A way to autonomous regulate the scanning speed

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Abstract. Analysing the basic feature of scanning process, this paper puts forward a new architecture to regulate autonomous scanning speed. In addition, this paper explains and demonstrates how the tracer scanning for successive and self-adjusting scanning speed and autonomy contact level between stylus of tracer and model according to the curved surface. The technical activities shown that the method of copy following error with a proper role and has potential application prospects.

1. Literature review
Tracer is one of the key parts of NC copy milling machine tool and its control system. As far as tracer is concerned, the typical and analog tracer from abroad can be listed as follow. The Gettys with the structure of swing move to scanning the model is from the United States, the Accura-trace 6 of Makino and the Tv-330b of Fanuc from Japan, the P5/K5/K2 of Fidia from Italy, are all with the structure of parallel move to scanning the model. 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.

Non-contact laser scanning technology also has serious disadvantages, 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℃, 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 main scanning equipment in measuring microvariable position. One is called touch probe (for example, Renishaw probe from British, Haidenhain 3D touch trigger probe from German). Probe belongs to digital measure equipment, which can only know his stylus at reset and not at reset, but cannot generate normal vector on it. Another is called copying or digitizing measurement equipment, which belongs to analog measurement equipment. During scanning, the stylus of copying or digitizing constant touch the model and record the model position and the position of the center of stylus. In this way, the normal vector can be calculated by the data of the center of stylus. In general condition, the efficiency of analog copying or digitizing is higher than digital probe, but the accuracy is lower than digital probe. Refer to figure 1.

2. The principle and process of scanning

2.1 Normal vector of stylus

Conjunction between tracer and stylus is flexible (not rigid), the stylus will slight deform by motor driven force, which is confined strictly by rate power of motor. The amount of spring pressure exerted on the stylus inside the head of tracer by the mechanical spring mounting when the stylus contacts the model is determined by establishing the pressure separately along each of the three mutually orthogonal X, Y and Z axes. Firstly, let us consider the situation when stylus with radius $R$ scanning on a semicircle surface of an object. While NC catches every value of the normal vector with the fixed cycle time of $T_i$, NC reads and takes the value of the normal vector of stylus as desired normal vector. The tracer senses the amount of translation of $DX$, $DY$ and $DZ$ on three orthogonal axes while scanning. The resultant direction is the normal vector of the contact point, and its module $DN$ is defined as the deflection of the tracer. Both the $DN$ of nominal deflection and the actual deflection $DR$ can construct the equation as following:

$$en = DR - DN. \quad (1)$$

$DR$: the value of actual deflection, which is confined within a specified range.

$DN$: the value of desired deflection, which is determined by the characteristics of the tracer. If the value of $DN$ is large, the pressure 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 dropping down from the model is increase great.

$en$: an important reference value to regulate the moving of machine tool around the $DN$ with a high frequent of $f_T$ to drive stylus scanning.

When $en > 0$ (overpressure of the stylus), the stylus shifts a tiny displacement up and down along the direction of normal vector while moving along the tangent vector (leaving the model);

When $en < 0$ (underpressure of the stylus), the stylus moves along the tangent vector and shifts a tiny displacement up and down along the negative direction of normal vector (approach to the model) at the same time.

For tracer, the magnitude of deflection affects the stability and accuracy of scanning. Before scanning, it is necessary to set an expected deflection $DN$. During scanning, the closer the actual stylus $DR$ is to the expected deflection $DN$, the higher the stability and accuracy of the scanning will be; on the contrary, the stability and precision of the scanning will be lower.
The essence of the scanning is: the stylus movement a tiny distance along the direction of tangent and at the same time shifts a tiny displacement up and down along the direction of normal vector. At the beginning of the next period $T_{i+1}$, the stylus still holds the same deflection of $D_N$.

2.2 The principle and process of scanning

Considering the general case of a semicircular surface of the models, supposed the first touch point is $A$ and $D_i$ is the normal vector of the stylus and the curve of $AC$ is anticipated route, refer figure 2. 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 $AB$ not the arc length of the $AC$. On one hand, the stylus driven by NC moving along the direction of tangent to the point of $B$ to make the stylus hold the value of the deflection around the $D_N$ at the next time $T_{i+1}$. On the other hand, the stylus shifts a tiny displacement up and down along the direction of normal vector to maintain itself constant contact the prototype at the duration time of $T_i$. Actually, the normal vector of the stylus is little or more deviation.

Figure 2. The $AB$ and $AE$ consist of direction stylus of $AP$

That means, the direction of both $AB$ and $AE$ consist of the compound direction of $AP$ which is the direction of the stylus, not the curve of $AC$. At this time, even stylus still attaches the model, the quantitative of the deflection actually has change and fail to maintain the principle of “keep always holding the same level of touching the model at all place”. The faster the speed, the greater the probability of the stylus drop down from the model. If the circle radius of the models is smaller and the curve degree is bigger, at this condition, the stylus cannot touch the model at every place and probably drop down from the model.

In this case of $D_R \geq D_{RMAX}$, the maxima limit criterion is exceeded by the stylus, the stylus will push overpressure on the object and even damage the object.

At the condition of $D_R \leq D_{RMIN}$, the minima limit criterion is exceeded by the stylus, there is a tendency that the stylus drop down from the model, that means reinforce must be properly added by NC in time in order to make the stylus press against the model along perpendicular and tangential directions respectively.

At the condition of $D_{RMIN} < D_R < D_{RMAX}$, the stylus will shift up or down at the normal direction and scanning along the tangent of the model surface under the range of the limit criterion.

2.3 Scanning direction and normal vector of stylus

Both copy machining and copy digitization rely on the deviation generated in the process of “tracking” the model by the contact of the stylus, and the movement track generated by the CNC copying machine tool is close to the shape of the model. Scanning on the curved surface, the stylus had better follow the shape of the surface. That is to say, in order to prevent the stylus from dropping down from the surface of the model. It is necessary to construct an appropriate scanning way for the stylus to closely follow the constant changing of the shape of the surface.
Figure 3. The relationship between scanning direction and normal vector of stylus

Assuming that the stylus with a radius of $R$ to contact the model at the point $P$, the stylus move along the direction of tangent point to scanning the model. With the deflection value of $e_n$, the stylus scan along the direction of the normal vector through the point $O$. Take the end point of the line $en$ as the initial point to construct a line that parallel the tangent vector and intersects with the circle at point $Q$. The direction of the line $OQ$ is just the movement direction of the stylus, refer to Figure 3.

In order to get the resultant velocity ($F_Y, F_X$) under the orthogonal coordinate system $YOX$ of physically-driving, we can construct the following formulas through the resultant velocity ($F_n, F_t$) in the orthogonal coordinate system $nO\tau$ of logically-driving. According to Figure 3, we can get the following formats:

$$\begin{align*}
F_Y &= F_n \cdot \cos \theta - F_t \cdot \sin \theta \\
F_X &= F_n \cdot \sin \theta + F_t \cdot \cos \theta
\end{align*}$$

The above formulas can be changed into the below formats with copy following errors:

$$\begin{align*}
F_Y &= F_n \cdot (e_{nx}/e_n) - F_t \cdot (e_{ny}/e_n) = (F_n \cdot e_{nx} - F_t \cdot e_{ny})/e_n \\
F_X &= F_n \cdot (e_{ny}/e_n) + F_t \cdot (e_{nx}/e_n) = (F_n \cdot e_{ny} + F_t \cdot e_{nx})/e_n \\
e_n \cdot |F| &= e_n \cdot |F_Y| + e_n \cdot |F_X| = |e_n \cdot F_Y| + |e_n \cdot F_X| \\
|F_Y| &= |(F_n \cdot e_{nx} - F_t \cdot e_{ny})| + |(F_n \cdot e_{ny} + F_t \cdot e_{nx})|
\end{align*}$$

The above formats clear show that the stylus scanning a tiny distance along the direction of tangent and at the same time shifting up and down with a tiny deformations at the direction of vector in order to make the stylus still holding the same deflection of $D_N$ at the beginning of the next period of $T_{i+1}$.

If the NC has the ability to regulate the level of the contact between stylus and the object at any point and can keep the actual deflection $D_R$ equal to the nominal deviation $D_N$, then the copy machine tool can move in accordance with the shape of the model. Due to the existence of $en$ and the value of $en$ accumulation, in order to improve the accuracy of scanning and reduce the possibility of stylus drop down from the model, $en$ needs to be automatically corrected in a timely manner.

3. Technical activity

3.1 A process before scanning to make deflection to 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 does not touch 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 centered zero-position, some compensation should be added to the tracer. One of the compensation activity is achieved through execute special command by software program. Being a several of installed processes, NC driving the stylus in five direction to touch the standard cube (for example the dimension is 40×40×60mm) mounted on the work table shown in figure 4. After the procedure is over, The NC can record automatically the clamping extent of the tracer in x, y and z axis respectively and automatically calculate the gains of x, y and z axis. The gains will be added before scanning.
3.2 The normal technical activity

If the deflection is too great to be compensated through touch cube processes, the potentiometer should be adjusted for $x$, $y$ and $z$ respectively in the electric circuit before touch cube processes.

Owing to the friction is forever exist, the normal vector $D_N$ to be generated on the stylus is little or more not accurate. The less smooth the surface, the lower the accuracy. In many cases, there are many different size of stylus used. 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 of the stylus (sometimes refer to theoretical tool) and tool have to be the same and the shape have to be similar. The tolerance is allowed that the dimension of the tool is 10% smaller than the stylus as defined by the following:

$$ R_{DEF} = \text{radius of the stylus} - \text{radius of the tool} $$

(7)

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, 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. Both the normal vector $D_N$ and $x$, $y$ and $z$ position of the model will be 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:

$$ R_{com} = \text{radius of the stylus} - \text{radius of the tool} $$

(8)

Comparing formula (7) with formula (8), we can know that the digitizing way can get more accurate milling by add compensation. In formula (7): $R_{DEF}$ represents the allowance for copy milling. In formula (8), it represents the value of compensation to be added in milling. Though formula (7) is similar to formula (8), but the idea is total different.

3.3 Experimental activity

In the following experience, a steel noodle product is shown at figure 5. 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. The radius of the smallest tool = 0.5mm and $R_{DEF} = 0.75$. Under a given tolerance, the small products need to be digitized before milling. The step of production is as following:

1) Firstly, digitizing a similar prototype of steel noodle by scanning with tracer to recording NC codes for machine tool.

2) Machining steel noodle with the above codes.
4. Conclusions
This paper proposes a new architecture to regulate autonomous scanning speed. The results that the proposed method and formulas can better autonomous regulate the scanning speed when stylus encounter special curved surface and improve the accuracy and efficiency of scanning. The stratagem of machining workpiece with special curved surface is: first collect workpiece data by scanning method, and then carry out digital machining, so as to obtain a higher machining accuracy.

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