Automatic profile tracking of deformed surface in mirror milling based on ultrasonic measurement

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Abstract. Mirror milling is an effective and environmentally friendly means to manufacture large thin-walled parts. The remaining wall thickness of such parts is supposed to be strictly controlled to balance strength and weight reduction. However, the clamping deformation will lead to overcut or undercut if the nominal tool path is directly utilized. To address this issue, it would be helpful to scan and reconstruct the deformed unknown workpiece surface and then adjust the nominal tool path. In this paper, an automatic profile tracking approach is proposed to adaptively sample the deformed surface and reconstruct the surface model, based on a multi-ultrasonic-probe measurement system. The adaptive sampling algorithm calculates the position and surface normal of the next sampling point simultaneously based on a curvature sphere, which utilizes the surface information of the local area covered by the multi-ultrasonic-probe system. Moreover, a boundary processing algorithm is proposed to ensure the sampling process is carried out inside the boundary. The feasibility of the proposed automatic measurement method was validated through experiment.

1. Introduction

Large thin-walled parts are widely used in aerospace applications, such as rocket storage tanks, engine nozzles and aircraft skins [1]. In order to balance the strength and weight reduction for these parts, the remaining wall thickness should be strictly controlled. For example, the thinnest wall thickness of a large holistic structure with dimension $4200mm \times 2600mm \times 120mm$ is supposed to be $1.5 \pm 0.15mm$ [2]. The mirror milling system (MMS) is the most efficient method for manufacturing such parts [3]. However, the weak rigidity of thin-walled parts usually induces severe clamping deformation so that the nominal tool path generated from the designed CAD model will lead to overcut or undercut in mirror milling of the deformed surface [1]. To solve this problem, it would be helpful to scan and reconstruct the deformed workpiece surface, and then adjust the nominal tool path.

There are lots of works focusing on surface measurement. The existing measurement methods can be divided into two categories: contact measurement and non-contact measurement. Contact measurement mainly conducts through touch-trigger probes or scanning probes [4, 5] but has low measurement efficiency. Additionally, it is not recommended to be used for measuring large workpieces due to the high-cost. Laser scanning as a method of non-contact measurement can achieve fast measurement of large surfaces [6]. The possible drawbacks of laser measurement involve the generated dense points may be a burden for the following CAD/CAM software and the laser measurement performs poorly for reflective materials, e.g., the metal thin-walled structure. But above
all, any one of the aforementioned surface measurement methods depends on an independent measurement system, which will cause extra cost for the mirror milling process. Zhen et al. [7] pointed out that the ultrasonic measurement system also has the ability of surface sampling, which was utilized to correct the imprecise robotic trajectory for the ultrasonic C-scan. Naturally, it is the best solution if the surface could be sampled by utilizing the robotic ultrasonic measurement system, which is originally designed for monitoring the workpiece thickness during mirror milling.

In fact, the robotic ultrasonic measurement system can be regarded as a kind of multi-axis noncontact surface measurement system. For the multi-axis noncontact surface measurement of unknown free-form surfaces, the position and orientation of the multi-axis tool should be determined for sampling points. Due to the absence of the CAD model, some researchers [8-10] developed the multi-sensor system for online surface measurement first, which then navigates the following measurement process. Although this is an effective measurement strategy, the multi-sensor measurement system is very complicated and expensive. Liu et al. [6] proposed an adaptive surface measurement method for unknown surfaces based on the point laser scanner. The dynamic reference was established from the previously measured points for predicting the next sampling control point, through the hybrid extrapolation mode, which combines the constant curvature extrapolation and the tangent extrapolation. However, the method only concerned the tool position for point sampling. Therefore, it is improper to be applied in the multi-axis ultrasonic measurement, as the position and orientation of the multi-axis tool are both required.

In this paper, an automatic profile tracking approach is proposed based on the local surface information, which is covered by the ultrasonic measurement system. The rest of this paper is organized as follows: Section 2 presents the ultrasonic measurement system developed for mirror milling. Section 3 presents an overview of the proposed automatic measurement algorithm, and the details are described in Section 4. Section 5 conducts the verification experiment. Conclusions are given in Section 6.

2. The ultrasonic measurement for mirror milling

The mirror milling of a thin-walled part is as illustrated in figure 1 (a). A milling head and a supporting head respectively locate at the mirror positions with regard to the part. In other words, their center lines are collinear and assumed to be perpendicular to the part surface. Specifically, the milling head is responsible for cutting the part. The supporting head carries a squirting ultrasonic measurement system for monitoring the part thickness during the milling and, at the same time, provides stiffness support for the part with weak rigidity through the high-pressure jetting water. While carrying out the mirror milling, the two heads are supposed to move synchronously by following a predefined tool path, which should be generated from the CAD model of the practical workpiece. However, the clamping usually induces severe deformation for a large and week-rigidity workpiece, which means the original CAD model is not appropriate to generate the tool path. The purpose of this study is to carry out an adaptive profile tracking of the deformed surface and provide data support for generating the practical tool path. There are two issues needing to be addressed: sampling path planning and boundary processing.

![Figure 1](image_url)

**Figure 1.** Architecture of the MMS and the developed measuring head: (a) a sketch map of the MMS, (b) architecture of the developed measuring head.
The structure of the multi-probe ultrasonic measurement system is shown in figure 1 (b). Five ultrasonic probes are distributed in a cross pattern, where one probe locates in the center and the other four probes surround the center probe. The ultrasonic signals of the five probes are synchronously acquired by ultrasonic transmitting and receiving system EUT3160M8.

As shown in figure 2, the zig-zag scanning pattern will be adopted in the measurement process based on the isoplanar method [6]. The scanning plane is defined as the plane passing through the measurement point $P_0$ and parallel to the $y_wO_wz_w$-plane, which is defined by the workpiece coordinate system $\{O_w\}$. The feeding plane is the plane passing through $P_0$ and parallel to the $x_wO_wy_w$-plane. A tool coordinate system $\{O_t\}$ is established with the multi-probe ultrasonic measurement system, where the $z_t$ axis coincides with the center probe axis, the $x_t$ axis and $y_t$ axis are respectively parallel to the two crossing axes formed by the four surrounded probes. The origin $O_t$ is away from the end face of the center probe with a distance of $D_0$ to avoid the collision between the measuring head and the workpiece surface.

The original output of ultrasonic measurement is the distance from the probe to the workpiece, i.e., $d_0$, $d_1$, $d_2$, $d_3$, $d_4$ respectively corresponding to the five probes. Based on these measured distances, the resulting five sampling points on workpiece are denoted in tool coordinate system as follows

$$\begin{bmatrix}
0 & L & 0 & -L & 0 \\
0 & 0 & 0 & 0 & 0 \\
D_0 - d_0 & D_0 - d_1 & D_0 - d_2 & D_0 - d_3 & D_0 - d_4
\end{bmatrix}$$

where $L$ is the distance between every surrounded probe and the center probe, as shown in figure 1 (b). Each column of $P^T$ denoted as $P_i$ is a sampling point, which is expressed in workpiece coordinate system as follows

$$\begin{bmatrix}
w_i \\ 1
\end{bmatrix} = w_{iT} \cdot \begin{bmatrix}
P_i \\ 1
\end{bmatrix}$$

where $w_{iT}$ is the homogeneous transformation matrix of $\{O_t\}$ relative to $\{O_w\}$.

### 3. Overview of proposed automatic measurement algorithm

An overview of the proposed automatic measurement algorithm is shown in figure 3, mainly including two modules: initialization module and tracking module.

Figure 3. Flow chart of the automatic measurement algorithm.
3.1. Initialization module
In the beginning, the boundary is discretized into a series of points, which are counterclockwise ordered as control points, as illustrated in figure 6 (a) that will be introduced later. Before automatically tracking the workpiece profile, the five-probe measuring head should be manually positioned at the initial measurement point. Firstly, the $x_t$, $y_t$, and $z_t$ axes are respectively adjusted to be parallel to the $z_w$, $x_w$, and $y_w$ axes, as shown in figure 4 (a), so that the measured points corresponding to the five probes are nearly located at the scanning plane and the feeding plane during the measurement process. This procedure is beneficial for simplifying the subsequent sampling point prediction in both the scanning plane and the feeding plane, which is crucial for our proposed automatic profile tracking. Later, the measuring head is manually adjusted to make $O_t$ approximately coincide with the initial measurement point and the $z_t$ axis of $\{O_t\}$ perpendicular to the workpiece surface, as shown in figure 4 (b). The purpose of coinciding the origin of the tool coordinate system $\{O_t\}$ with the measurement point on the workpiece surface is to simplify the expression of measurement points in the tool coordinate system. In other words, the $d_0$ in Eq.(1) is equal to $D_0$.

![Figure 4](image.png)

**Figure 4.** Schematic diagram of some steps of the automatic measurement algorithm:
(a) and (b) manual positioning of the measuring head at the initial measurement point, (c) surface normal measurement and the orientation adjustment of measuring head.

3.2. Tracking module
In tracking module, the workpiece profile is automatically tracked and sampled with the robotic ultrasonic measurement system, mainly including the following steps:

1. Surface normal computation and the orientation adjustment of measuring head. As shown in figure 4 (c), the surface normal at the current position is first computed according to the measurement output of five ultrasonic probes and then the axis of the measuring head is adjusted to coincide with the surface normal. This step is to ensure the accuracy of ultrasonic measurement.

2. Adaptive sampling point prediction. After adjusting the measuring head orientation, the next sampling point will be predicted based on current measurement data in the scanning plane or the feeding plane. The sampling point prediction has utilized the extracted local surface information.

3. Boundary processing. While approaching the measurement boundary, the “zig-zag” measurement process should stop and start measurement in the next scanning plane. The identification of the measurement boundary and the response to the predicted next sampling point locating outside of the boundary will be detailly described in the following.

4. Implementation details

4.1. Adaptive sampling point prediction
As shown in figure 5, given current measurement points from the five probes, i.e., $wP_{1,\ldots,4}$, two quadratic Bézier curves [11] are interpolated and respectively pass through $wP_1, wP_0, wP_3$ and $wP_2, wP_0, wP_4$. The unit surface normal vector of $wP_0$, denoted as $n$, is the cross product of the tangent of the two curves. In order to predict the next sampling point in the scanning plane and the feeding plane, a curvature sphere should be introduced first. The curvature radius $\rho$ is estimated according to the interpolated Bézier curves and the sphere center $wP_c$ is estimated from $\rho$ and $n$. They are calculated as follows.
where $\hat{P}(t)$ is the first derivative of the Bézier curve. $k$ is a coefficient related to the curvature direction, which is expressed as

$$k = \begin{cases} -1, & \hat{P}(t_1) \cdot n < 0 \\ 1, & \hat{P}(t_1) \cdot n \geq 0 \end{cases}$$

The position of the next sampling point is predicted based on the assumption of curvature continuity. In addition, the sampling point should also meet with the constraints of a given maximum chordal deviation $\delta_m$ and the maximum tangential feeding step $L_t$, in order to control the sampling density. According to the maximum chordal deviation or the maximum tangential feeding step, the next sampling point is predicted as follows

$$wP_0' = wP_c + k \cdot \rho \cdot n$$

where $wP_c$ and $\rho$ are respectively the projections of $wP_c$ and $\rho$ to the scanning plane or the feeding plane. $n$ is the unit vector obtained by projecting $n$ to the plane of interest. $Rot(m, \varphi)$ is a $3 \times 3$ rotation matrix and has different expressions in the scanning plane and in the feeding plane

$$Rot_s = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos(m \cdot \varphi) & -\sin(m \cdot \varphi) \\ 0 & \sin(m \cdot \varphi) & \cos(m \cdot \varphi) \end{bmatrix},
Rot_f = \begin{bmatrix} \cos(m \cdot \varphi) & \sin(m \cdot \varphi) & 0 \\ -\sin(m \cdot \varphi) & \cos(m \cdot \varphi) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where $\varphi = 2 \cdot \cos^{-1}((R - \delta_m)/R)$ is the rotation angle calculated based on $\delta_m$. $m$ is a coefficient related to the moving direction and the topography of the measured area, expressed as

$$m = \begin{cases} 1, & h \cdot k < 0 \\ -1, & h \cdot k \geq 0 \end{cases}$$

where $h = +1$ when the moving direction deviates to the positive direction of the $x_w$ axis or the $z_w$ axis. Otherwise, $h = -1$.

Comparing the distances between current measurement point and the next sampling points obtained from equation (6) and equation (7), the final next sampling point is the one closer to current measurement point. Furthermore, the surface normal at the next sampling point can be predicted as

$$n' = \frac{wP_0' - wP_c}{\|wP_0' - wP_c\|}$$

Figure 5. Schematic diagram of the adaptive sampling algorithm.

4.2. Boundary processing
The recognition of the measurement boundary and the subsequent response of the following measurement operation is inevitable for the adaptive measurement. Lu et al. [5] utilized the step signal from an extra laser sensor to identify the workpiece boundary. Unfortunately, such specialized sensor hardware is expensive to be adopted. Liu et al. [6] presented a boundary processing method to determine the start point and end point of each scanning path by assuming the measured area as a ruled quadrangular region area. However, the assumption is not suitable for complex boundary shapes. In order to solve the above problems, a boundary processing algorithm for complex shapes was proposed in this paper.

As illustrated in figure 6 (a), the boundary is discretized into a series of points $Q_i$ ($i = 0,1,2,...,n$) in counterclockwise order. To facilitate the following description, we denote $Q_i^-$ as the projection of $Q_i$ to the plane perpendicular to both the scanning plane and the feeding plane. The profile tracking process is adaptively controlled based on the relative position between the next sampling point and the boundary segments. If there are no intersections between the scanning plane and all the boundary segments, the sampling is accomplished. When the projection of the predicting sampling point is on the right of the nearest boundary segment $Q_i^-Q_{i+1}^-$, which passes through the current scanning plane, the predicting sampling point is outside the boundary. It is necessary to predict a new sampling point and let it locate inside the surface boundary, while the sampling point reprediction is the same as the method described in Section 4.1. The workflow of boundary processing is referred to figure 6 (b).

**Figure 6.** Boundary processing algorithm: (a) schematic diagram of the boundary processing algorithm, (b) flow chart of the boundary processing algorithm.

### 5. Experimental verification

To validate our proposed method, experiments have been implemented on a workpiece with a free-form surface, as shown in figure 7 (a). The dimensions of the free-form surface are $300mm \times 300mm \times 70mm$. The multi-probe ultrasonic measurement system is mounted on a MOTOMAN-MH80 industrial robot, as illustrated in figure 8 (a). The accuracy of the ultrasonic measurement is up to 0.005mm. During the measurement process, as described in Section 3.2, there are two times of ultrasonic measurements at each sampling position, one for orientation adjustment and the other for measurement points collection and the next sampling point prediction. The maximum chordal deviation is set as 0.015mm and the maximum tangential feeding step is set as less than or equal to 5.0mm, which is an empirical data to balance the profile tracking efficiency and the accuracy of predicting sampling points. Specifically, two verification experiments are conducted in this paper: one experiment is to verify that the automatic method proposed in this paper can be used for the profile tracking of unknown surfaces with complex boundaries, and the other experiment is to validate the superiority of the method in the measuring head orientation prediction.
Figure 7. Verification experimental results: (a) the obtained measurement points of a local workpiece surface, (b) the incident angle during the measurement process, (c) the measurement accuracy of the proposed profile tracking method.

To illustrate the feasibility of tracking profile with complex boundary, the local surface region with a boundary as shown in figure 6 (a) was selected, rather than the entire surface of the workpiece, to be measured. The obtained measurement points are shown in figure 7 (a), which validates that our proposed profile tracking approach is suitable for the automatic measurement of surfaces with complex boundaries. The measurement error is analyzed by computing the deviation between the practical measurement point and the design model, as shown in figure 7(c). The maximum measurement error is around \( \delta \), which is mainly possible to be induced by the positioning error of the industrial robot. Although it is comparable to the machining accuracy of the large thin-walled parts, this measurement accuracy is sufficient for the adjustment of the nominal tool path, because the main purpose of the tool path adjustment is to partially compensate for the machining error caused by clamping deformation. As there is usually an online thickness compensation to ensure the accuracy of the remaining wall thickness [12], the nominal tool path adjustment will reduce the amount in the following online compensation and be helpful to improve the machining accuracy.

Furthermore, the prediction of the measuring head orientation plays a vital role in the successful implementation of automatic ultrasonic measurement. Ideally, the orientation of the measuring head should coincide with the surface normal, i.e., the incident angle of the ultrasonic beam should be equal to \( \theta \). Therefore, in our proposed method, the measuring head orientation at the next sampling point is predicted as the surface normal \( \mathbf{n} \). To further validate the superiority of our proposed method in the orientation prediction, comparisons have been conducted between the proposed method and another two possible orientation determination methods: one is that the orientation remains constant, i.e., parallel to the \( y_w \) axis, the other is that the current surface normal \( \mathbf{n} \) is used as the orientation at the next sampling point. The schematic diagram of the abovementioned three orientation determination methods is illustrated in figure 8 (b). The comparison test is carried out along the test scanning line (the red line) shown in figure 8 (a). figure 8 (c) shows the comparison result. It can be seen that the method of constant orientation was aborted because the measuring head orientation has significantly deviated from the surface normal. When the surface normal of current measurement point is used as the predicted surface normal at the next sampling point, the deviation to the practical surface normal is larger than that of our proposed method. However, there are still some fluctuations of the normal prediction by our proposed method, mainly due to two reasons. To facilitate the following explanation, we denote \( \alpha \) (shown in figure 5) as the angle between \( \mathbf{n} \) and the scanning plane, and \( \theta \) (shown in figure 4 (c)) as the incident angle of our proposed method. The first reason is that the change of \( \alpha \) is...
not considered when the measuring head is moved to the next sampling position. As shown in figure 5, the predicted surface normal $\mathbf{n}$ at the next sampling point is determined by the vector from $wP_e$ to $wP_0$, which can be regarded as rotating $\mathbf{n}$ around the axis perpendicular to the scanning plane. It means that the method didn’t predict the change of $\alpha$ between adjacent sampling points. The second reason is that the curvature estimation accuracy is limited by using only three points for the estimation. figure 9 shows the projection of incident angle $\theta$ to the scanning plane, which is mainly related to curvature estimation accuracy. Fortunately, as shown in figure 8 (c), after the orientation adjustment described in Section 3.2 (1), the incident angle can be controlled in $0.2^\circ$, which is sufficient to ensure the accuracy of ultrasonic measurement.

6. Conclusions
In this paper, an automatic profile tracking is proposed for sampling the deformed surface in mirror milling. The main contributions of this paper are as follows:

1) A multi-probe ultrasonic measurement system was designed to extract the local surface information, which is used for analyzing surface curvature and surface normal.

2) To determine the next sampling point, an adaptive sampling point prediction method was proposed based on the curvature sphere. The constraints of a given maximum chordal deviation and a given maximum tangential feeding step were introduced to control the sampling density. Different from existing adaptive sampling methods, this method predicts the next sampling point based on surface information instead of curve information, and it can simultaneously predict both the position and the surface normal of the next sampling point.

3) Taking the automation of profile tracking into consideration, a boundary processing algorithm was proposed, including recognition of the measurement boundary and subsequent response to the boundary. Thus, it enables our profile tracking method to be applied to surface with complex boundary.
(4) The experiment of sampling a local surface with a complex boundary has been carried out to verify the feasibility of our proposed method.

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