Calibration and Control of a Rotary Fast Tool Servo

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Abstract

In this paper we present calibration and control methods developed for a diamond turning machine that includes a novel rotary fast tool servo. We have built a prototype turning machine specialized for the production of plastic spectacle lenses to test this concept. This machine can turn 100 mm diameter toric parts having surface asymmetries of up to 3 cm. The fast tool servo can track trajectories at frequencies of up to 500 Hz, and accelerations of 500 m/s^2. The calibration methods developed in this paper determine precise values for the arm length and encoder index locations. The control system consists of a conventional inner position control loop, feedforward filtering, and repetitive control. We present experimental results demonstrating the ability of the machine to turn a toric surface with tracking errors of less than 2 μm.

1 Introduction

A fast tool servo is a specialized axis on a lathe that allows the machine to turn asymmetric parts. Examples of these parts include cams, off-axis paraboloids, and ophthalmic lenses. Our focus in the present research is on the commercial production of plastic spectacle lenses. Traditional fast tool servos in the literature carry the cutting tool through an essentially linear path. However, a consequence of a linear design is that the bearings, actuator, and support structure all contribute equally to the mass that must be accelerated along with the cutting tool. The resulting reaction force applied to the base can excite structural resonances, and so counter-masses are often used in an attempt to contain this force [4].

The cutting tool in our rotary fast tool servo is carried at the end of an 8 cm arm that pivots about an axis of rotation. In this fashion, only the cutting tool at the end of the arm moves through the largest displacement. The bearings, actuator, and sensor, located closer to the axis of rotation, contribute less to the overall inertia. The benefits of this rotary configuration over a linear system include significantly reduced reaction forces, higher achievable accelerations (experimentally demonstrated at 500 m/s^2), lower cost, and more compact size. To further develop this concept we have built a prototype turning machine with a rotary fast tool servo, as shown in Figure 1. The mechanical design of the prototype machine has been documented in [1] and [2]. In this paper, we present calibration and control methods developed for it. A significant mechanical change to the machine design since the documented work has been the addition of a double-ended arm. The arm carries a polycrystalline diamond tool for roughing cuts on one end, and a single-crystal diamond tool at the other. It also contains an integrated flexure assembly for tool height adjustment within a 20 μm range. An advantage of the rotary-arm configuration is that the extra tool can be added for no increase in machine size, and only a small increase in inertia.

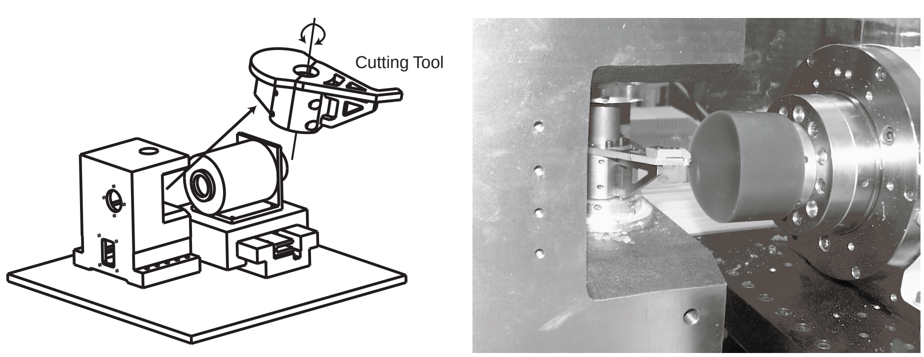

Figure 1: Drawing and photograph of the prototype turning machine using the rotary fast tool servo.

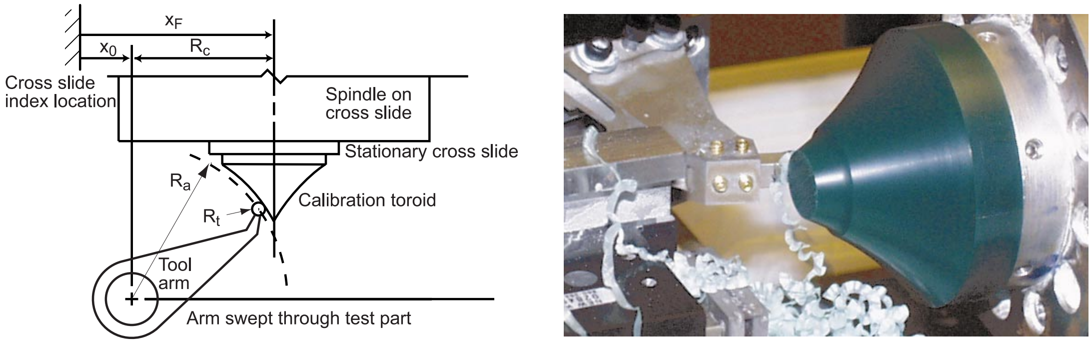

Figure 2: Diagram and photograph of the technique for determining arm length and cross-slide offset.

2 Calibration Techniques and On-Board Metrology

This section presents our latest calibration methods for determining more exact values of the tool arm length, and the location of the index pulses on the tool axis and cross slide encoders. A great asset in calibrating the machine as well as determining the lens error profile is our on-board metrology, which consists of a 0.1-μm resolution linear encoder mounted to the tool servo housing. This encoder measures part depth with a scanning probe of known radius R_p. By scanning the probe over the part, a surface profile is generated.

We developed a method which determines the tool arm length R_a and the cross-slide offset x_0, shown in Figure 2. After the tool is in place and the tool arm height is adjusted, we cut a test part with the cross-slide axis fixed at a known position x_F. This forms a toroidal surface obtained by revolving the arc of a circle about an axis. Once we cut this calibration toroid, we then use the probe to profile its surface. The gathered data is used to find the arc radius and distance R_c from the cusp to the arc center through a least-squares fit. The measured arc radius is equal to the sum of the tool arm length R_a and tool radius R_t, less the probe radius R_p. The cross slide offset x_0 is equal to the sum of R_c and x_F. This method allows us to determine these parameters to an accuracy on the order of one micron.

Figure 3 depicts the method for determining the tool arm offset angle, b_0. The machine cuts a series of flat lenses, and for each pass, we record the tool arm angle b_i. After each pass, we stop the spindle and measure the depth p_i with the probe. As seen from the figure,

$$R_a \sin(b_0 + b_i) = p_i - (R_t + p_0), \tag{1}$$

where p_0 is the depth of the tool axis in the frame of the indicator. The value of R_a is known from the preceding experiment. A least-squares fit to the data to determines the unknown parameters: the relatively unimportant $(R_t + p_0)$, and the tool arm offset angle b_0. This method allows us to determine the tool arm offset angle to within 0.01 mrad.

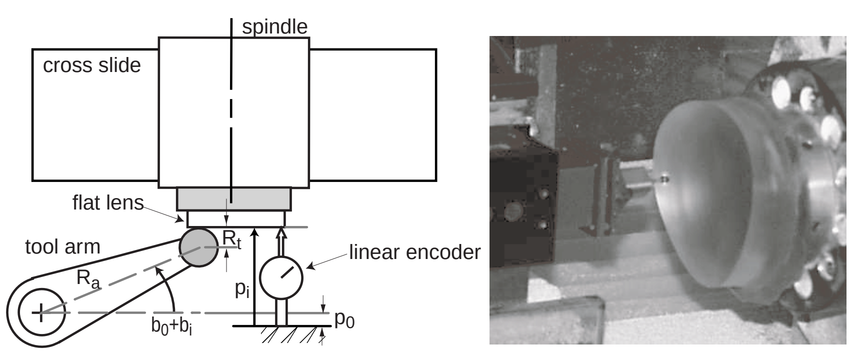

Figure 3: Procedure for calculating the tool offset angle.

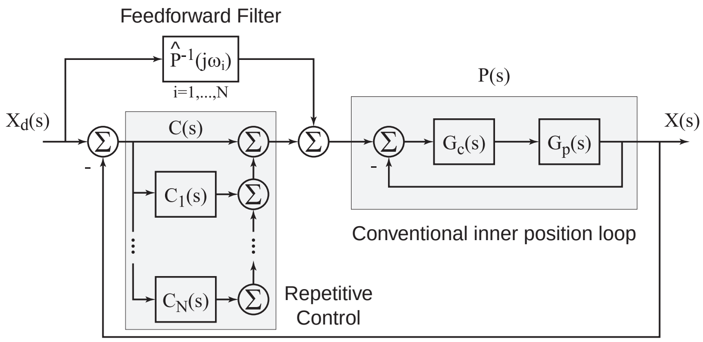

Figure 4: Overall control system design for the fast tool servo axis. The controller contains a conventional inner position loop, a feedforward filter that inverts the position loop response on a frequency-by-frequency basis, and a repetitive control algorithm to correct for modeling error and external disturbances.

3 Control System Design

The control system for the fast tool servo consists of three parts. The first is a position loop that achieves a closed-loop bandwidth of 230 Hz with conventional lead-lag compensation. The second part of the control system is a feedforward filter that pre-shifts the required tool trajectory by the measured frequency response of the position loop. This open-loop technique is sensitive to modeling errors and external disturbances (such as cutting loads). These are corrected for with a repetitive control algorithm which increases the dynamic stiffness of the axis at the multiples of the spindle frequency where the required trajectory and the disturbances are concentrated. Figure 4 shows a block diagram of the overall tool axis control system. All of the algorithms are implemented in discrete-time on a PC-based digital signal processor at a 10 kHz sampling frequency.

The required tool position is created in real-time from the the measured positions of the spindle and cross slide. Such a scheme exploits the high-bandwidth, high-acceleration capabilities of the fast tool servo to adjust for positioning errors in the other two axes. The software stores the coefficients of a Fourier Series representation of the toolpath, and thus the required trajectory consists entirely of a summation of sinusoids at integer multiples of the spindle rotational frequency. Representing the required tool position as z, the cross slide position as x, and the spindle angle as θ, we have that

$$z(x,\theta) = \sum_{n=0}^{N} a_n(x)\cos n\theta + b_n(x)\sin n\theta \tag{2}$$

The coefficients a and b are stored in the lookup table. Typically we require between 6 and 10 harmonics to capture to true shape to within sub-micron errors. We then use the measured frequency response of the position loop to pre-shift the tool trajectory on a frequency-by-frequency basis, thus approximately canceling the plant dynamics. Such a feedforward filter is very accurate at inverting the plant at particular frequencies, and is not affected by the presence of non-minimum phase zeroes. Feedforward filtering alone typically reduces our tracking errors to less than about 2%.

A repetitive control scheme further increases the tracking accuracy. This particular algorithm is based on work in adaptive feedforward cancellation by Messner and Bodson [3]. It contains a series of sinusoidal generators that produce the required control effort to drive the tracking error to zero. The concept is similar to using an integrator for achieving zero errors under constant inputs. This algorithm is equivalent to the linear system given by

$$C(s) = k\left(1 + \sum_{n=1}^{N} \frac{g_n s}{s^2 + n^2\omega_s^2}\right), \tag{3}$$

where ω_s represents the fundamental spindle frequency, and g_n is a constant gain. We are currently applying repetitive control to the first five even harmonics of the spindle frequency.

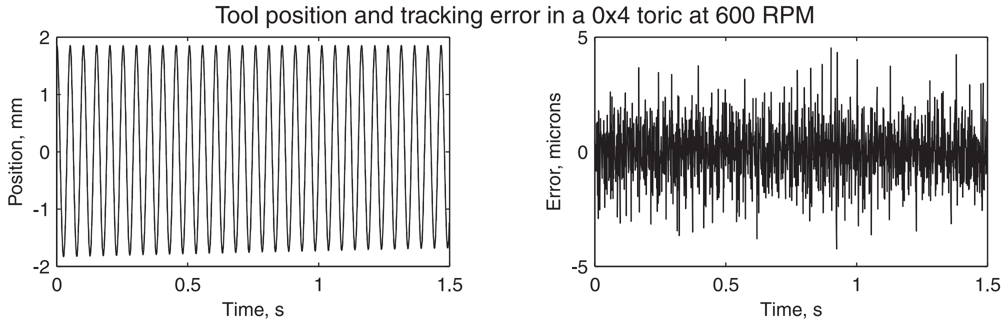

Figure 5: Tool servo tracking performance while turning a 0x4 toric surface in an optical plastic at 600 RPM. The left trace shows the position, and the right trace shows the tracking error.

4 Results

We are now concentrating on applying the calibration and control algorithms with the goal of turning plastic spectacle lenses with form accuracies of approximately one micron, and surface finishes of less than 200 nm R_q. It then becomes feasible that such lenses can be coated to optical clarity direclty, eliminating an existing time-consuming and inaccurate lapping and polishing process. We are near to such performance in the present prototype machine. Figure 5 shows the tracking performance of the fast tool servo system when turning a toric surface in CR39 (a common optical plastic) with the single-crystal tool. The trace was gathered at a cutting radius of about 30 mm and a spindle speed of 600 RPM. This lens surface is flat along one axis, and has a concave radius of 132.5 mm along the other. The resulting cylindrical surface is considered a very difficult prescription to cut by present standards. The residual tracking error has an rms value of 1.2 microns, and is concentrated at the 12th harmonic of the spindle frequency. The repetitive control algorithm can be expanded to attenuate this component of the error, but at present we are at the limits of processing capability on our DSP. We plan to upgrade it in the near future, and proceed with a second-generation machine design.

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