INTRODUCTION
Nanocoining is a technique developed at the PEC that can cover a surface with sub-wavelength features at very high speeds. The process has been described in previous papers at ASPE and the current work is focused on the design and fabrication of the 2D actuator that must operate ultrasonically with a specific ratio of vertical to horizontal motion. The heart of the device is an aluminum beam driven by piezoelectric actuators. The 20 µm square diamond die has been Focus Ion Beam (FIB) machined to produce 6400 posts each with an area of 250 nm square. The challenge in designing the actuator is creating two resonant modes with the same natural frequency and with amplitudes three times larger perpendicular to the workpiece than along it (FIGURE 1).

ACTUATOR DESIGN
The elliptical indenting motion is generated at 40 kHz using a 2D beam-type resonant actuator. The actuator geometry is designed such that two orthogonally vibrating modes occur at the same frequency, allowing a single input frequency to excite both directions of motion. FIGURE 2 shows the two vibration modes and the superimposed vibration if they are excited out of phase. The front end of the actuator decreases in cross-sectional area to act as an ultrasonic concentrator which amplifies the displacement in ultrasonic applications. FEA was used to design the actuator shape to exhibit the desired resonant behavior.

TUNING TECHNIQUES
Uncertainties such as stiffness of the epoxy connections, dynamic changes of that connection, node locations, and mount contact stiffness affect the resonant frequencies and are not easily captured in a the finite element model. Several methods have been developed for tuning these resonant frequencies such that both of the active vibration modes can be adjusted to occur at the same frequency despite model/fabrication differences.

When a difference in the two desired resonances is measured, a systematic method of moving the mode frequencies relative to each
other has been developed. Methods such as selectively modifying the geometry of the actuator after assembly and strategically adding mass to the system can be used to tune the resonant frequencies. However, this can also change the location of the nodes which will result in a large decrease in amplitude.

FIGURE 4. Configurations for altering the resonant behavior of the actuator.

FIGURE 4 illustrates various methods investigated to tune the resonant response of the system. FIGURE 4 (a), (b), and (c), involve removing material at the rear of the actuator to change the effective length and mass distribution of the system. FIGURE 4 (d) and (e) illustrate methods of adding mass at specific locations. These methods have been verified using both simulated and experimental results.

FIGURE 5. Untuned amplitude response (a) and tuned amplitude response (b).

The technique demonstrated in FIGURE 4(e) was used to modify the combined response of the two vibration modes in FIGURE 5. FIGURE 5(a) shows a difference of 270 Hz in the frequency of the two desired modes. This was changed by iteratively adding mass to lower the transverse resonant mode and create the response shown in FIGURE 5(b). With the desired modes aligned, this configuration was used in indentation experiments.

ACTUATOR CONTROL
During extended operation, the resonant frequency of the system can drift due to piezo self-heating effects and other environmental influences. To maintain a consistent elliptical vibration path, a form of resonance-tracking control is needed to continuously update the drive frequency to the actuator. This is performed by measuring the phase between the current and voltage across the piezo inputs. Due to the interconnection of the piezoelectric actuators and beam, the electrical phase reflects the mechanical response of the beam. This concept is often referred to as minimum impedance tracking because mechanical resonance corresponds to minimum electrical impedance.

FIGURE 6. System to automatically modulate frequency $\omega$ to track actuator resonance.

A lock-in amplifier was used to automatically synchronize the drive signal frequency and the measured current signal. The output frequency is modulated to maintain a specified current-voltage phase that corresponds to system resonance. A GUI is used to condition the drive signal to power the two piezo elements out-of-phase (FIGURE 6).

CONCLUSIONS
Generating structured surfaces using nanocoining requires an elliptically vibrating, 40 kHz resonant actuator. This motion is achieved by designing the actuator such that two orthogonal vibration modes occur at the same frequency. However, due to model inadequacies, a systematic method of tuning the actuator is required to optimize performance. A control system was developed to automatically track resonance and maintain desired actuator behavior. The effectiveness of the system is demonstrated by rapidly generating sub-wavelength surface structures over a large area.