\begin{array}{c} \mathbf{YE}, \mathbf{HEE} \ b = 0, \ b \in \mathbf{M}^{*}\\ \mathbf{YE}, \mathbf{HEE} \ b = 0, \ b \in \mathbf{M}^{*}\\ \mathbf{HE}, \mathbf{HEE} \ b = 0, \ \mathbf{HE} \ b \in \mathbf{M}^{*}\\ \mathbf{HE}, \mathbf{HEE} \ b \in \mathbf{M}^{*}\\ \mathbf{HE}, \mathbf{HE} \ b \in \mathbf{HE}, \mathbf{HE} \ \mathbf{HE}, \mathbf{HE}$	THE APPLIES INTO A COMMUNICATION OF A COMMUNICATION	127. [A47] [0.4], [0.17] 128. [0.16] [0.4], [0.16] 128. [0.16] [0.4], [0.16] 128. [0.16] [0.4], [0.16] 128. [0.16] [0.4], [0.16] 128. [0.16] [0.4], [0.16] 128. [0.16] [0.4], [0.16] 129. [0.16] [0.4], [0.16] 120. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16] 121. [0.16] [0.4], [0.16], [0.16] 121. [0.16] [0.4], [0.16], [0.16], [0.16] 121. [0.16] [0.4], [0.4], [0.4], [0.4], [0.4]	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	$\begin{array}{c} 177, 1929 & 1-4, 1839 \\ 187, 1429 & 1-4, 1821 \\ 187, 1429 & 1-4, 1821 \\ 191, 1919 & 1-3, 2174 \\ 191, 1919 & 1-3, 2174 \\ 191, 1919 & 1-3, 2174 \\ 191, 1919 & 1-3, 2174 \\ 191, 1919 & 1-3, 2174 \\ 191, 1919 & 1-3, 2174 \\ 191, 1919 & 1-3, 2174 \\ 191, 1918 & 1-3, 2174 \\ 191, 1918 & 1-3, 2174 \\ 191, 1918 & 1-3, 2174 \\ 191, 1918 & 1-3, 2174 \\ 191, 1918 & 1-4, 2073 \\ 193, 1918 & 1-4, 2073 \\ 193, 1918 & 1-4, 2073 \\ 193, 1918 & 1-4, 2073 \\ 193, 1918 & 1-4, 2073 \\ 193, 1918 & 1-4, 2073 \\ 193, 1918 & 1-4, 2073 \\ 193, 1910 & 1-4, 2073 \\$	$\begin{array}{c} (35, 57)^{-2} - (-31, -310) \\ (51, -300) - (-31, -310) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -37) \\ (51, -300) - (-31, -30) \\ (51, -$	$\begin{array}{c} \pi_{11} (205 1^{-1}, 1^{-1}$	$\begin{array}{c} V_{1}, M(0) = 1-010, M(0) \\ V_{1}, M(2) = 1-010, M(0) \\ V(10), V(10) = 1-01, M(0) \\ V(10), V(10), V(10), V(10) \\ V(10), V(10), V(10), V(10), V(10), V(10) \\ V(10), V(10), V(10), V(10), V(10), V(10) \\ V(10), V(10), V(10), V(10), V(10), V(10), V(10) \\ V(10), V(10), V(10), V(10), V(10), V(10), V(10), V(10), V(10) \\ V(10), $	$\begin{array}{c} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0$	$\begin{array}{c} 101006 b=05\\ 001 10011 \\ 0011 0011 \\ 0011 0011 \\ 00111 \\ 00111 0011 \\ 00111 \\ $

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or and place	14 15.0703 0-04.1743	100.000	100.0004 1-1.0075	the start of the	when No. of Arrist	upper service in-ort. And her	THE AREA IN A DOTE	THE PLAN NUMBER	WHEN PLAN D. LTR. MILLING	10.000 0.000 0.000	with some up house	The second is a second	100.0008 1-0.0045	100.7141 1-4.0007
and load and	and the least 1.415 arest	which downed with channels	The sear and down.	THL. 6252 210-5288	and here and here	who wrome in the based	The second second second	110, 110, 010, 010, 000	way with man't likely	10,0000 0.00,0001	40 Juli 4041	194.4899 114.4479	100. 714 0.0. 74	store thanks in the lower
	10.1410 1-10.4001	and the second	the second second	144.3813 1-0.3046		total second to a linear	114,1818 1-6,5614	118.1-1. 1-11.1084	where comments in the comments	17.1404 0-00.4007	the second second	100.0001 1-0.0	the set of the	the second second second
	17,2424 2-22,4217	100 U.S. 101	100,000,000,000,0	145.7138 2-1.76	110,0007 1-1,0007	100.001 010.011	127,1428 8-7,8783	100.0001 5-11.0005	the second second second	Y*.4577 0-08.2015	10.0701 0704.0740	100 00	141.4447 1-1.4475	1.11. ATTA 1.4. MOIT
1.1.2000 1-18	11,4011 1-01,000	11.1111 11.111		148.8084 2-1.0075	141.4288 1-0.4243	1011-1041 0-4-0011	118.1715 1-6.9618	100.0019 8-0.0019		124,7248 2-07,8271	10.2008 2122.0001	1124.0000 10.0000	101.0000 0-0.0010	100A285 110.A280
10.0.7548 1-14	1010 110.7147 1-17.417	14.2003 1-01.4001	100. DOLD 10. DOLD	1214.0082 2-0.0075	TEL.2013 1-2.4246	131.0424 1-3.7877	111,4085 5-5,7488	114.1010 1-6.9616	100.0111.010.0000	Y11.4080 0-07.088	17,1408 1-00.8007	41.0-01.0783	110.0000 1-0.0	1884.2855 1-2.5085
108.3718 1-12	1088 Y11.419 1-17.2431	11.1434 1-01.4307	10.0-07.4780	1018.0081 2-0.5	101.1130 0-1.70	128.0007 1-2.0007	100.4871 8-5.2275	121.1428 8-1.5721	120.0003 (-0.0003	VIA Alles 1-14, Mart	17,8077 1-06,2115	10.0701 0-04.1743	00.05	1985.7943 3-5.76
108.3080 1-11	3428 115,0000 1-14,088	1 11.4111 1-01.004	10.5705 0-04.1743	400.023	100.0004 (-1.00 ⁻⁰)	141.4283 1-1.4243	with, 11.45, mill, 20101	108.0708 1-6.0806	101.4513 (-0.1019	which They'l in-day laboury	108.7148 2-17.8277	tes, banks in-178, street	3344,9888 15.0008	case, boost 1-1, and the
102.4879 1-6.	18 115,7546 2-14,127	1000.Tort 8-07.8077	18,3863 1-25,4887	ware county one service	VER. 8882 1-0.0075	144.2023 1-2.0248	which happy much fights	with sides and, base	124.2018 1-0.0016	ting which is one little	101.4098 0-17.245	TO LARSE IN CO. MINUT	01 0-27,4783	other county of the darket
104,2807 1-4.	T18.5714 1-12.214	101.408 0-17.0401	17.1404 0-00.4007	ALC: 11-127. 077073	Vin. 8882 1-0.1	1945. 70.98 (0-0.74	with spart such spart	100.0071 0-0.0076	107.043 8-7.070	The design of the local data	115.0004 1-14.0847	The second second second	10.0701 0-04.1743	1000 00000 1 -0.0
service and	101 YOR. 6880 S. 11. 163	a propagation of the state	yr. add y an add avoid	and some some simple	445.475	tests manage in the second	and share and share	with These have been	128.0703 0-6.0008	the second of the second	web, frank parts, parts		10.0004 1.01.000F	1000.0000 1-0.0
and along him	100 Anto 1.4.104	work from month through	124. 1247 2-13.4277	11-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1-1	and dealer the second	other manage in the starting	the second second		with second in-to beaut	100.0014 010.0014	108 ATER 1.10	ADD. TORE DOLLARS	17. 1418 SR. AND	
	the second second	and the second second	with still have been	14.0863 S-03.4080	and a second second	the second second second	188.2850 8-2.0248	10041 0-0.0411	which shares in the low the	124.2014 1-4.3030		111.4291 1-17.249	and second sounds sound	1.00
		108-101 B-10-0388	and down a to the	11.0434 8-08.4057	48 2-21 APR	state products and the	185.7108 8-1.78	110.0008 1-1.0081	and there are seen	127.143 2-7.272		112.0004 1-04.0007	The second second second	8-0.2301 1-0.7808
10.4049 1-5	114 107. 1408 1-1. 1101	ADD. STOLE B. CO., NUM	110.0000 0-11.0000	17.4577 0-08.2514	12.8121 2-24.2162		185,5005 8-1,0075	141.4343 1-1.4343	125.1252 215.2021	128.2703 1-4.3408	100.4074 0-0.1075	101.7047 3-04.0077	100.1148 0-11.0014	1000
100.718 (-4.1	10.111.111.1.4.1414	1012.0012.0-0.108	120.7286 0-24.0278	HOR. NEW DLD. BOTH	11.2014 1-23.4007	score, score us .com	Y58,8008 D-0.4875	144.2034 1-1.0243	111,1421 1-3,1811	¥18.4086 p.c. 7688	120.2010 1-0.0010	128.0708 1-02.0204	111.4251 0-11.045	
107.1425 8-3.	878 101.4284 3-5.7447	1214.0008 3-0.0004	118.1717 1-12.1768	which which in our little party	17.1414 1-01.4007	40.0-07.8783	yon, and p-0.4	145.7139 2-1.74	120.0000 2-2.0007	when shares much strength	107.140 0-1.578	when shares in our balling	TEL.0004 (-14.0047	
110.0008 1-2.	110.4543 1-5.2114	1071.0408 (p-1.570)	120.0002 0-11.3638	with many point from	17.4071 2-00.0014	10.0701 8-04.0763		148.1888.1-1.0875	141.4383 1-0.4343	with first part form	108.8715 2-4.9425	which spectra in the barries	TTL. 7147 8-14.1079	
the side and	188 VIN. 788 8-8.0018	with third build being	100.4070 1-4.1214	one lines of the latest	with Trans In. ort. sports	the local party strength	which shake up once	The little line dama	148,2894 1-0.0045	the second second second	with allow out, hand	the second second second	****. \$718 m-12. Field	400
the last and	and with balls and balls	who where put have	128.2858 2-8.8616	and which is not been	TTL	orth couring sources, accounts	The second second	THE REAL LOCAL	145.7138 0-0.74		with solid and light	the second second second	with dealer arrive ballet	
and ball and	· · · · · · · · · · · · · · · · · · ·	when show much provide	107.1408 0-1.0101	the second second second	with states in the states	ort sectors produce county	the second second second	100 UK	148.0888 1-0.0975	the second second second	alle, that and lotte	and the second second	100, 0014 p0, 1014	
	and shall be a share		100 STLA Lot Bally	total and a second	111.0004 1-04.0004		10.0721 0725.1750	the second second second	The same that don't	111,4004 (,4040	which have a to have a	108.0108.018.0005	who have not serve	
the second second	the last total total	and a second second second	and allow and have	100.0013 0-0.1019	****. ***** *****	and the second second second	18.1888 1-11.8987		100	181.3894 1-0.0045	the same to a serve	121.4088.0-0.7088	100 141 1-1 UT	
	110.2002 112.0218	111.000	tion when a set of the	104.0638 1-8.9808	118.0111 8-00.0088	10.0. April 10.0.1. April	17,1408 1-00.8007	404 U-071-07180	100,0000 0.0.0	185.704 0-0.78	100.0008 212.0001	100.0070 0-0.2070	111.111 0-1.111	
100.000 1-0.0	145.7537 3-1.74	121.000.0000	100.407 0-0.0176	101.0478 0-7.8708	121.0001 1-01.0005	10.1. MINH 8-1/4. MINH	17,4079 1-10,2111	11.1101 0-04.1143		YES, 8886 1-1, 5875	141.4288 1-1.4343	128.7042 0-4.3237	124.1724 2-1.9423	
	180.8000 1-1.0875	1943.4088 B-0.4088	100.714 1-4.0008	108.0104 8-8.3428	121.4113 1-0.1010	10.5.7046 2-04.1078	120.7548 2-17.8277	14.3864 1-33.4887	ALLS	154.8000 2-0.4875	188.2855 1-1.0243	127.0408 0-0.7677	111.4284 1-1.7888	
174,3888 15,3	08 154.8802 2-1.4474	1984.0002 0-0.0000	117.1428 1-3.1018	101.4085 1-0.7448	124.2018 1-0.0026	10.8.1717 8-12.2084	122,428 2-27,285	11.1434 1-38.8357	10. J-27. ATRA	100.0000 L-0.5	180.754 2-1.74	visa, anno 1-2, anno	101.4078 1-1.2079	
10.1-17.4783	180.800 2-0.5	1485, 71277 (p-1, 74)	100.0004 1-3.0007	1010 MOT 8-5. 2176	121.1428 1-1.0701	1010. MERC 2-11. Math	115.000x D-14.00x8	11.0071 0-00.0105	13,5701 0-04,1743	400.000	180.0008 2-1.0075	test with 1-0 silest	128.7143 1-4.3227	
10.0703 0-04.	140 00 00	tons, many p-1, perce	101.4282 2-2.4284	state there are all the	tion office land, maked	1000.00713 0-0.10718	125. Then p-14. 1978.	true. Tons and America	18.3868 p-03.4007	ALL DATE AND ADDRESS OF	154,8805 2-0.4475	tens limits in a street	127,3428 2-3,3871	
10.0001 0-01.	107 x7x, 5858 x8, 5568	title many in-th surviv	188.2852 8-2.6584	which have a second	with which party lines	still internal in an and the		which which the other hand	VT. Adds to do. Alary	and the second second	100.0000 L-0.5	terms into a state	1218.0008 1-1.0007	
17.1010 1.01	18.0 AL 81.01 8180	true was not a	week, build many, but	NAME OF A DESCRIPTION O	when were not been		118.1-1-1 1-11.1044		which and an and an and	10 P.		100.00 pro.00	and while but other	
	and another and a start		and some and dealers	CONTRACT D-D' MANA	the design of the second	stress benefits the statement	110.0001 1-11.0004		which forces on and second	11.1101 0-08.1740	string some up owned	111.0000 1-0.0010		
		100 101	the second second second	140.4080 1-1.4080	125.7151 1-1.2028	NUMBER OF STREET, STRE	120.4070 0-0.1078	101. TOT 1-14. 0011	with state particular	11,2004 0-00,4000	ALDR. 1994 11.0004	1214.0002 1-0.0070	144-1464 1-1-2014	
100, 100, 1-11	11.18.1880 1-11.4881	total control officiation	the search and a	1984-2002 1-0.00MB	121.0404 0-0.7078	1010. ADMS 10-0. 79940	TIN. 2850 1-0. MIN	108.0101.0-03.0004	and share have been	11,1434 0-00,8007	0. 1-11.4783	1218.0004 1-0.5	145.7141 0-1.74	
111,429 8-11,	11,1408 1-00.8001	401 B-071 APRO	120.0001 0.0.0	1985. 70/08 (1-1.78)	121.007 1-0.007	102.887 2-8.2578	107.1403 0-7.8701	101.0003 1-01.303	TTL. BOOK D. DW. SONT	Y1.4071 0-00.2115	10.3781 8-04.1743	408 01	148,3887 1-1,0875	
110.0000 0-00	1048 11,4511 1-20,2114	12.2101 0-04.1740	107 10	1103. MENE 1-1. 0075	141.4242 1-1.4042	105.7L40 E-4.2007	128.5715 2-6.5625	101.4973 1-8.1078	ETE OF THE PERSON	104,7040 0-17,4079	10.1008 1-11.4001	10145. MINE 10. 1008	124.0008 0-0.0012	
100.7948 0-04	1018 YOR, 7547 \$157.827	* 114.3863 0-01.4087	ABS. 2010 10.0008	1744 ABBND 2-0.4875	144.2813 1-1.0248	107.1408 1-0.7877	vis. sight p.d. hand	124.2859 1-8.869	128.2707 0-02.2308	YES, AND DOLD, DR.	17,1434 8-36,4357	ALL 10-171-187813	758.8888.0-0.5	
108.3716 8-13	2348 YEA.409 1-17.3451	171.14284 (1-00.4007)	10.1-17.4783	units status and b	945.7038 p-1.74	1000, SHOP 12-D. MINT	when shall not built	1071.0409 0-7.0700	121.003 1-11.003	work dollar process taken	Y1.4571 2-24.2125	two writes in the United	-00 05	
	1474 yos. 4860 p-14.884	a set approx proper proved	10.3781 1-04.1743		task works that success	test, adding \$1-17 Address	and have been been	tring, spring, p., of the last	122.4073 1-0.1079	with first state that the	which where another approximately approximat	the logic states and	10144, 9984 VS. 0004	
100.0010 0-0.	10 YON, PLAN 2-14, 197	state, based married approxi-	18.3863 2-23.4897	vise serve up once	The sease 10. serve	tent (MAG) pD. Allers	with tanks and bally	WHIL ADDRESS IN CA. COMMAN	124.0809 p-4.MOM	and which some lines	111.4081 0-17.045	and being to be allowed	101 0-01 0101	
124,2427 2-4.	414 YO ATTA 4-14 744	a service and an other states	17.1414 1-01.4007	and in the second	when manual in-the lat	cash, builds and the	the second second second	which provide the design of	127.141 8-7.570	and share a state balls	with doubt in-list court	and second in the later	was selling in the other	
107 Aug 1-1		and shares a second	10.0070 0.00.0014	100 B-0-0-0-00		the second second second	Tim, man are, man	the second second second	THE OTHER D. P. MANNE	101	which being the second second	Ar when have been	an inter solid state	
and serve and		and the second second second	week front mouth mouth	13.3705 1-18.1762	100 U.S.	1000 0000 1-1-00-0	TEL. 4080 8-0.4080	and the second second second	when any part of the second	101.0010 1-0.1010	when which in the lines	THE PART PLAN AND		
and all and		and the second second second	THE APR 1.111 AVE.	19.2003 1-10.4000	ADDR. AND IN ADDR.	the second second	THE. 2010 1-2.1018	Concernent and the second	when second parts, but the	121.000 1-0.0000	when dealer should be be	T11.4751 0-17.245	and second second second	
	120.2018 1-8.0014	108.0101.010.000	121.409 1-11.045	17.1404 1-10.8087	43 2-27 APR3	100.0002 1-0.5	web. 7630 p.c. 76	COLUMN 1-0. NORT	120.0010 0-0.0010	1071_040 p-1_870	100.0003 8-11.0634	WV5	11.4511 1-05.0115	
100.0008 2-5.	100.1408 0-1.0101	108.000 0-11.000	111-1011 1-14.0048	17.8077 1-10.2114	83-3703 3-04-1740	40.15	180.0005 2-1.0075	110.1083 010.4040	100.000 0-0.000	108.010 2-6.9426	102.0010 2-0.1210	WV5. TONY INCLUSION	T10.798 8-01.8277	
100.714 (1-4.2	10.1/18.1-6.1424	1003.0070 0-0.708	125,7148 2-14,0278	100.7047 1-17.4077	38.2864 1-23.4887	1004. MON 10.3008	114. Mile 2-1.4475	THE. 2854 E-2.5245	The rest is the second	121.4288 1-1.7888	121.2010 2-0.9030	wid. 1718 1-12. Jims	111.4251 0-11.263	
101-1403 (1-1)	110 x10.4268 2-5.1447	1014.0008 0-8.8808	118.5717 5-13.0385	100.409 2-17.345	17.3434 3-01.4057	10.0-17.8780	100,0000 I-0.8	145.7538 p-1.74	125.008 1-1.807	1282.0071 2-0.2176	101.040 0-1.070	101.0003 (-11.360s)	111.0004 0-04.0047	
108,8884 8-8.	100 x10.4149 1-1.2114	1074 Junior 1-7, 8701	120.0052 1-11.3675	THE MERT LARS THEFT	who wanted in other strength	with All the second schedule		tonia, benefit area, dontra	181.4083 1-0.4040	with Their Data Street	128.8715 2-4.8425	target another them. therein	1018, Todd S-104, 10079	
101.4081 0-0.	144 VID. 714 2-4 2218	tion office live, ballet	100.0070 0-0.1070	100. Then 2.18. 1978	which which the set of the second	the lease states and	VILLA AND UN ADDR	table billing to a gardine	188.0004 1-0.0045	with open p. b. terry	121.4284 1-1.7444	total come in a second	104 STOR 5-12 Thes	
THE REAL PLACE	which haven much haven	who writes that have	the lots and being	100. 100 1-10.00	and the second land	and building in this work to	ALLE, SUPPORT D. AURI	taking belowing an at the	water, building start, first	All of the second	100 A070 5-0 1070	ALC: UNDER LOTING MALERING	who don't is it hits	
cash, build much	 tim some tot some 	state shirt in a first st	107. 1428 a-1 0100	118-1-12-12-1245		in antis a la la la la	48 8-27,8780	the second second second	ward, should be a district	The same features.	with Third I was been	REATING D-1794	and store in a work	
	100,000 112,000	1.20.201 0.0.2110	and other had being	120.0000 1-11,2675	TTL. BOOM 1-144, State	THE REPORT OF LAND	10.3708 0-08.1740	NO 10	and share to be shared	141,408 1-1,4141		108.0108.0-6.0405	the development of the second	
	151.525. 272.5285	1.25. 1.2 2.4. 22.08	who where and have	100.4010 1-8.1018	111. THE 1-14. 1978	THE PERSON NEW YORK, NAME	TR. 2868 1-10.4987	store, store the store	and senter and a	144.000A 1-1.01Ab	11-11-11-11-11-11-11-11-11-11-11-11-11-	121.4286 2-5.7688	121.201 2-0.0021	
	100.2002 1-2.0208	1021-DADE D-D. NETE	which which is a contract	104,0058 1-8,9836	A18.941. 0-00.50m	101.429 2-17.285	17.1408 1-20.4007	48.0-07.8783	THE REAL PLANE	141,708 2-1,74	120.0000 2-2.0001	102.0012 1-0.2276	101.043 0-1.010	
110.000 1-0.1	180.7107 2-1.78	128.0008 2-2.0008	100.007 075.015	107.1403 2-7.3701	121.0002 1-01.0005	113.000x D-14.50x8	17.4079 1-00.2118	10.5703 0-04.1740		141,006 1-1,0075	181,4084 (-0.404)	101.7043 (-4.007	124.1714 2-4.9421	
10.15	180.3000 1-1.0070	THE ACRE D-0.4044	100.7041 0-4.3138	108.5714 2-4.9625	100.0013 0-0.1010	103.7548 2-18.1078	10.0. TLAN 1-17. 4079	1H.2868 2-23.4087	\$1.24. MINE 10. 2008	1014 10100 1-0.4475	344.3855 1-1.8143	WWW. And Mr. DD., Spirit	121.4287 2-5.7668	
112.2010 10.0	104.3040 1-0.4474	1984.2002 1-1.0248	127.2428 2-3.1018	the slat s-t. test	121.2018 1-0.0020	108.8717 0-12.2088	VII. 409 1-17, 185	17.1408 1-18.8087	\$1. 0-07. APRO	1718. WHER 1-0.5	185,754 2-1,74	1776 MARKS 11-2, March	101.4070 1-1.2179	
0. p-21.8761	150.000 2-0.5	140.7071 2-6.76	120,0006 1-1.0007	with any set of the	121.1428 1-1.1010	108.0882 2-11.0828	THE OTHER DATE ADDRESS.	17.4079 2-28.2128	12,212, 2-24, 2742	ALC: 101	145,0004 2-1,0075	THE ADDRESS THAT ADDRESS	1210,7143 1-4,3127	
10.0701 0-04.	143 40 15	tosts many 1-4 carry	141.4043 1-3.4344	with light size light	when drive and sector	and agents and horse	with them in the later	100.7548 1-17.8070	VA., 2004 1-27. ADM	still many an once	154,0005 1-0.0475	tions include the states	127.1478 1-3.7877	
10.2012 1-21.	AND ADDRESS OF ADDRESS	title internet that shares	\$84,3852 1-1.0044	and some such have	with some last land	the land the serve	110. The D-18. 1977	THE ATT D. CT. LAN.	we have a do about	and the second second	1988, 0884 Bull 5		with some hard ment	
on balls holds	197 IN D. IN STREET	tion many parts in	1445, TUBE 1-1, TA	the second second second	and the second second second	the lots to be been	118.3717 2-12.2284	the same plan and	WE ADDRESS IN THE PARTY OF	the second second second	ALC: 10 10 10 10 10 10 10 10 10 10 10 10 10	1983-1998 (1-1), FR	and alles in a close	
17.4077 1-04	the second process	and the second second	100,0004 1-1 00Th	100 million 100 mi	A	the same had been	120.0000 2-12.0408	100 Date 1-10, 1987	week Wroom in-175 address	A	state, same on some	And west 1-1, 1915		
and front south	TR. 1741 1-14.1741		The sear 1-2 down	140.0000 210.0000	122.122.212.222	108.1118 D-8.3628	122,4070 2-6,1278	total class D-18, 5810	with some party last	11.000 at 25.4987	and a second second	124.000 1-0.0075	100.0000 B-0.0000	
the second second	18,1863 1-12,4881	10.000 TO.0008	the second second	188.2853 1-2.5246	121.2424 1-3.3675	100.4080 S-0.7488	124.2859 1-8.3828	108.0101 0-10.0088	The second second second	17.008 1-06.8187	46 STAT. 4783	won.mms p-0.5	245.7241 0-1.74	
	TT. 1408 2-00.8007	NO. 8-47-8780	100.0000 2-0.0	140.7528 2-1.76	121.3111-1.307	102.801 14.215	107,3409 2-7,5705	108.0000 0-11,0408	111-June D-LH, 50807	17.4070 1-26.2111	11.1111.0-04.1143	488 123	148,3887 1-1,0875	
101,000 2124	10,400 1-10,1114	10.1710 0-08.1780		180.000s 2-1.0075	941,4242 1-2.4040	100.7545 2-4.2027	108.5715 2-6.5628	100.8570 (-8.1016)	110.000 0-18.1000	100.7088-0-01.8277	10,0000 1-03.4001	10143-10008 10.3008	254,8894 1-0.0475	

Appendix: G codes of optimized method 1 page 1



Appendix: G codes of optimized method 1 page 2

X0 Y23.2551 X-0.0096 Y23.256 X-0.0097 Y0.0101 G3 X0.0051 Y-0.0086 G1 X149.9942 Y-0.0088 G3 X150.0093 YD.0063 G1 Y4.1272 x149.9093 G0 Z5 x2.0453 Y14.1452 G2 X2.0281 Y14.056 2-12.5 G17 G2 X2.0193 Y14.051 G1 X2.0281 Y14.056 X1.991 Y14.0624 X148.0094 Y9.0634 X1.9918 X1.9926 ¥4.0644 x150.0093 x150.0094 ¥18.1354 X150.0094 118.1354 X0 118.1302 X=0.0096 Y18.131 X=0.0097 Y0.0101 G3 X0.0051 Y=0.0086 G3 X150.0093 Y0.0063 G3 X150.0093 Y0.0063 G1 ¥4.0644 x149.9093 GD 25 X148.0086 Y9.2738 2-10.7972 G2 X148.0057 Y9.3646[2-15.5] G17 G2 X148.0057 Y9.3646 G1 X148.0094 Y9.3648 X1.9912 x1.9923, ¥4.3668 x150.0093 x150.0094 y13.7403 364 x0 Y13.7356 X-0.0097 Y13.7363 v0.01b1 G3 X0.0051 Y-0.0086 G1 X149.9942 Y-0.0088 G3 X150.0093 Y0.0063 G1 ¥4.3668 X149.9093 G0 25 X147.4958 Y6.8923 2-13.7972 2-13.7972 G2 X147.4393 Y6.9635 Z-18.5 G17 G2 X147.3667 Y7.0479 G1 X147.4035 Y7.0061 x147.4393 ¥6.9635 x148.0094 ¥7.4325 ×1.991 x1.9925 ¥2.4345 >0 x150.0093 x150.0094 Y9.8756 x0 ¥9.8713 x-0.0097 ¥9.8721 Y0.0101 G3 X0.0051 Y-0.0086 G1 X149.9942 Y-0.0088 10.0 G3 X150.0093 Y0.0063 G1 ¥2.4345 X149.9093 60 25 x4.225 ¥0.7113 2-16.7972 G2 X4.3155 Y0.7032 2-21.5 G17 G2 X4.3549 Y0.7038 300 X3.1539 Y1.9744 X4.4036 Y3.2001 G1 X1.9918 X150.0093 x150.0094 Y6.4069 X0 Y6.4028 X-0.0097 Y6.4036 Y0.0101 G3 X0.0051 Y-0.0086

G1 X149.9942 Y-0.0088 G3 X150.0093 Y0.0063 G1 Y3.2001 X149.9093 GD 25 X102.9763 Y1.6227 z-19,7972 G1 X150.0093 Z-24.5 Y3.2531 X0 Y3.2492 x-0.0097 y3.2498 Y0.0101 G3 X0.0051 Y-0.0086 G1 X149.9942 Y-0.0088 G3 X150.0093 Y0.0063 G1 Y1.6227 x149.9093 00 25 x102.9763 Y0.1736 Z-22.7972 G1 X150.0093 Z-27.5 Y0.3548 X0 Y0.3511 X-0.0097 Y0.3518 Y0.0101 G3 X0.0051 Y-0.0086 G1 X149.9942 Y-0.0088 G3 X150.0093 Y0.0063 G1 10.1736 ×149,9093 G0 24.5001 230 xo to -- o sate point H5 H9 G0 G153 Z-0.11 D0 G0 G153 X-449,76 Y-378,77 D01 G0 G153 Z-0.11 D0 001 \$6366 H3 G0 X=0.2301 Y=0.7809 230 G17 X156.5212 Y48.43 24.5 G1 Z-1 F1782.54 G3 X150 Y51.1638 F1336.91 G1 X149.6019 Y51.0009 F1782.54 G3 X-5 Y46.0009 F1336.91 G0 24.5 x156.0426 Y43.7384 G1 2-1.5 F1782.54 G3 X150 Y47.4109 F1336.91 G1 X149.6019 Y47.3137 F1782.54 G3 X-5 Y42.3137 F1336.91 GD 24.5 G2 24.5 X155.7803 Y40.3961 G1 2-2 F1782.54 G3 X150 Y44.469 F1336.91 G1 X149.6019 Y44.4 F1782.54 G3 X-5 Y39.4 F1336.91 G0 24.5 x155.7795 y30.0521 G1 2-2.5 F1782.54 G3 X150 Y42.126 F1336.91 G1 X149.6019 Y42.0571 F1782.54 G3 X-5 Y37.0571 F1336.91 GO 24.5 x155.6359 Y35.7494 G1 2-3 F1782.54 G3 X150 Y40.0199 F1336.91 G1 X149.6019 Y39.965 F1782.54 G3 X-5 Y34.965 F1336.91 G0 24.5 x155.6219 Y33.937

G1 2-3.5 F1782.54 G3 X150 Y38.2259 F1336.91 G1 X149.6019 Y38.1723 F1782.54 ХŪ G3 X-5 Y33.1723 F1336.91 60 24.5 x155.5793 y32.1291 G1 2-4 F1782.54 G3 X150 Y36.4732 F1336.91 G1 X149.6019 Y36.4237 F1782.54 20 G3 X-5 Y31.4237 F1336.91 G0 24.5 X155.5172 Y30.5408 G1 2-4.5 F1782.54 G3 X150 Y34.9635 F1336.91 G1 X149,6019 Y34,9196 F1782,54 G3 X-5 Y29,9196 F1336.91 G3 x5-129,9196 F1336.91 (G) 24.5 x155.5172 y29.1034 G1 2-5 F1782.54 G3 x150 y33.5261 F1336.91 G1 x149.6019 y33.4823 F1782.54 G3 X-5 Y28,4823 F1336,91 G0 24.5 X155.5186 Y27.6697 G1 Z-5.5 F1782.54 G3 X150 Y32.0908 F1336.91 G1 X149.6019 Y32.0468 F1782.54 360 G3 X-5 Y27.0468 F1336.91 G0 24.5 X155.4612 Y26.3665 G1 2-6 F1782.54 G3 X150 Y30.8583 F1336.91 G1 X149.6019 Y30.8195 F1782.54 30 G3 X-5 Y25.8195 F1336.91 00 24.5 x155.4435 Y25.1509 G1 2-6.5 F1782.54 G3 X150 Y29.664 F1336.91 G1 X149.6019 Y29.6268 F1782.54 G3 X-5 Y24.6268 F1336.91 G0 Z4.5 X155.4435 Y23.9586 G1 2-7 F1782.54 G3 X150 Y28.4717 F1336.91 G1 X149.6019 Y28.4345 F1782.54 G3 X-5 Y23.4345 F1336.91 G0 24.5 X155.4072 Y22.7877 G1 2=7.5 F1782.54 G3 X150 Y27.3443 F1336.91 G1 X149.6019 Y27.3103 F1782.54 ×0 G3 X-5 Y22.3103 F1336.91 G0 24.5 X155.39 Y21.7322 G1 Z-8 F1782.54 G3 X150 Y26.3091 F1336.91 G1 X149.6019 Y26.2766 F1782.54 300 G3 X-5 Y21.2766 F1336.91 G0 24.5 X155.3907 Y20.7209 G1 Z-8.5 F1782.54 G3 X150 Y25.297 F1336.91 G1 X149.6019 ¥25.2644 F1782.54 300 G3 x-5 Y20.2644 F1336.91 G0 24.5 ×155.3904 ¥19.7087 G1 2-9 F1782.54 G3 X150 Y24.2851 F1336.91 G1 X149.6019 Y24.2526 F1782.54 303

G3 X-5 Y19.2526 F1336.91 G0 24.5 X155,3741 Y18.7187 G1 2-9.5 F1782.54 G3 X150 Y23.3142 F1336.91 G1 X149.6019 Y23.2831 F1782.54 300 G3 X-5 Y18.2831 F1336.91 G0 24.5 X155.3493 Y17.7866 G1 Z-10 F1702.54 G3 X150 Y22.411 F1336.91 G1 X149.6019 Y22.382 F1782.54 100 G3 X-5 Y17.382 F1336.91 G0 24.5 X155.3493 Y16.913 G1 2-10.5 F1782.54 G3 X150 Y21.5374 F1336.91 G1 X149.6019 Y21.5085 F1782.54 300 G3 X-5 Y16.5085 F1336.91 G0 24.5 x155.3498 Y16.0401 G1 Z-11 F1782.54 G3 X150 Y20.6639 F1336.91 G1 X149.6019 Y20.6349 F1782.54 105 G3 X-5 Y15.6349 F1336.91 G0 24.5 X155,3376 Y15.1592 G1 2-11.5 F1782.54 G3 X150 Y19.7971 F1336.91 G1 X149.6019 Y19.7692 F1782.54 G3 X-5 Y14,7692 F1336.91 G0 24.5 X155.3396 Y14.3249 G1 Z-12 F1782.54 G3 X150 Y18.9606 F1336.91 G1 X149.6019 Y18.9325 F1782.54 315 G3 X-5 Y13.9325 F1336.91 60 24.5 X155,318 Y13.5352 G1 2-12.5 F1782.54 G3 X150 Y18.1955 F1336.91 G1 X149.6019 Y18.1692 F1782.54 G3 X-5 Y13.1692 F1336.91 G3 24.5 X155.318 Y12.7717 G1 2-13 F1782.54 G3 X150 Y17.432 F1336.91 G1 X149.6019 Y17.4058 F1782.54 312 G3 X-5 Y12.4058 F1336.91 G0 24,5 X155,318 Y12.0085 G1 2-13.5 F1782.54 G3 X150 Y16.6688 F1336.91 G1 X149.6019 Y16.6425 F1782.54 G3 X-5 Y11.6425 F1336.91 G0 24.5 x155.3079 Y11.2353 G1 Z-14 F1782.54 G3 X150 Y15.9071 F1336.91 G1 X149.6019 Y15.8817 F1782.54 105 G3 X-5 Y10.8817 F1336.91 G0 Z4.5 X155.3168 Y10.5084 G1 2-14.5 F1782.54 G3 X150 Y15.1701 F1336.91 G1 X149.6019 Y15.144 F1782.54 303 G3 X-5 Y10.144 F1336.91 GD 24.5 X155,293 Y9,7896 G1 2+15 F1782.54

Appendix: G codes of optimized method 1 page 3

G3 X150 Y14.4703 F1336.91 G1 X149.6019 Y14.4542 F1782.54 :x0 G3 X-5 Y9.4542 F1336.91 G0 24.5 x155.293 ¥9.1159 G1 Z-15.5 F1782.54 G3 X150 Y13.8046 F1336.91 G3 X150 Y13.8046 F1336.91 G1 X149.6019 Y13.7806 F1782.54 305 X0 G3 X-5 Y8.7806 F1336.91 G0 Z4.5 X155.293 Y8.4421 G1 2-16 F1782.54 G3 X150 Y13.1308 F1336.91 G1 2-10 F1702.34 G3 X150 Y13.1308 F1336.91 G1 X149.6019 Y13.1067 F1782.54 300 G3 X-5 Y8.1067 F1336.91 G0 24.5
 G1 2-16.5 F1782.54
 X0

 G3 X150 T12.4571 F1336.91
 G3 X-5 Y0.8946 F1336.91

 G3 X150 T12.4571 F1336.91
 G0 24.5

 G1 X149.6019 Y12.4329 F1782.54
 X155.2576 Y0.6511

 X0
 G1 Z-22.5 F1782.54

 G3 X-5 Y7.4329 F1336.91
 G3 X150 Y5.3794 F1336.91

 G0 Z4.5
 G1 X149.6019 Y5.3583 F1782.54

 X155.2849 Y7.0925
 X0
 x155.2934 ¥7.7688
 G0 10.0
 X155.2849 Y7.0925

 G1 2-17 F1782.54
 G3 X-5 F0.000

 G3 X150 Y11.7903 F1336.91
 G0 24.5

 G1 X149.6019 Y11.7669 F1782.54
 X155.2576 Y0.1149

 Y0
 G1 2-23 F1782.54

 G3 X150 Y14.94433 F1336.91
 G3 X150 Y4.8433 F1336.91

 Y0
 Y149.6019 Y4.8222 F178
 x155.2932 Y6.4543 G1 Z-17.5 F1702.54 G3 X150 Y11.1428 F1336.91 G1 X149.6019 ¥11.1186 #1782.54 300 G3 X-5 Y6.1186 F1336.91 60 24.5 x155.2739 ¥5.8205 G1 Z-18 F1782.54 G3 X150 Y10.5306 F1336.91 G1 X149.6019 Y10.5082 F1782.54 G1 Z-24 F1782.54 G1 Z-24 F1782.54 G3 X-5 Y5.5082 F1336.91 G0 24.5 x155.2736 ¥5.2209 G1 2-18.5 F1782.54 G3 X150 Y9.9315 F1336.91 G1 X149.6019 19.909 F1782.54 310 G3 X-5 Y4.909 F1336.91 G0 24.5 X155.2736 Y4.6215 G1 2-19 F1782.54 G3 X150 T9.3321 F1336.91 G1 X149.6019 Y9.3097 F1782.54 310 G3 X-5 Y4.3097 F1336.91 GD 24.5 x155.2735 ¥4.0223 G1 2-19.5 F1782.54 G3 X150 Y8.7329 F1336.91 G1 X149.6019 Y8.7105 F1782.54 300 G3 X-5 Y3.7105 F1336.91 G0 24.5 x155.2735 x3.423 G1 Z-20 F1782.54 G3 X150 Y8.1337 F1336.91 G1 X149.6019 Y8.1112 F1782.54 20 G3 X-5 Y3.1112 F1336.91 G0 24.5
 60
 x155.2652
 y2.8373

 61
 z-20.5
 F1782.54
 G3
 x45

 63
 x150
 y7.5572
 F1336.91
 G9
 z4.5

 61
 x149.6019
 y7.5355
 F1782.54
 x155.2443
 y-3.3938

 61
 x149.6019
 y7.5355
 F1782.54
 x155.2443
 y-3.3938

 61
 x149.6019
 y7.5355
 F1782.54
 y150
 y1.3493
 F1
 X155.2652 Y2.8373

GD 24,5 G0 24,5 X155,2683 Y2,2726 G1 2-21 F1782,54 G3 X150 Y6,9891 F1336,91 G1 X149,6019 Y6,9671 F1782.54 310 G3 X-5 Y1.9671 F1336.91 G0 24.5 X155.2576 Y1.7235 G1 2-21.5 F1782.54 G3 X150 Y6.4519 F1336.91 G1 X149.6019 Y6.4308 F1782.54 X0 G3 X-5 Y1,4308 F1336,91 G0 24.5 X155.2576 Y1.1874 G1 2-22 F1782.54 G3 X150 Y5.9157 F1336.91 G1 X149.6019 Y5.8946 F1782.54 G1 X149,6019 Y4,8222 F1782.54 302 G3 X-5 Y-0,1778 F1336.91 G0 24.5 x155,2576 Y-0,4214 G1 2-23.5 F1782.54 G3 x150 Y4.307 F1336.91 G1 X149.6019 Y4.2859 F1782.54 310 G3 X-5 Y-0.7141 F1336.91 G3 X150 Y3,7862 F1336.91 G1 X149,6019 Y3,7664 F1782.54 300 G3 X-5 Y-1.2336 F1336.91 G0 24.5 X155.249 Y-1.4504 G1 2-24.5 F1782.54 G3 X150 Y3.2876 F1336.91 G1 X149.6019 Y3.2672 F1782.54 300 G3 X-5 Y-1,7328 F1336.91 G0 24,5 X155,2447 Y-1,9468 G1 2-25 F1782.54 G3 X150 Y2.7958 F1336.91 G1 X149.6019 Y2.7758 F1782.54 300 G3 X-5 Y-2.2242 F1336.91 G0 24.5 X155.2445 Y-2.4293 G1 2-25.5 F1782.54 G3 X150 Y2.3136 F1336.91 G1 X149.6019 Y2.2936 F1782.54 315 G3 X-5 Y-2,7064 F1336.91 G0 24,5 X155,2443 Y-2,9116 G1 2-26 F1782,54 G3 X150 Y1,8315 F1336.91 G1 X149.6019 Y1.8115 F1782.54 G3 X-5 Y-3.1885 F1336.91 G3 X150 Y1.3493 F1336.91

G1 X149,6019 Y1,3293 F1782,54 305 G3 X-5 Y-3.6707 F1336.91 G0 24.5 X155.2446 Y-3.8755 G1 2-27 F1782.54 G3 X150 Y0.8673 F1336.91 G1 X149.6019 Y0.8473 F1782.54 300 G3 X-5 Y-4.1527 F1336.91 G0 24.5 X155.2468 Y-4.3549 G1 2-27.5 F1782.54 G3 X150 Y0.3855 F1336.91 G1 X349.6019 Y0.3653 #1782.54 305 G3 X-5 Y-4.6347 F1336.91 G0 24.5 2.30 x-0.2301 x-0.7809 G64 70 ыú H30



Appendix: Simulation data of five methods