Adaptive Sampling based 3D Profile Measuring Method for Free-Form Surface

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Abstract. In order to solve the problem of adaptability and scanning efficiency of the current surface profile detection device, a high precision and high efficiency detection approach is proposed for surface contour of free-form surface parts based on self-adaptability. The contact mechanical probe and the non-contact laser probe are synthetically integrated according to the sampling approach of adaptive front-end path detection. First, the front-end path is measured by the non-contact laser probe, and the detection path is planned by the internal algorithm of the measuring instrument. Then a reasonable measurement sampling is completed according to the planned path by the contact mechanical probe. The detection approach can effectively improve the measurement efficiency of the free-form surface contours and can simultaneously detect the surface contours of unknown free-form surfaces with different curvatures and even different rate of curvature. The detection approach proposed in this paper also has important reference value for free-form surface contour detection.

1. Introduction
The surface profile detection device can be used to detect the surface profile of a manufactured mechanical part. As an indispensable instrument in reverse engineering, profile inspection device plays an important role in the mechanical field [1-3]. The current surface profile measurement approach is mainly contact and non-contact two categories [4, 5]. Wang C L et al. designed a measuring system of the cone pipe thread profile based on the principle of laser triangulation. The automatic measurement of thread profile was realized by non-contact scanning approach [6]. Sun Y L et al. analysed the causes of the non-linear error in the process of large-scale contact profile measurement, improved the structure of the measuring bar, and established the nonlinear error model [7]. Zhu D H et al. used the technical reverse engineering to fuse contact measurement technology and non-contact measurement technology [8]. Therefore, the combination of
contact measurement and non-contact measurement technology is an important approach to realize efficient and high-precision detection of self-adaptive profile and free-form surface parts [9-11]. In this paper, we propose a high efficiency and high precision detection approach for surface profile of free-form surface parts, which based on self-adaptability. Aiming at the issues of self-adaptability, precision, and efficiency on the free-form surface profile detection, we design a surface profile measurement technique based on contact measurement and non-contact measurement. Through the planning of the scanning path, the detection device can adapt to detect the free-form curved surface, and improve the efficiency and precision.

2. Design of self-adaptive detection device for surface profile of free-form surface parts

The mechanical structure of the surface profile detection device for the free-form surface part designed in this paper can be divided into three parts: supporting parts, driving parts and measuring parts. The support part comprises a base, a workbench and a bridge bracket. The driving part comprises a guide rail, a connecting rod which is CMM (Coordinate Measuring Machine) main shaft, and a rotating table. And the measuring part is composed of a touch sensor and a non-touch sensor.

The detecting device can accomplish the motion of multiple free-form degrees and perform the profile detection for the components of the free-form curved surface. The worktable is equipped with a sliding guide rail, and the whole bridge bracket can be moved along the guide rail. The guide rail is also mounted on the beam, and the CMM main shaft can be moved along the rail. The measuring part is mainly composed of touch-trigger probe and laser probe. The structure of the measuring part and the rotating table are shown in figure 1.

![Diagram](image)

(a) Measuring part  (b) Rotating table
1-Telescopic rod, 2-Rotating table, 3-Laser probe,
4-Touch-trigger probe head, 5-Touch-trigger probe

**Figure 1.** The structure of the measuring part.

3. Scanning process and principle of adaptive profile scanning

As shown in figure 2, the sequential scanning process of the free-form profile surface of the entire part is designed. In the scanning process, the laser sensor (LP) which is in front of the touch-triggered sensor (TP) collects and sorts the data, and pre-judges the sampling frequency of TP. If we only scan the path L1, we can get the outline of L1. The concrete steps are as follows:

*Step 1* After manually determining the initial scan point and the positive direction of the X and Y, the starting point of the probe path L1 is determined by LP. When LP captures the mutated signal, the coordinate value is recorded, i.e. LP enters the boundary point of the surface. At this point, the servo motor which controls the movement of Y axis is locked. At the same time, the servo motor of the rotary table is locked, and the sensor cannot rotate around the Z axis. Then, the measuring system moves in the
positive direction of the X axis. When TP moves to the boundary point, then re-measurement starts and the result is integrated into the system and recorded as the starting point. If the error between measured value and the coordinate value recorded by LP is greater, the machine alarms, all movement stops.

**Step 2** In the process of scanning in the X positive direction, LP has been in the front-end detection, and L_1 is measured at a pre-set unit length ΔX to obtain the coordinate information of the surface profile point. When the curvature value K_i of TP scan section is greater than the pre-set curvature value K_0, the scanning frequency increases. When the curvature value K_i of TP scan section is smaller than the pre-set curvature value K_0, the scanning frequency reduces. Due to the higher precision of TP and combined with the measurement results of TP, the key points of the rough curve are modified to synthesize the final curve.

**Step 3** When LP captures the mutated signal, the coordinate value is recorded. Then, the measuring device continues to move distance d+Δd in the positive direction of X (d is the horizontal distance between the centre axis of the TP rod and the laser beam emitted by LP, and Δd is the pre-set value of the measuring instrument). When TP moved to the boundary point, re-measurement is performed and the results are integrated into the system to synthesize the curve. If the error between measured value and the coordinate value recorded by LP is greater, the machine alarms, all movement stops.

**Step 4** The turntable servo motor motor unlocks and rotated 90° around the Z axis, so that LP is on the left, TP is on the right. Then, the turntable servo motor is locked.

**Step 5** The servo motor which controls the movement of the Y axis unlocks and the measuring device move ΔY in the positive direction of the Y axis. Then, the servo motor is locked. At this point, according to whether the focus is on the measuring table, LP judges whether the surface has been entered or not. If so, LP continues to move in the positive direction of the X until the mutation point of the signal is encountered. Then step (6) begins to be executed. If not, the step (6) is executed directly.

**Step 6** Repeating steps (1) to (5) to scan the path L_2 until the entire free-form curved surface is scanned.

![Figure 2. Flow chart of sequential scanning.](image-url)

(The X direction is the scanning direction; the Y direction is the feeding direction)
4. Information flow and signal processing during scanning

In the adaptive sampling process, the measurement system is responsible for collecting the relevant point information and control system to determine the validity of the point. And it plans the adaptive sampling path. Then the path information is uploaded to the computer to achieve man-machine interaction and control the execution path of the drive system. The protection system is responsible for real-time monitoring, the system will alarm if illegal operation or to reach the movement limit. The flow of information during the scanning is shown in figure 3.

![Figure 3. Information flow in scanning process.](image)

The two measuring heads of TP and LP work separately and sample individually at a certain time interval. The signal processing includes the elimination of noise signals, data smoothing, and data compression. TP sampling point instead of LP sampling points and other procedures. The data processing flow of LP is shown in figure 4.

![Figure 4. Data processing flow of LP.](image)

Step 1 Data acquisition. In the measurement system, LP collects data and uploads the data to the control system for processing. The sampling interval of data acquisition is $\Delta x$, which is the setting value by users. The smaller the $\Delta x$ is, the higher the sampling precision of LP is.

Step 2 Noise removals. Noise removal is the pre-treatments of control system for the data. The coordinate abnormal points will appear during the scanning process. And in order to improve the final fitting of the rough curve to achieve a certain quality requirements, we need to remove these abnormal points in advance to improve the signal to noise ratio.

Step 3 The traditional signal noise processing is the spectrum analysis. But the data collected by LP is a two-dimensional discrete point, with a certain degree of particularity. We can take a more simple approach of data pre-processing.

Step 4 We use the two-dimensional discrete lattice captured by LP as a separate aggregation. In order to reduce the amount of data processing, only X, Z coordinates points are extracted, that is the aggregation of $G_i(X_i, Z_i)$. When the angle between the line $G_{i-1}G_i$ and the line $G_iG_{i+1}$ is smaller than the pre-set angle, $G_i$ are judged as unusable points, and the points are deleted immediately.

Step 5 Data smoothing processing. The linear smoothing algorithm is used to smooth the available points after noise removal, which is convenient for the final curve creation. The smoothing algorithms used in this paper are as follows:

$$G_i = (G_{i-1} + G_i + G_{i+1})/3$$
$$G_0 = (5G_0 + 2G_1 - G_2)/6 \quad (i = 1, 2, L, m-1)$$
$$G_m = (-G_{m-2} + 2G_{m-1} + 5G_m)/6$$
Step 6 Data compression. When the amount of scanning is very large, the computer ability of processing the data will slow down, and we need to compress the digitized data after removing the unusable points.

Step 7 Curve rough fitting. The curve fitting approach is based on the spline curve fitting approach.

Step 8 Creating adaptive sampling path. When the computer obtains the data captured by LP to complete the rough curve fitting, the results will be uploaded to the control system. According to the specific criterion approach, the control system generates decentralized adaptive points, which are the sampling points of TP.

5. Conclusions

In this paper, the adaptive sampling approach based on front-end prediction is proposed to adjust the sampling frequency for the parts system with different surface. Moreover, we propose a two scanning process using the section subdivision method in the feeding direction of the scanning. Furthermore, we initiate the design of the rotary table in the international, which effectively integrates the laser probe and touch-trigger probe, and add the C axis degrees of free-form.

The results from the design of the adaptive sampling approach based on front-end prediction indicate the following: (1) compared with the current traditional uniform point cloud scanning, the speed of scanning and the precision of surface fitting are greatly improved; (2) the scanning precision is improved in the Y axis direction; (3) the operation flexibility of the new measuring instrument greatly increase and the real value of the measured data is obtained by coordinate compensation mechanism; (4) In the measurement process, the probes can be replaced directly to fit the profile detection of different surfaces.

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