A novel way of avoiding stylus drop down from model while scanning

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Abstract. Based on analysing the basic feature of scanning process, this paper proposes a new architecture to regulate autonomous scanning speed with the nominal vector $D_N$. In addition, explains and demonstrates how to introduce the nominal vector $D_N$ into the tracer scanning for successive and self-adjusting scanning speed and autonomy contact level between stylus of trace and model according to the curved surface. The technical activities and experimental results shown that the parameter of nominal vector $D_N$ play a proper role in the case of retaining tracer contact on curved surface especially when stylus scanning from horizontal plane to the vertical plane.

1. Introduction
Stylus is employed in the shape of unknown curved surface and hence the stylus may be experiencing the surface for the first time. The stylus may not have been in a similar situation before. In addition, in actual applications, the stylus normally suffers from drop-down and perturbations inflicted upon its control system, making it extremely important to propose a new architecture which would be able to cope with such problems. The nominal deflection of stylus is known as a proper solution due to its remarkable capabilities. A novel approach based on nominal deflection of stylus has been presented in this study for the scanning of such stylus in their concerted motion. Simulation results demonstrate the efficacy of the proposed method.

Typically, the tracer provides center-of-tool information that directly translates into tool-path data. However, surface data of the model can be acquired using the appropriate stylus and stylus-deflection values. In addition to the $XYZ$ data for each point, the system calculates the appropriate surface normal. Each point contains $XYZ$ coordinates and $IJK$ vector data at that point. Calculating the position of center of stylus, the numerical control (hereinafter referred to as $NC$) can generate normal vector and record space position values of the models. Both vector and position values can be used to generate $NC$ codes for machine tool to directly machining parts.

As we known, at one hand, scanning speeds are absolutely limited for scanning with high speed at some smooth geometric models; at the other hand, sometimes scanning speeds cannot be autonomous regulated when scanning from the horizontal plane to the vertical plane for avoiding stylus drop-down from the model. Therefore, the functions of the tracer must be studied both autonomously and dynamically to adjustment the scanning speed for optimize the scanning process and avoiding stylus drop-down from the model.
2. Literature review

Measurement methods of curved surface can be divided into contact and non-contact methods. In actual contact measurement, analog stylus and trigger probe are often used. Non-contact measurement mainly adopts laser triangulation method. In production practice, contact analog measurement is widely used in engineering due to its advantages of high measurement accuracy, mature technology and low cost.

Laser is typical one of the non-contact measurement equipment. Laser scanning technology also has some disadvantages, for example, in order to prevent stray reflection, the surface of the workpiece needs to be sprayed a layer of white powder before measurement. If the inclination of the measured surface exceeds 45°C, the radiation blind area (known as the shadow effect) will appear. Thus, in terms of blind area, the laser scanning is incapable of accurately measuring the workpiece surface. Although the shadow effect can be reduced or eliminated through multi-axis control, the cost will be increased but the accuracy is still low. The scanning process effected by a various of factors and no more reported about this method to be widely applied in real production.

There are two distinct types of contact measurement: tracer scanning and touch-probe digitizing. Tracer scanning uses a tracer stylus corresponding in size and shape to the anticipated tool that will be used to mill the workpiece. The electronics sensor of stylus senses the deflection conducted the stylus continuously scans the surface of the model and collecting data of the surface. Typically, the data is center-of-stylus information that is accepted by a CNC milling machine as an NC program or cutter path.

Touch-probe digitizing uses a Renishaw probe typical of CMMs and provides actual surface data. The surface points are used to automatically construct a math model of the surface, commonly referred to as wireframe. Wireframe data usually is used by designers and tooling manufacturers in CAD/CAM environment. Probe belongs to digital measure equipment, which can only know his probe at reset and not at reset, but cannot generate normal vector on probe. Copy or digitizing measure equipment belong to analog measure equipment. During scanning, the stylus of copy or digitizing constant touch the model and record the model position and the position of the center-of-stylus. The normal vector can be calculated by the data of the center-of-stylus. The efficiency of copy or digitizing is higher than probe, but the accuracy is lower than probe.

As far as contact measurement equipment of analog is concerned, there are a various of contact measurement equipment of analog and are widely applied in the copy milling and digitizing machine tools. The typical analog measurement equipment from abroad can be listed as follow. The Gettys with the swing movable structure is from the United States. Both the Accura-trace 6 of Makino and the Tv-330b of Fanuc are from Japan, the P5/K5/K2 of Fidia from Italy, three types of them are all with the parallel movable structure. Both the setups of copy milling control system and tracer from Fidia dominant the fields for a long time. In China, in the early 1980s, a team led by Mr. Lu jiechi from Dalian university of technology first carried out the research and development of the copy instrument and offered a prototype DIGIT-02C of NC copy system and corresponding tracer to be mounted on milling machine tool of type X4450 of their own, and milling machine tool of type XKF718 from Changzheng machine tool company. Institute of Optics & Electronics of Chengdu from Chinese Academy of Sciences in the 1990s also studied and provided a prototype FCG-1 of tracer to be mounted on milling machine tool of type XKF718 from Changzheng machine tool company. But from now, no literatures and reports show that the above mentioned two tracers to be widely mounted on copy milling machine tools[1,2].

3. The principle of scanning

3.1. Normal vector of stylus

Let us consider the situation when stylus with radius $R$ scanning on a semicircle surface of an object. Figure 1 shows the initial point $P_1$ of the stylus just contact the model. In the process of tracking and scanning, the stylus contacts and presses against the surface of the model. Under the action of normal
reaction force, a space pressure deviation is generated at the center C of the stylus. Assuming that there is no friction between the stylus and the model surface, the line $CO$ is just the normal direction $D_N$ of the model at the contact point $P_1$ between the stylus and the model surface. The $V_N$ is the normal speed at the contact point of $P_1$, to be applied to keep the stylus in contact with the model. The $V_T$ is the tangential speed to be employed to keep relative motion of the stylus and scanning the model. The $V$ is the resultant speed of the $V_N$ and the $V_T$, as well as the scanning speed of the stylus, and also the feed speed of copy milling machining. The speed vector $V$ of the stylus motion is derived from the displacement detected by the tracing stylus.

The DR represents the amount of actual deflection along the direction of the normal vector, which is confined within a specified range.

The DN expresses the amount of expectation deflection (also known as nominal vector), which is determined by the characteristics and criterion of the tracer. If the value of DN is large, the pressure of the stylus against the model will be greater, and the possibility of damage the model will also be increase. If the value of DN is small and the scanning speed of the stylus is fast, the stylus cannot keep always contact with the model and the possibility of drop-down from the model is increase greatly. Both the DN of nominal deflection and the DR of actual deflection can construct the following equation:

$$e_n = D_R - D_N.$$  

$e_n$: an important reference value to regulate the moving of machine tool around the value of $D_N$ along the tangential direction with the speed of $V_N$ to shift stylus up or down.

When $e_n > 0$ (overpressure of the stylus), the stylus shifts a tiny displacement up along the direction of normal vector of the model (leaving the model); the stylus tends to decrease the value of $e_n$, which conduct the stylus decrease the level of pressing the model and the stylus should be given properly additional force with the normal direction of leaving to the object.

When $e_n < 0$ (underpressure of the stylus), the stylus moves along the direction of tangent of the model and shifts a tiny displacement down along the negative direction of normal vector (approach to the model) at the same time. The stylus tends to increase the value of $e_n$, which conduct the stylus increase the level of contact the model and the stylus should be given properly additional force with the normal direction of pointing to object.

### 3.2. The motion of the stylus without friction

Tracking and scanning on the model surface, the stylus detects and feedbacks information about the position and situation of the model surface to the NC. NC by the information drive the tracer movement and make the stylus always maintain the specified pressure and deviation and along the surface of the model for scanning. Generally, the speed of the stylus is proportional to the amount of the deviation perceived at that sampling point of $P_t$. Supposed the tangential speed is $V_T$, its components in the directions of $X$ and $Y$ is $V_{TX}$ and $V_{TY}$. The $e_n$ can also be decomposed along the $X$ and $Y$ into $e_{nx}$ and $e_{ny}$. Refer to figure 1, the follow formals can be deduced respectively.

$$V_{TX} = \pm V_T * D_{Ry}/D_R$$  

$$V_{TY} = \mp V_T * D_{Rx}/D_R$$

When the model is on the right side of the stylus, the upper symbol is taken; when the model is on the left side of the stylus, the lower symbol is taken. In the coordinate system, both $V_{TX}$ and $V_{TY}$ with signed symbol, and both $D_{Rx}$ and $D_{Ry}$ also with signed symbol, that means, the above formulas can be applied to any quadrants.

### 3.3. The motion of the stylus with friction

In fact, at one hand, due to the friction between the stylus and the model surface is forever exist, the normal line between the line of $CP_i$ and the vector line of $OP_i$ at the contact point of $P_i$ is no longer coincident. On the other hand, due to the existence of $e_n$ and the value of $e_n$ constantly altering and
accumulating, in order to improve the accuracy of scanning and reduce the possibility of stylus drop-down from the model, \( e_n \) needs to be automatically regulated in timely. The curve of \( P_1P_2 \) is anticipated route, refer to figure 1. If the NC fails to automatic drive the stylus moving on the model within frequent of \( f_t \), the stylus tendency shifts a tiny target displacement of the \( P_1P_3 \) not the arc length of the \( P_1P_2 \). If the scanning speed is still calculated by the equations (2) and (3), the value of the \( e_n \) will inevitable decrease to less than zero, so that the stylus probability drop-down from the model. Therefore, an additional force must be employed in the direction of \( CP_2 \) to make the resultant speed \( V \) of the stylus parallel to the tangent line of the model surface[3-9].

The direction and size of \( V_N \) should be guaranteed that the value of \( D_R \) is rough equal to \( D_N(e_n = D_R - D_N) \). On the other hand, the value of the parameter \( V_N \) is regulated by \( e_n \) in order to making the value of \( D_R \) close to the value of \( D_N \). The correction formal by the way of proportion adjustment to regulate the \( V_N \) is shown as below:

\[
V_N = K \times D_R \tag{4}
\]

\( K \) is the proportional coefficient, the components of \( V_N \) in the coordinate axis of \( X \) and \( Y \) are respectively \( V_{NX} \) and \( V_{NY} \), the following equations can be get respectively by equations (4).

\[
V_{NX} = V_N \times D_{Rx}/D_R \tag{5}
\]

\[
V_{NY} = V_N \times D_{Ry}/D_R \tag{6}
\]

By the equations (2) and (5), and (3) and (6), the following equations can be obtained respectively.

\[
V_X = V_{TX} + V_{NX} = \pm V_T \times D_{Rx}/D_R + V_N \times D_{Rx}/D_R \tag{7}
\]

\[
V_Y = V_{TY} + V_{NY} = \mp V_T \times D_{Ry}/D_R + V_N \times D_{Ry}/D_R \tag{8}
\]

4. Technical activity

4.1. A process before scanning to make deflection to zero and get gains of x, y and z axis

When the stylus does not touch model, the value of the deflection should be roughly zero. Being the varied of weight and shape of the tracer, even if the tracer dose not contact the model, the value of the deflection will not always be zero. In order to get accurate scanning data, based on the principle of establishing a nominal deflection of the stylus with respect to its cantered zero-position, some compensation should be added to the tracer. One of the compensation activity is achieved through execute special command by software way. If the deflection is too great to be compensated by software way, hardware way should be employed by adjusting the potentiometer for \( x, y \) and \( z \) respectively in the electric circuit.
4.2. The normal technical activity

In many cases, there are many different sizes of stylus used. Copy milling requires a certain relationship between the diameter of the tool and the size of the stylus of the tracer. In the actual processing of a batch of parts, because there is wear, a small amount of compensation need to make for tool, otherwise the parts milled will not be qualified.

When a new tool replaced, there exists the shape and the dimensions between the original stylus does not exactly conform to the new tool, for this reason, an inconvenient method is to replace the stylus. This is inconvenient, however, that means a lot of extra styluses are needed.

In addition, there always exists tool wear when milling a large part, and also exists the phenomenon that the accuracy of the initial processing parts is not the same accuracy of the subsequent processing parts with the same tool. This means tool compensation need to be made.

Accordingly, the stylus and tool should be given some restriction in the actual milling in order to get accurate scanning data:

① The shape of the stylus and tool must be similar.
② The dimension and size of the stylus and tool have to be the same. The tolerance is allowed that the dimension of the tool is 10% smaller than the stylus as defined by the following:

\[ R_{\text{DEF}} = R_{\text{stylus}} - R_{\text{tool}}. \] (9)

The above formula shows: If the radius of stylus is shorter than the tool, the tool will cut too much raw material, which could result in interference with the walls of the part, especially when milling near internal edges, and the problem of over deflection will appear.

In generally, copy milling is taken as roughing and not for the final finishing. In order to get accurate milling finishing, digitizing method (also refer to as differ copying) to be used. Normal vector and x, y and z position of the model are recorded by digitizing on the disc of the computer. While milling, the NC takes the normal vector as proportion to be added as 3D dimension tool compensation, which consist of the milling program to be executed by NC. The compensation can be drawn by the following expression:

\[ R_{\text{com}} = R_{\text{stylus}} - R_{\text{tool}} \] (10)

Comparing formula (9) with formula (10), we can know that the digitizing way can get more accurate milling by adding compensation. In formula (9): \( R_{\text{DEF}} \) represents the allowance for copy milling. In formula (10), \( R_{\text{com}} \) represents the value of compensation to be added in milling. Though formula (9) is similar to formula (10), but the idea is total different[10-14].

4.3. Experimental activity

In the following example, a steel noodle product is shown at figure 2. The radius of the smallest tool = 0.5mm and \( R_{\text{DEF}} = 0.75 \). Under a given tolerance, the small products need to be digitized before milling. The shape of steel noodle is a more comprehensive product. It is clear that this small product can’t be used with copy milling method.

Before scanning, multiple-trace boundaries limits have to be established for automatic scanning of the part. When the stylus recognizes a trace boundary, the mill machine tool will automatically stop, index over, and continue digitizing in the opposite direction for lace mode, or retract to a plateau and continue scanning in the same direction for box mode. When the system completes scanning a defined surface patch, the tracer will retract to a safe position and automatically continue digitizing another area of the part. Trace boundaries can be viewed or modified. Another scanning feature is anticipation: a command that adjusts scanning speed when the stylus senses a sudden change in the surface.

The step of production is as following:

①. Execution the zero process of stylus before scanning.
②. Digitizing a similar prototype of steel noodle by scanning with tracer to recording NC codes.
③. Machining steel noodle with the above codes.
5. Conclusions
As nominal vector $D_N$ to be introduced in tracer scanning on curved surface, the tracer can autonomous regulate the scanning speed of stylus of tracer and hold contact level between stylus and the object. The formula deducing and experimental results shown that the parameter of nominal vector $D_N$ play a proper role in the case of retaining tracer contact on curved surface.

① Using DN can better realize to self-adjust scanning speed when stylus encounter special curved surface, and improve the accuracy and efficiency of scanning.

② The stratagem of machining with special curved surface is: first collect workpiece data by digitizing, then carry out milling, so as to obtain a higher accuracy.

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