Design and Construction of a Low-Cost Diamond Turning Lathe and Workflow for Ultra-Precision Manufacturing

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Diamond turning lathes (DTL's) are the state of the art in ultraprecision manufacturing and enable modern high precision mass production. They use monocrystalline diamond cutting tools in conjunction with nanometer precise kinematic frames to machine parts to sub-micron accuracies with optical quality surface finishes, seen in Figure 1. Limitations to the state of the art include cost and inefficient workholding techniques like vacuum chucks. A low-cost diamond turning lathe was developed concurrently with a novel kinematic coupling based workholding system to address these limitations and bring ultra-precision manufacturing capability to Auburn University. The goals for this project included less than 1 μm and 10 nm Ra (roughness average) form and surface roughness tolerances, respectively.

The design of the machine was carried out using principles of precision machine design laid out by Moore [1], Slocum [3], Smith [4], and others. The main subsystems of a two-axis diamond turning lathe are the spindle, the X axis, and the Z axis. To achieve the accuracy required, one must design a system that uses accurate guideways and bearings without mechanical contact between the elements, actuators that do not impart undue influence on these axes, and high-resolution feedback devices.

The opposed-cone air bearing spindle used for the work spindle was generously provided by Professional Instruments Co. (PICo), along with frameless BLDC motor components which were integrated for motorization. Custom hydrostatic bearings in a box way configuration were designed for the X axis, which was driven by an ironless linear motor. This was done in accordance with the theory and procedures laid out by Rowe [2]. A surplus aerostatic stage was used for the Z axis, driven by a unique non-influencing friction bar drive to achieve backlash free coupling with exact kinematic constraint. Both the X and Z axes used Heidenhain LIP-382 linear encoders with Zerodur scales. This enables sub nanometer position feedback resolution enabling ultra-precise servo control of the axes.

Fig. 1. Diamond turning a planar aluminum mirror.

The workholding solution consists of a quasi-kinematic coupling developed to act as a standard zero-point pallet system across machines, seen in Figure 2. A three-toothed coupling with six contact faces at 45 degrees emulates a traditional style of kinematic coupling but provides face-to face contact, significantly increasing rigidity. The loss of ideal kinematic contact is made up for by elastic averaging between faces. Parts can be taken on and off the lathe with sub-micron repeatability with this system, removing the need for manual alignment techniques.

Cost estimation of this design determined it can be manufactured for approximately $75k, a vast cost savings over other commercial options, which start well

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above $100k and can exceed 1 million dollars.

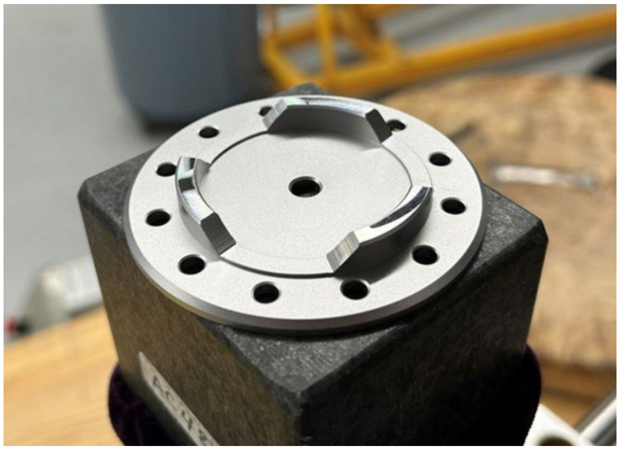

Fig. 2. The quasi-kinematic coupling used to eliminate inefficient workholding practices

The DTL was not only designed by the authors but also constructed, assembled, and tested in-house. Research and development in the field of precision machining was required to accomplish this. Tolerances held on key parts of the lathe, like the hydrostatic bearing components, define the maximum possible geometric accuracy of the machine. Thus, these must be machined to tolerances as tight as the lathe is meant to hold. The X axis guide rail and all hydrostatic bearing components were surface ground flat, square, and parallel to a tolerance of 1μm. A novel method of machining granite to flatness tolerances of less than 2.5 μm was also developed to aid in the construction of the machine base. One of the most critical components from a machining perspective is the flange that the spindle mounts to, as any out of flatness will distort the spindle stator, inducing error motion in the spindle. Using a Dover air bearing spindle, the spindle mount was rotary surface ground to a flatness of 0.5 μm.

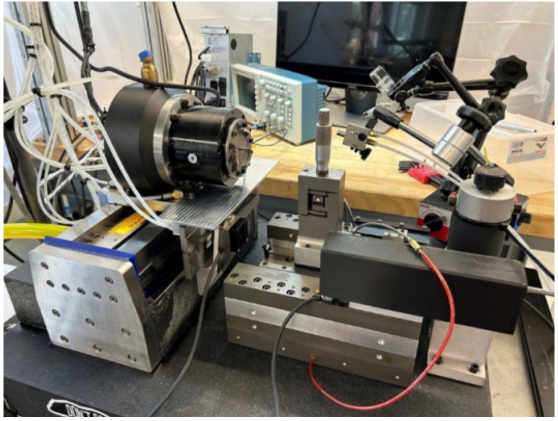

Fig. 3. The completed DTL on a vibration isolation table.

After machining, the DTL was assembled and aligned to similarly tight tolerances. The squareness of the two axes and co-axiality of the spindle to the Z are the most important parameters in this process. The finished lathe can be seen in Figure 3. More accurate mechanical alignment techniques are being developed but there is an opportunity to compensate for these errors in software as well. With these errors removed, the linear positional accuracy of the axes may be <125 nm over the 150 mm travel, the rated accuracy of the LIP-382 scales. Overall machine accuracy would then be thermal growth limited. Currently, the only significant source of heat is the oil hydrostatic bearing system. The nature of the Z drive is inherently thermally isolated, and the absence of high forces or dynamic movement means the Z, X and spindle do not generate appreciable heat on their own. For example, operating at 2000 rpm, the spindle draws ~2 Watts of power. The axes were all controlled via Granite Devices IONI-PRO servo drives. The spindle was run in velocity mode using a 10- bit rotary encoder. The X and Z axis were tuned and run in position control mode. The X axis maintained a position stability of 2 nm or less, while the Z had a positional stability of ~30 nm due to oscillations inherent to the air bearings used.

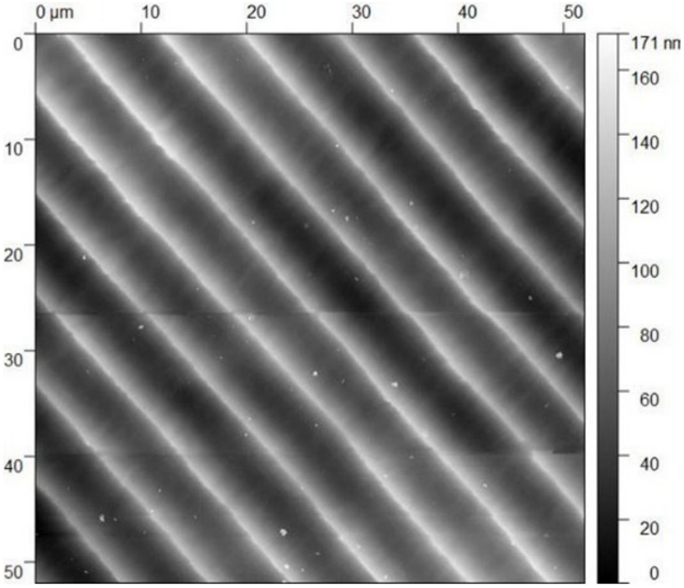

Fig. 4. AFM scan of copper part (500 rpm, 6 μm FPR).

Several test parts were turned using a monocrystalline diamond tool generously provided by Edge Technologies. These were inspected for form and finish via a Fizeau-type interferometry system, and close contact atomic force microscopy (AFM), respectively. As of current, the best finish form achieved is 1.5 μm and the best finish achieved is 14 nm Ra, defined in Equation 1. An AFM scan of one of the test parts can be seen in Figure 4. The pallet system coupling was also tested at this time, the results of which are shown in Table 1. It proved to be repeatable to under 0.5 μm.

$$R_a = \frac{1}{L}\int_0^L Z(x)dx \tag{1}$$

Table 1 Repeatability testing results for quasi-kinematic zero- point system.

Sensitive direction	Average total deviation from 0	Average mount-to-mount repeatability
Tilt	7 μrad (1.45 arcseconds)	---
Radial	423 nm (16.7 μ")	345 nm (13.6 μ")
Axial	523 nm (20.6 μ")	142 nm (5.6 μ")

There is still future work to be completed on the DTL. A control software enabling synchronous real time control of the axes is being developed to enable higher precision motion control and the machining of arbitrary mathematically defined aspheres. This software will also include error compensation features to remove almost all remaining geometric errors and incorporate a thermal error model.

Statement of Research Advisor

Cyrus has designed, manufactured, and verified an ultra- precision diamond turning lathe that is beyond the capabilities of machines currently on campus. The accuracy and precision of the manufactured parts, and their fits are orders of magnitude beyond even good undergraduate machining.

- Dr. Jordan Roberts, Department of Mechanical Engineering, Sameul Ginn College of Engineering

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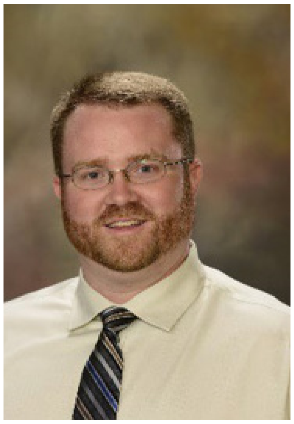
Authors Biography

Cyrus Lloyd is a Senior seeking his bachelor's degree in aerospace engineering at Auburn University and led the design and fabrication efforts for this project. His research interests include rocket propulsion, precision machine design, ultraprecision machining technologies, and all things precision engineering.

Nicholas Browning is a double major in Mechanical Engineering and History at Auburn University. They served as the CAD lead and their research interests include precision engineering, very flat objects, very round objects, esoteric firearms design, the Boer war, the Russo- Japanese war, tank combat, and wetland ecology.



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