

ROTARY-LINEAR HYBRID AXES FOR MESO-SCALE MACHINING

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1 Introduction

We have designed and built a prototype hybrid rotary-linear machine tool axis; this axis is a key subsystem for high speed, 5-axis machine tools intended for fabricating meso-scale parts. The hybrid rotary-linear axis is a cylinder driven independently in rotation and translation. This hybridization minimizes machine inertias and thereby maximizes accelerations allowing for the production of meso-scale parts with complex surfaces rapidly and accurately. We define *meso-scale* parts as having a size on the order of centimeters and thus falling between the domains of microfabrication and standard machining. Such parts might include dental restorations, molds, dies, and turbine blades.

This research was motivated by the desire to build a 5-axis machine tool for grinding customized dental restorations. If a machine existed which could automatically grind dental restorations from ceramic blanks as shown in Figure 1, it would revolutionize dentistry by eliminating the high costs of manual fabrication. Such a machine needs 5 axes of motion to generate the complex shape of teeth, and it needs to obtain shape accuracies of $20\ \mu\text{m}$. Existing 5-axis machine tools cannot achieve the high feedrates and accelerations required for fabrication in acceptable cycle times.

Existing 5-axis machine tools typically

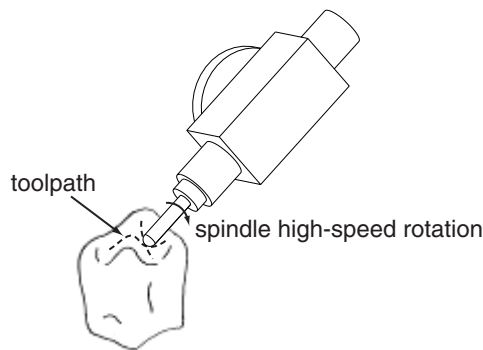


Figure 1: A high speed spindle traverses toolpaths on the complex occlusal surface of a dental restoration.

have axes stacked on top of each other, as shown in Figure 2(a). In this situation the bottom axis must accelerate the mass of all the axes and actuators further up the kinematic chain. Thus, bottom axes tend to have low accelerations which limit attainable feedrates and lengthen production times of small parts with complex surfaces. One way to achieve high accelerations in two axes is with a hybrid axis consisting of one moving part driven in two axes: the rotary-linear axis consists of a cylinder driven independently in rotation and translation as shown schematically in Figure 2(b). By eliminating one level of the machine tool's kinematic chain in this fashion we allow for significantly higher accelerations than would otherwise be possible.

We have invented a 5-axis machine topol-

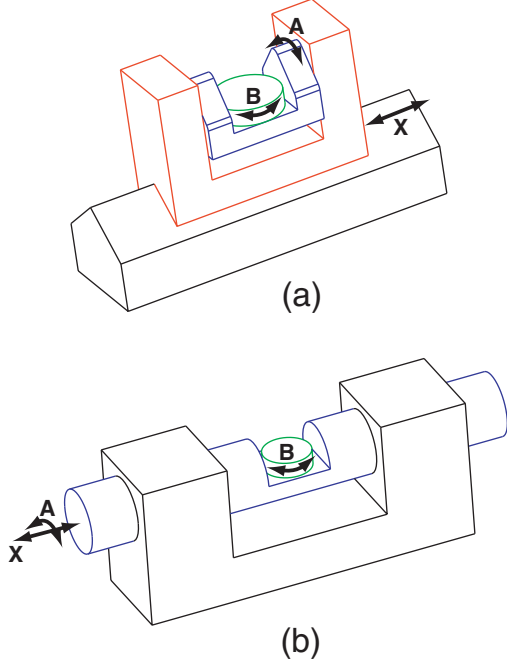


Figure 2: (a) Conventional stacked axis arrangement with a rotary table (B) stacked on a trunnion (A) riding on an X -axis. (b) Rotary-linear (A - X) axis with a rotary table (B).

ogy which we envision will have higher accelerations, control bandwidths, and accuracies than are currently possible. This improved performance is achieved by using two hybrid rotary-linear axes, each of which eliminates one level of stacking from the machine’s kinematic chain. The envisioned topology, shown in Figure 3, is kinematically similar to existing horizontal spindle 5-axis machine tools with trunnions. The envisioned topology combines the conventional trunnion (A) and linear axis (X) into a rotary-linear (A - X) axis to position the workpiece. Furthermore, it eliminates the conventional moving column providing infeed motion (Z) by combining this linear degree of freedom with the high speed spindle rotation using a second rotary-linear axis. The spindle is mounted to a conventional vertical slideway (Y) riding

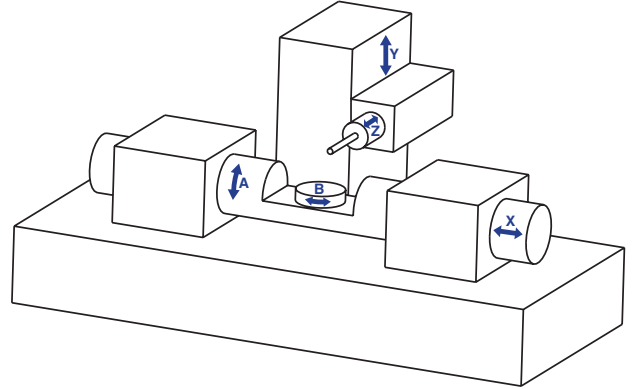


Figure 3: Envisioned 5-axis machine tool topology using two rotary-linear axes.

up and down a fixed column. The conventional rotary table (B) is replaced by a small indexing rotary axis. By indexing this fifth axis we lighten the A - X rotary-linear axis and thereby allow for higher accelerations in the A - and X -axes.

2 Prototype Axis

We built a prototype of the A - X rotary-linear axis for positioning the meso-scale workpiece in the machine topology shown in Figure 3. The hybrid rotary and linear motion provides special challenges for precision actuation and sensing. Our prototype rotary-linear axis is shown in Figures 4 & 5 and described in detail in [1]. It consists of a central shaft 3/4 inch (1.91 cm) in diameter and 15 inches (38.10 cm) long, supported by two cylindrical air bearings. The axis has one inch (2.54 cm) of linear travel and unlimited rotary travel. Two frameless permanent magnet motors respectively provide up to 41 N continuous force and 0.45 N·m continuous torque. The rotary motor is composed of commercially available parts; the tubular linear motor is completely custom-built. The permanent magnet rotors of the rotary and linear motors are shorter than their stators so that the axis can trans-

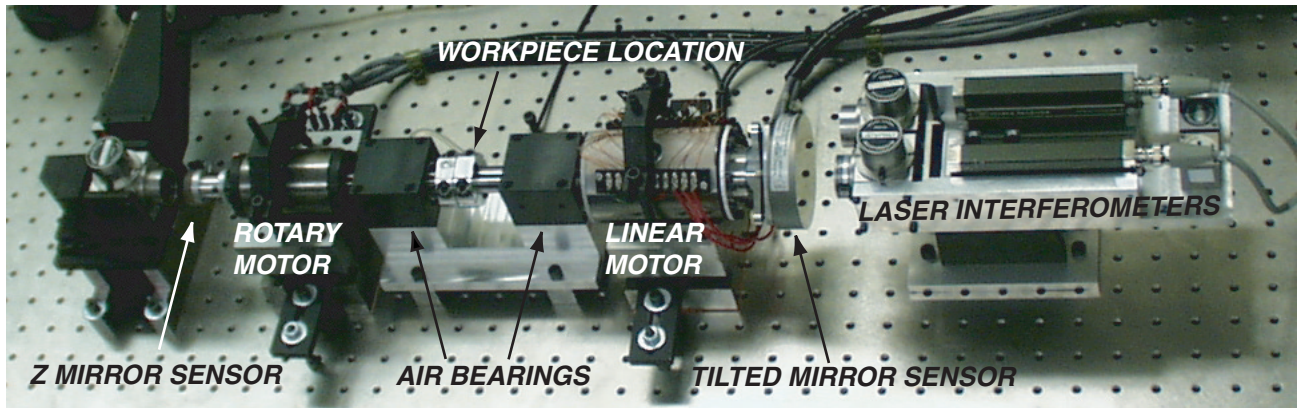


Figure 4: Prototype rotary-linear axis. The axis uses two separate permanent magnet synchronous motors to provide force and torque. On the far left is a 1 inch (2.54 cm) diameter mirror for z measurement, and on the far right is a 3 inch (7.62 cm) diameter slightly tilted mirror for θ measurement.

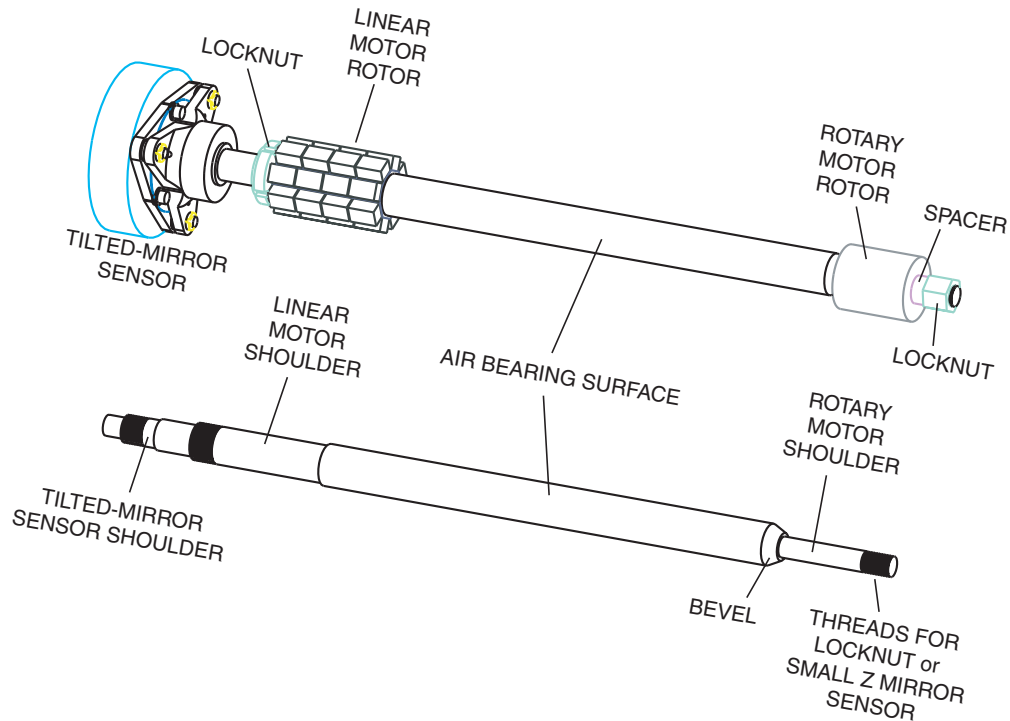


Figure 5: Prototype rotary-linear axis shaft geometry and assembled components. The motors are designed for high accelerations, and the masses and inertias of the moving shaft and attached components have been minimized. The magnetic rotors and mirror mounts are axially clamped to shoulders in the shaft. Thus, they can be disassembled and used on future prototypes.

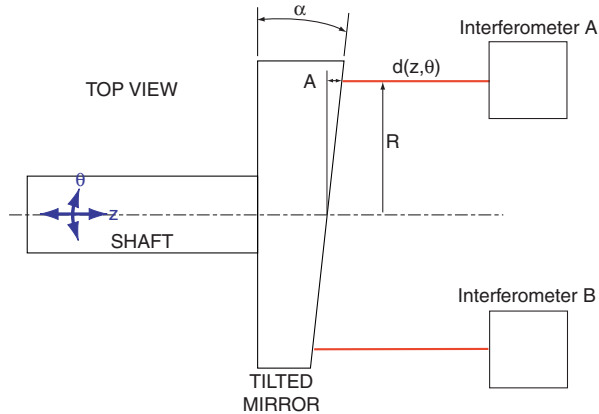


Figure 6: Tilted-mirror rotary sensor. The shaft’s rotation angle θ is sensed by measuring the distance in two places to a slightly tilted mirror. Maximum mirror tilt is $\alpha = 4.7$ mrad.

late axially without losing motor force. The prototype axis achieves a linear acceleration of 3 g’s and a rotary acceleration of 1,300 rad/s². With higher power current amplifiers and reduced sensor inertia, we predict the axis could attain peak accelerations of 12 g’s and 17,500 rad/s² at low duty cycles.

We examined several concepts for developing a precision rotary-linear sensor that can tolerate axial translation. Our prototype sensor, shown schematically in Figure 6, uses two laser interferometers to measure the orientation of a 3 inch diameter slightly tilted mirror attached to the shaft. The details of the sensor design are presented in [2]. This sensor has a resolution of 1,366,000 counts/rev (4.6 μ rad) corresponding to a linear resolution of 0.046 μ m at a 1 cm radius. Unfortunately, the inertia of this sensor dominates that of the rest of the axis, so we anticipate using a different sensor in future prototypes. A third interferometer measures shaft translation from a 1 inch diameter mirror on the opposite end of the shaft.

A program running on a DSP controls the hybrid axis. At the top level it uses finite

state control to run automatic calibration routines and respond to events such as a blocked laser. The automatic calibration routines determine parameters such as the mirror tilt which are used to calculate angular position during normal operation. The rotary axis has a closed-loop control bandwidth of 40 Hz; the linear axis has a bandwidth of 70 Hz. The rotary-linear axis has 2.5 nm rms linear positioning noise and 3.1 μ rad rms rotary positioning noise.

3 Conclusions

The precision positioning and high acceleration capabilities of rotary-linear axes make them an enabling technology for rapidly producing complex meso-scale parts to micron-level accuracies. Our rotary sensor is successful at achieving sufficient angular resolution, but its large mass and inertia limit the accelerations and control bandwidths that can be achieved with this first prototype.

4 Acknowledgments

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References

- [1] Michael K. Liebman. *Rotary-Linear Axes for High Speed Machining*. PhD thesis, Mechanical Engineering Dept., Massachusetts Institute of Technology, September 2001.
- [2] Marsette Arthur Vona. *Metrology techniques for compound rotary-linear motion*. Master’s thesis, Electrical Engineering and Computer Science Dept., Massachusetts Institute of Technology, June 2001.