Optimizing Slow Tool Servo Machining of Microlens Arrays Through Data-Driven Tracking Error Prediction and Trajectory Replanning

Zhiyue Wang[1], Zhenhua Jiang[2], Hao Wu[1], Yangqin Yu[1], and Xinquan Zhang[1,#]
1 School of Mechanical Engineering, Shanghai Jiao Tong University, 800 Dongchuan Road, Shanghai 200240, China
2 Institute of Artificial Intelligence, Donghua University, Shanghai, China
Corresponding Author / Email: zhangxinquan@sjtu.edu.cn, TEL: +86-158-0210-7897

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The application of microlens arrays (MLAs) based on slow tool servo (STS) machining is increasingly prevalent in the field of complex surface optics. However, current STS technique poses a significant challenge in balancing machining efficiency with surface profile accuracy, primarily due to the rapid variations in the spatial frequency of the microlens. To handle this dilemma, this study proposes a data driven tracking error prediction method and trajectory replanning approach. The specific method involves establishing a functional model that relates axis tracking error to the acceleration of the motion trajectory in STS machining. To further improve the predictive accuracy of this model, multiple calibration experiments were conducted, and a set of predictive model parameters was obtained based on least squares method. Furthermore, the original machining trajectory's acceleration was replanned, and combined with the predictive model results, to minimize the tracking error, thus optimizing the surface quality of microlenses in STS machining. To validate the effectiveness of the proposed method, diamond turning experiments were conducted on a three axis ultra precision machine tool. The experimental results showed that this method not only significantly improved the surface accuracy of the MLAs but also slightly increased the machining speed, resolving the predicament of STS machining MLAs.

NOMENCLATURE

e = Z-axis tracking error
a = acceleration of motion trajectory
$f(a)$ = lathe dynamic response for various accelerations
k = empirical coefficient of acceleration
T_{idle} = duration of the idle zone
cycleCount = number of cycles per working zone
f_i = working zone frequency for segment i
fResolution = resolution which f_i increase by

1. Introduction

The microlens array (MLA) is a vital optical microstructure used in various fields like imaging, optical communication, micr osensors, and head-up display, due to its light field modulation capability and additional features [1,2]. However, the growing de mands for higher precision in the manufacturing of MLAs have put significant pressure on existing machining techniques. Amon g the existing feasible techniques, including ultraprecision diamo nd turning, lithography, and laser processing, the servo-based tur ning process is the mainstream choice because of its deterministi c material removal and high flexibility. However, the dynamic p erformance of the large-mass slide in ultraprecision lathes create s a trade-off between surface quality and machining efficiency [3].

The servo-based turning process is categorized into slow to ol servo (STS) and fast tool servo (FTS). STS employs a linear motor with a large stroke and low bandwidth, while FTS uses a piezoelectric or voice coil motor with a small stroke and high bandwidth [4]. Recent research focuses on enhancing the Z-axis tracking in STS or W-axis in FTS to improve machining accura cy for MLAs [5-7]. Existing research encompasses hardware per formance improvements, control strategy advancements, dynamic modeling, the collaborative control of STS and FTS, and traject ory reconstruction. It is hypothesized that as research progresses, the boundaries between STS and FTS will gradually blur and eventually converge. A promising research direction involves opti mizing both the accurate identification of dynamic responses and the reconstruction of motion trajectories simultaneously. This approach aims to maximize the machine's hardware potential and resolve the trade-off between machining quality and efficiency.

In this study, to achieve high precision dynamic modeling of the ultraprecision lathe, data-driven tracking error prediction model is established. The information of motion trajectory acceleration is utilized to provide comprehensive reference for accurately predicting axis tracking error. Since the controller performs spline interpolation on the input tool path points to obtain the practical axis movement trajectory. It is feasible to use knot insertion and knot removal algorithms to adjust the density of local control points while maintaining the original spline curve shape. Finally, the proposed data-driven tracking error prediction and trajectory replanning method is validated through a series of cutting experiments on ultraprecision lathe.

2. Methodology

2.1 Data-driven model for tracking error prediction

Determining the frequency domain response of a dynamic system is a widely recognized evaluation method [8]. This dynamic response enables accurate simulation of lathe axis tracking errors. The conventional approach to modeling the dynamics of an ultraprecision lathe treats it as a constant dynamic system, typically using a single transfer function or frequency response data (FRD) model to evaluate various working conditions. However, the ultraprecision lathe is a variant dynamic system, and a single transfer function cannot accurately characterize its behavior. Therefore, it is logical to identify the dynamics of an ultraprecision lathe based on its varied responses to different motion trajectory accelerations. This study proposes a methodology to model the dynamics of an ultraprecision lathe and predict tracking errors using a data-driven approach. This approach is more robust and accurate.

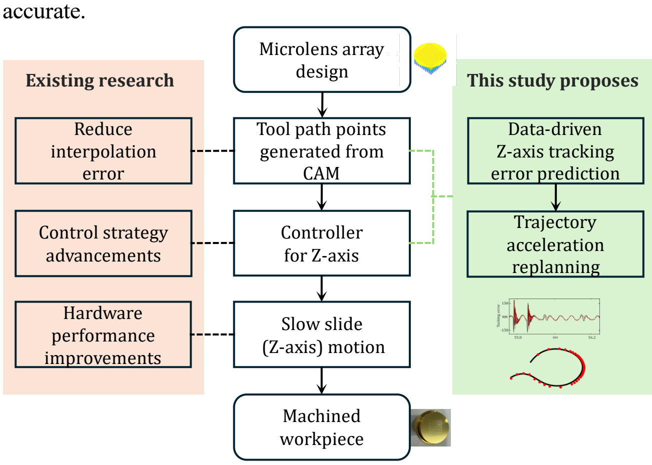


Fig. 1 Comparison between existing research and this study proposes on STS machining MLA

The functional model that relates axis tracking error to the acceleration of the motion trajectory in STS machining of MLA is an empirical formula as shown in Eq (1).

$$e = ka + f(a) \quad (1)$$

The empirical formula requires calibration experiment to be conducted to determine the k coefficient. Since the formula is related to motion trajectory acceleration, the motion trajectory of the calibration experiment is designed to cover a range of acceleration. The input signal is similar to sweep-frequency signal and is described in Eq (2).

$$\begin{cases} 0, t \le T_{idle} \\ 0.01\sin(2\pi f_i(t - T_{idle})), T_{idle} < t < \frac{cycleCount}{f_i} + T_{idle} \end{cases} \quad (2)$$

$$f_i = fResolution \times i, i = 1,2 \dots n \quad (3)$$

The motion trajectory for the calibration experiment is divided into n segments, each of which includes an idle zone and a working zone. Since the abruption in motion trajectory acceleration will trigger overshoot and oscillation in tracking error, the function of the idle zone is to leave sufficient time for the oscillation to attenuate. Combine all the segments and the whole trajectory is shown in Fig. 2, with detailed parameters listed in Table 1.

Table 1 parameters of calibration trajectory

T_{idle}	0.2 s
cycleCount	30
fResolution	0.5 Hz
f_i range	0.5 Hz – 60.0 Hz

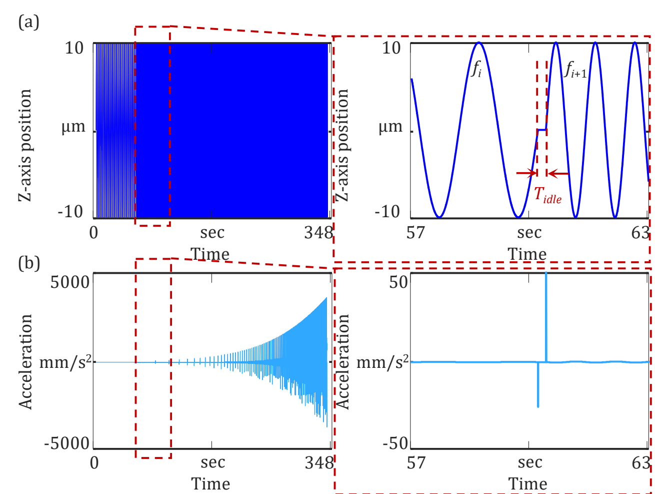


Fig. 2 Motion trajectory for calibration experiment (a) Z-axis position (b) acceleration

2.2 Trajectory replanning

The controller uses a uniform rational B-spline algorithm to perform spline interpolation on the input tool path points to obtain the practical axis motion trajectory. To realize trajectory replanning, it is necessary to decelerate in high-acceleration segments and accelerate in low-acceleration segments. One approach is to assign different weights to each trajectory point, a principle consistent with the fundamental concept of non-uniform rational B-splines (NURBS). However, this method is not supported by the controller's underlying system. An alternative approach involves using knot insertion and removal algorithms to adjust the density of local control points while maintaining the original spline curve shape, thereby controlling the trajectory' acceleration. It is important to note that these algorithms mathematically guarantee that the original curve shape remains unchanged. Therefore, it is safe to modify the distribution of trajectory points to realize trajectory replanning without affecting the original trajectory shape. As shown in Fig. 3, the curve shape after trajectory replanning remains unchanged, and the acceleration is significantly reduced.

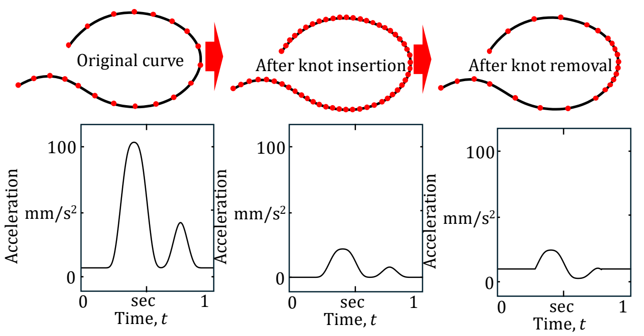


Fig. 3 Schematic of trajectory replanning

3. Experimental analysis and discussion

3.1 Experiment setup

In this study, the calibration and cutting experiments were conducted using the ultraprecision lathe (LD-CL100 V2, Leading Optics, China), equipped with an STS drive. The slow slide axis is driven by a linear motor. The command and actual position data for each axis were recorded via a Power PMAC controller with three-axis analog channels, sampled at 2250 kHz from the corresponding sinusoidal encoder. The experimental setup is shown in Fig. 4, with detailed parameters listed in Table 2.

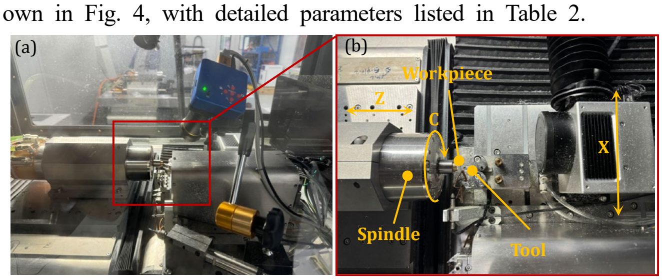


Fig. 4 Experiment setup

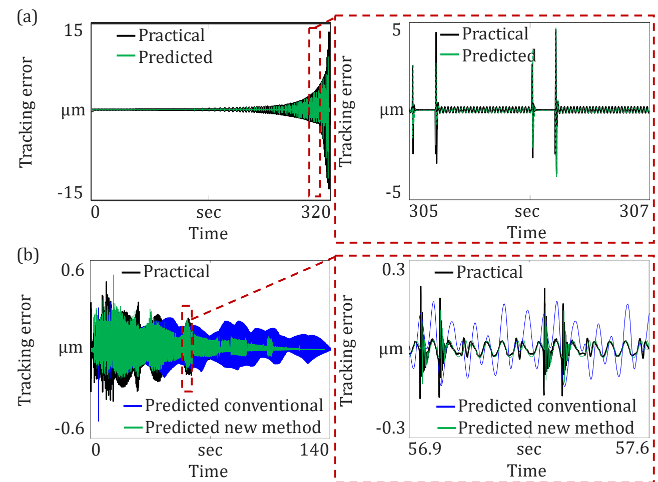
Table 2 parameters of machining experiments

Turning tool nose radius	0.512 mm
Clearance angle of tool	12.5°
Radial feed per revolution	10 μm/rev
Rotary speed of spindle	83 RPM

3.1 Experimental analysis and comparison

Prior to cutting experiments, the calibration experiments were conducted to obtain the high precision data-driven model for tracking error prediction, using the calibration trajectory described in Eq (2). Fig. 4(a) shows the comparison between practical and predicted tracking error in calibration experiment. The prediction error peak-to-valley (PV) is 52 nm and RMSE is 68 nm. As a validation, a different trajectory is applied to the tracking error prediction model and is compared to the conventional method, whose dynamic system is identified with one transfer function model. The design surface applied in the experiment is described in Eq (4). Compared to conventional method, the new data-driven method reduces the deviation PV from 193 nm to 30 nm, RMSE from 76 nm to 41 nm.

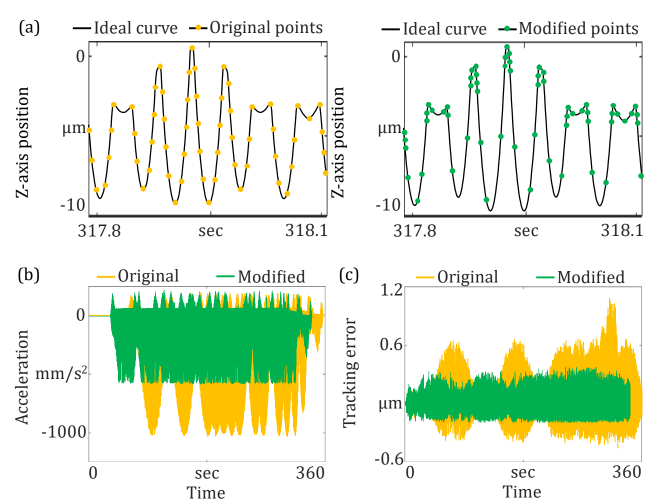
$$z = f(x,y) = 0.01 \sin\frac{2\pi}{0.4189}x \sin\frac{2\pi}{0.4189}y \quad (4)$$



Calibration	PV: 52 nm	RMSE: 68 nm
Predicted Conventional	PV: 193 nm	RMSE: 76 nm
Predicted New method	PV: 30 nm	RMSE: 41 nm

Fig. 5 Effect of data-driven model for tracking error prediction (a) calibration experiment (b) validation experiment

Having obtained the high precision tracking error prediction model, cutting experiments were conducted. The trajectory of a 10 × 10 microlens array with rectangular pattern is applied, whose saggital is 10 μm, radius of curvature is 8 mm, and clear aperture is 0.56 mm.



Original	Max acceleration: 1029 mm/s²	PV: 1.550 μm	Duration: 360 s
Modified	Max acceleration: 503 mm/s²	PV: 0.578 μm	Duration: 342 s

Fig. 6 Experimental result of cutting experiment (a) trajectory before and after replanning (b) acceleration comparison between Original and Modified (c) tracking error comparison between Original and Modified

As demonstrated in Fig 6, the motion trajectory is replanned as per the approach introduced in 2.2. The trajectory before and after replanning is denoted as "Original" and "Modified" respectively. The max trajectory acceleration is reduced from 1029 mm/s^2 to 503 mm/s^s after replanning. Both groups are machined, and their corresponding tracking errors are shown in Fig. 6(c). The tracking error PV is reduced from 1.550 μm to 0.578 μm, with the processing duration reduced from 360 s to 342 s. The machining speed is increased by 5%.

After the cutting experiment, the surface roughness of Original and Modified was measured using Zygo white light interferometer (Nexview NX2, 20X objective lens). The raw height data is analyzed to calculate the PV of surface form error and surface roughness Ra, with the results presented in Fig. 7. The surfaces roughness Ra is reduced from 51.8 nm to 10.0 nm, while the surface form error PV is reduced from 1.253 μm to 0.490 μm. It is observed that the oscillations on the lens surface near the edge have been significantly reduced.

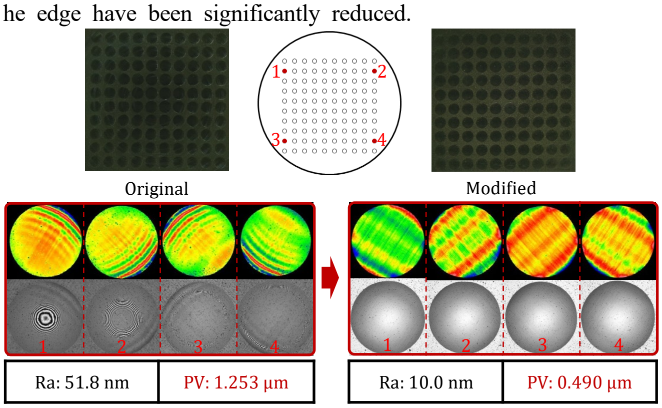


Fig. 7 Comparison of surface roughness and form error between Original and Modified

4. Conclusions

A novel tracking error prediction model is introduced to achieve high precision prediction. Based on this model, a trajectory replanning approach is developed to balance surface accuracy and machining efficiency. The tracking error prediction deviation PV is significantly reduced compared to conventional methods. Moreover, the trajectory replanning approach not only improves surface accuracy but also enhances machining efficiency. This work offers a new perspective on ultraprecision machining, combining easy deployment, high accuracy, and speed. The approach introduced in this study has strong potential for industrial adoption.

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