INTRODUCTION
The development of a Fast LOng Range Actuator (FLORA) is driven by the need to create non-rotationally symmetric (NRS) optical surface with millimeters of sag at high production rates on diamond turning machines. The existing technology on tool positioning with the PZT FTS is limited by stroke or the slow slide servo is limited by speed. The actuator proposed in this paper is supported by an air bearing, driven by a linear motor, measured by a high-resolution linear encoder and controlled by a high-speed DSP based controller [1] as shown in Figure 1. The goal is to retain the surface quality (form error and surface finish) of existing diamond turning machines while moving the tool over a range of 4 mm at a frequency of 20 Hz.

To meet the ultraprecision tool positioning requirement in the machining process, the actuator has been optimized from both physical design and control design.

(1) Have a system easy to control. The physical construction of this actuator is free of major nonlinearities such as hysteresis, backlash and friction commonly seen in other motion systems.

(2) Develop an effective control approach to minimize the influence of error, noise and disturbance on the system performance.

More specifically, there are four critical tasks to be addressed in the development of the actuator.

(1) The reaction force in the linear actuation process shall be cancelled out by a symmetric dual motor design.

(2) The heat generated in motor coil shall be removed for continuous high-speed operation.

(3) The air bearing and supporting structure shall be designed as stiff as possible

(4) The tool motion command shall be accurately generated and closely followed.

MOTION SENSING
To create a freeform surface, the position of the tool is synchronized to the position of the DTM axes by generating its motion command ($Z$) as a function of the spindle angular position ($\theta$), z-slide position ($Z_s$) and cross-feed slide position ($X$). All the position measurement in the four motion axes will be involved. It is desirable to have any measurement induced tool positioning errors to be less than a few nanometers. Laser interferometers installed on the ASG-2500 can provide measurement resolution and errors below 2 nm for z-slide and x-slide position. However, there are measurement errors in the other two motion axes discussed later.

The ability to follow the trajectory command within tens of nanometer is first dependent on the tool position measurement. The laser-scale encoder (Sony BH25) generates two differential sinusoidal signals with 250 nm pitch. The encoder interpolator sub-resolves the analog signal pitch by a factor of 256 for 1 nm resolution. To maintain the position measurement resolution up to 250 mm/s tool
speed, a signal processing and interpolation algorithm is implemented in the firmware of the PMDi interpolator, so that interpolation frequency limit is increased to above 1 MHz.

The quality of motion synchronization depends not only on the profile tracking performance of the actuator but also on the real-time generation of tool motion commands. For the 20,000 count/rev Heidenhain rotary encoder used for spindle angular position measurement, the effective measurement resolution is increased by filtering the raw encoder reading without introducing phase distortion in the estimation process. With this technique, the maximum contribution of quantization error in the command due to the limited encoder resolution is reduced to 20 nm. Furthermore, a small amount of runout in the rotary encoder disk will appear as a non-uniform pitch of the angular steps when read by the stationary read head. This pitch error repeats each revolution and since the spindle speed is constant over a single revolution, it can be determined and compensated at the servo sampling rate.

CONTROL SYSTEM DESIGN AND TESTING
The functional requirement for the FLORA is to follow the tool motion profile as closely as possible while minimizing the effects of measurement errors and disturbances. The disturbance force to the tool motion could be from the errors in motor actuation force generation process, or from the tool-workpiece interaction process which largely depends on the tool wear condition, and the material properties of the workpiece.

**Position feedback controller** ($K_{POS}$)
Based on the measured open loop system frequency response characteristic, the position feedback controller with different lead-lag designs [1] are applied to obtain three loop gain crossover frequency at 100 Hz, 600 Hz, and 1000 Hz. Figure 3 shows the Bode diagram for each controller. The system with 100 Hz crossover frequency has much lower peak magnitude but it has the slowest response and lowest stiffness. The system with 1000 Hz crossover frequency has the highest servo stiffness but it caused saturation of the amplifier during the tracking experiments.

![Bode Diagram](image)

**Figure 2. FLORA controller structure**

Figure 2 shows a block diagram of the proposed controller structure to achieve the control task. A position feedback controller ($K_{POS}$) is designed to establish the basic closed-loop control system. An acceleration feedforward controller ($K_{FFA}$) is applied to improve profile tracking. An adaptive feedforward controller ($K_{AFC}$) is designed to further improve trajectory tracking and disturbances rejection at selected frequencies.

**Position feedback controller ($K_{POS}$)**

**Acceleration feedforward controller ($K_{FFA}$)**

An acceleration feedforward controller generates most of the current for the desired acceleration and reduces the phase lag in profile tracking. Equation (1) shows the form of the feedforward algorithm:

$$K_{FFA}(s) = \frac{\hat{m}}{\hat{K}_s} s^2$$

where $\hat{K}_s$ is the estimated motor force constant, $\hat{m}$ is the estimated moving mass, the term $s^2$ is to take double-derivative of the desired position motion path $r(t)$.

**Adaptive feedforward controller ($K_{AFC}$)**

Because of the speed and resolution demands in ultraprecision machining, a control system with position feedback and acceleration
feedforward may not be sufficient. To improve the profile tracking and disturbance rejection, an adaptive feedforward control (AFC) approach [2] has been explored. The basic principle of this control approach is to estimate the magnitudes and phases of the position error at selected frequencies and to generate the control effort needed to remove the error at these frequencies. Functionally, it is equivalent to putting a model of the disturbance signal into the feedback control to create larger feedback gains at these selected frequencies.

The transfer function $G_c$ from the basic position feedback controller ($K_{POS}$) for the open loop system $G$ in Equation (3) is used to find the parameters for the adaptive algorithm in Equation (4) at the selected frequency, $\omega$.

$$G_{w}(j\omega) = A_C e^{j\omega}$$

$$G_C(s) = \frac{G(s)}{1 + K_{POS}G(s)}$$

$$K_{AFC}(z) = \frac{2\alpha z^2 \cos(\varphi) - z \cos(\omega T_s - \varphi)}{A_c z^2 - 2z \cos(\omega T_s) + 1}$$

where $T_s$ is the sampling interval, the parameter $\alpha$ is a convergence coefficient, $A_C$ and $\phi$ are nominal magnitude and phase derived from the frequency response of the transfer function $G_c$ from $u_{AFC}(t)$ to $z(t)$. The controller parameter $\alpha$ is selected to maximize the convergence rate of the adaptive controller (shorten the transient response) while maintaining the stability (robustness) of closed-loop controller.

Figure 3 shows the positioning error in a test of sinusoidal profile tracking at the amplitude of 2 mm and the frequency of 20 Hz. A combination of PID, AFC and acceleration feedforward controller is used in this test. The frequency $\omega$ in Equation (4) was the sine wave excitation frequency (20 Hz) and the parameter $\alpha$ was selected as 0.001. The tracking error in Figure 3(a) is ±70 nm (only 0.0035% of the positions command) compared to ±170 nm a similar experiment without the AFC. The frequency spectrum in Figure 3(b) shows the tracking error has negligible magnitude at the fundamental frequency (20 Hz) but has peaks at 2 and 3 times this frequency. For the tool motion path in the machining of typical freeform surface, only the first few harmonics of the spindle rotational frequency have significant magnitudes. The position error at these frequencies can be eliminated by putting the basic element of AFC in Equation (2) in parallel with the closed loop controller.

![Figure 4](image_url)

**FIGURE 4.** 2mm 20 Hz sinusoidal tracking test (a) Tracking error for four motion cycles (b) Frequency spectrum of tracking error

### CUTTING PERFORMANCE

A flat surface was machined to test the ability of the FLORA piston to hold position while excited by the forces of machining. The flat was machined on a hard-plated copper substrate with a 0.53 mm radius diamond tool at 500 rpm with a 1 mm/min feedrate (2 µm/rev) and 2 µm depth of cut on the finish pass. The theoretical finish is 1 nm PP. The Zygo NewView measurement in Figure 4 shows a 144×108 µm patch that represents approximately 72 tool passes and has an RMS surface finish of 7.4 nm.

Table 1 compares the RMS of flat surface finish when the tool is locked or positioned by the control system. For the locked case, the air was removed from the lower sides of the triangular piston. Comparing to the case of the locked tool, the three controllers increased the surface roughness. The active closed-loop control adds 3.7 nm RMS error for the 100 Hz lag-lead controller, but a larger error for higher crossover frequency controller designs. The results indicate that it is desirable to remove the major peaks in the 600 Hz and 1000 Hz controller design (Figure 3). To maintain the speed of response and servo stiffness, it is necessary to
have an amplifier with faster current loop dynamics.

**FIGURE 4. ZYGO image of surface finish (RMS=7.4 nm) on a plated copper flat**

**TABLE 1. Comparison of RMS error with a locked and position controlled tool holder**

<table>
<thead>
<tr>
<th>RMS (nm)</th>
<th>Tool holding method</th>
<th>LL* (100Hz)</th>
<th>LL* (600Hz)</th>
<th>LL* (1kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piston Motion</td>
<td>Locked</td>
<td>1</td>
<td>14.4</td>
<td>16.0</td>
</tr>
<tr>
<td>Surface finish</td>
<td>3.7</td>
<td>7.4</td>
<td>11.4</td>
<td>10.5</td>
</tr>
</tbody>
</table>

Note: LL stands for lag-lead controller

A tilted flat was machined to evaluate the ability of the servo to create NRS optical surfaces. The tilted flat requires a sine wave motion of the tool with the amplitude changing linearly with the radius. This part is a good test of the linearity of the actuator as the amplitude changes but the frequency remains constant. However, the machined surface should be a flat and thus easy to measure in a laser interferometer. Only a combination of acceleration feedforward controller and PID controller is used for the tool motion control in tilted flat machining. Acrylic tilted flats with 50.8 mm diameter and 4 mm sag were created at spindle speeds from 300-1200 rpm. The measurement of flatness by the Zygo GPI laser interferometer for the tilting surface shows the surface residual error with the best-fit tilted flat removed. The flatness error is 1 µm in Figure 6. The measured average surface finish is 22 nm (RMS) or twice the holding position value.

**CONCLUSIONS**

When the FLORA is used to cut freeform surface with two millimeters of motion at high spindle speed (1200 rpm), it is critical to reduce the tool positioning error to retain the surface quality possible for symmetric diamond turned parts. The performance of the FLORA has been significantly improved as a result of upgraded hardware and control algorithms over the original prototype [3]. Further improvement will involve an amplifier with higher current loop bandwidth, implementation of faster and/or more advanced control approaches, a faster DSP processor and stiffer mechanical components.

**ACKNOWLEDGEMENT**

Principal funding for this research is through the NSF Grant DMI-0556209 monitored by G. Hazelrigg. PMDi provided software support to implement the control system and increase the interpolation speed of the linear encoder.

**REFERENCES**

