A Rotary-Linear Hybrid Machine Tool Axis

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Abstract: We are developing a rotary-linear hybrid machine tool axis for meso-scale parts. It consists of a cylindrical element driven in both rotation, θ, and linear translation, z. This hybridization reduces machine inertias thus allowing much higher accelerations than are possible in conventional machine tools made up of stacked axes. Our prototype hybrid axis runs on air bearings and is actuated by two separate permanent magnet brushless motors—a rotary one and a tubular linear one. We are designing a rotary-linear sensor which uses plane mirror interferometry off of a tilted mirror mounted on the end of the axis.

Introduction: We are developing novel hybrid machine tool axes as key components of new manufacturing machines for meso-scale parts. By *hybrid*, we mean that some of the axes of motion of the machine are combined within a single component. We define *meso-scale* parts as having a size on the order of fractions of a millimeter up to centimeters, and thus falling between the domains of microfabrication and standard machining. On the small end of the scale, such parts include micromechanical devices; on the large end of the scale are elements such as dental restorations and turbine blades.

We are designing and building a promising hybrid axis in which a cylindrical element is driven in both rotation, θ, and linear translation, z. This hybridization allows the minimization of machine inertias and thereby the optimization of acceleration in order to produce small parts rapidly and accurately. Such a hybrid axis can form the core of novel machines for fabricating meso-scale parts and thus catalyze the development of the manufacturing infrastructure for such devices.

One challenging meso-scale application is the cutting or grinding of metal and ceramic dental restorations. Our vision is to make it possible to rapidly produce the complex geometries of these elements with a 5-axis machine incorporating two of our hybrid axes—one carrying the part, the other carrying the cutting tool. Currently, we are designing and fabricating the hybrid axis carrying the part; this axis is described herein.

Motivation: Our principal perspective in this research is that machines for optimally manufacturing parts on the meso-scale will not be simply scaled-down versions of present-day conventional manufacturing devices. For this purpose, existing 5-axis machines are oversized, slow, and expensive. Most such machine tools consist of massive rotary and linear axes stacked in series. These serial machines end up having large inertias in the outermost axes and are therefore not suited to machining small parts which require high accelerations. A more recent class of machine tools is the parallel type in which a group of actuators act in parallel on a spindle or workpiece. These machines have difficulty in achieving stiffness and avoiding singularities in the workspace where degrees of freedom are lost. Our proposed hybrid axis combines the advantages of both the serial and parallel structures and will make small, cost-effective, high-speed 5-axis machine tools feasible.

The manufacturing, medical, automotive, aerospace, and electronics industries require many small parts with delicate features and demanding tolerances. Often each part required has a unique geometry. This makes it inefficient to produce parts such as molds, dies, and dental restorations with electrical-discharge machining or investment casting techniques as is the current practice. A direct 5-axis CNC machining operation will be a superior way of producing these parts. It will allow for faster and easier fabrication, lower costs, more accurate parts, and more flexibility. Unfortunately, no small, accurate 5-axis machine tools exist today which can produce these parts efficiently.

Conventionally, machine tool designers have implemented multiple degrees of freedom by stacking axes. An example of such a serial arrangement is shown in Figure 1. Machine tool manufacturers such as Makino [1], Mazak [2], Toshiba [3], and Yasda [4] use this arrangement in their horizontal 5-axis machine tools. This configuration uses a rotary index table (B) mounted on a trunion (A) which is mounted on a linear axis (X). The stacking of axes quickly leads to a large machine tool with correspondingly large inertias. There are thus significant inherent acceleration limits in stacked axis designs like this one. For example, the trunion motor can be made very large to achieve high rotary acceleration, but then the X-axis which carries this trunion will see a very large inertia and hence have slow acceleration. Furthermore, stacked axes lead to large machine tools even for small working volumes which is undesirable and expensive. In addition, the errors developed in the individual axes accumulate in such serial machine structures.

Recently, machine tool designers have developed parallel machine configurations such as the hexapod [5]. In such parallel machine tools, a number of struts attach to a platform which can be moved and rotated by changing the length or position of the struts. While these machines are still actively being researched by a number of groups, they have some problems, particularly in the small-scale, high-speed arena [6]. In parallel structures, the machine stiffness changes drastically throughout the workspace, and when machining complex surfaces, the machine often will approach singular positions in its workspace. Singular positions are locations in which at least one degree of freedom is lost, usually because two axes have lined up. Parallel structures remain much larger than serial structures as the workspace shrinks which is another reason why we do not consider them further for small parts.

Our proposed linear-rotary axis eliminates the problems associated with conventional stacked axis arrangements. It is shown schematically in Figure 2. By combining the X- and A- axes into one moving cylinder, we have drastically reduced the rotary and linear inertias compared to the stacked axis case. The resulting machine structure is also much smaller, which allows for smaller actuators and a reduced machine footprint.

This simple, small combined axis has a much higher structural resonant frequency than a large stacked arrangement of axes. This allows for significantly higher machine control bandwidth and thus the ability to track the high-frequency surface features of meso-scale parts with improved machine accuracy.

The combined linear-rotary axis can also be used to provide rotation and infeed for a spindle. In this application it will allow much higher infeed acceleration than is possible by moving a whole spindle on an independent infeed stage as in current practice.

Prototype Hybrid Axis: We are currently designing and fabricating a prototype rotary-linear hybrid axis. As shown in Figure 2, this axis will provide rotation (A) and translation (X) for a small workpiece. Our goal is to achieve 0.1 μm resolution over a 2 cm travel in X and 1 arcsecond resolution in A over a travel of at least 180°. We expect to achieve on the order of 8 g's linear acceleration and 4,500 rad/s^2 rotational acceleration.

Our concept for the hybrid axis is shown in Figure 3. In designing this axis, we attempted to maximize motor force and torque while minimizing the shaft mass and inertia. We chose permanent magnet synchronous motors for actuators because they are much more power efficient than induction motors at this small size. We considered using a single checkerboard magnet array for both rotation and translation but found this approach to be less power efficient than separate motors. Our plan is to obtain a frameless brushless permanent magnet rotary motor from a commercial vendor since these are readily available. We are fabricating the tubular, linear brushless permanent magnet motor ourselves since it is not yet easily obtainable. In both motors, the stator will be 2 cm longer than the rotor so that the motors provide force and torque while allowing the stage to translate. We chose short rotors as opposed to short stators because we want to minimize the mass and inertia of the axis.

The central stainless steel shaft is mounted in air bearings. The workpiece location is between the two air bearings. On one side of the shaft are magnets for a rotary motor, and on the other side are magnets for the tubular, linear motor. The rotors are located on shoulders of the shaft and clamped axially with locknuts. The sensing of the z and θ axes is non-trivial. We would like to have a sensor which mounts on the end of the axis as opposed to taking up surface area along it which would increase mass and inertia. The sensor design is a critical part of the hybrid axis, and we describe it next.

Rotary-Linear Sensor: The combined rotary-linear motion of our machine axis rules out the use of most existing high resolution rotary sensors. Standard sensors including encoders and resolvers cannot be used because they will not allow for concurrent axial translation. Such sensors are commonly employed in stacked-axis machines where there is an inherent separation of the rotary and translational motions, but for a combined axis a new approach is required.

As shown in Figure 4, a tilted mirror can be used with a standard plane mirror interferometer to map rotation into translation. The incident beam is sent in parallel to the z axis. It is reflected back at a slight angle 2α where α is the angle that the mirror is tilted, and sweeps out a cone as θ is varied. As long as this angle is within the angular acceptance of the interferometer detector (about 5 arcminutes) the interferometer will still work. At a measurement radius of 1 inch, a tilt of 5 arcminutes gives an apparent path length difference of 75 μm for each half-rotation of the axis. If we assume the full 0.5 nm resolution of the interferometer is usable, that gives us sufficient angular resolution. However, based on initial tests, we only have obtained a reliable resolution of about 50 nm from the interferometer due to air column noise. We hope to improve this resolution by using a more compact optical arrangement and using a larger mirror tilt.

Our experimental test setup for investigating the tilted mirror approach is shown in Figure 5. An adjustable wobble plate holding a mirror is mounted on an airbearing spindle. The spindle is mounted on a stacked Y-Z stage to allow for alignment and Z-axis motion. Two laser interferometer channels measure displacement to the mirror and provide quadrature measurements.

We are currently developing DSP software to read the interferometer channels and calculate the rotation angle of the axis in realtime. We are also developing a calibration routine that will determine the radii of the two measurements and the angular displacement between them. This calibration will work by extracting relative phase and amplitudes from a quadrature data trace taken while the Z-axis is held fixed and the angular axis is allowed to decelerate under constant viscous and Coulomb friction.

Conclusion: We are building a prototype rotary-linear hybrid axis to achieve high accelerations for meso-scale machining. We will shortly be testing our first rotary-linear sensor concept based on interferometry with a tilted mirror. We are also fabricating the tubular linear motor for the axis and assembling the bearings, motors, and sensor for the prototype axis.

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References

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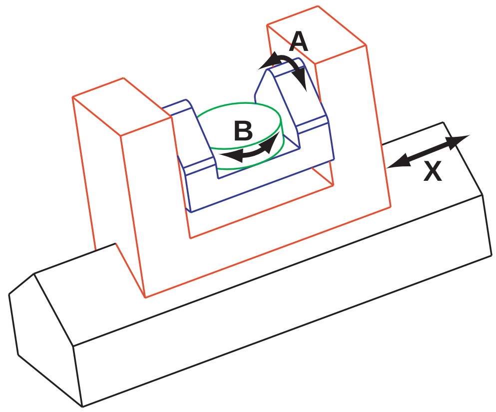

Figure 1: A common stacked-axis arrangement used in horizontal multi-axis machine tools. A rotary index table (B) is mounted on a trunion (A) which is moved by a linear axis (X).

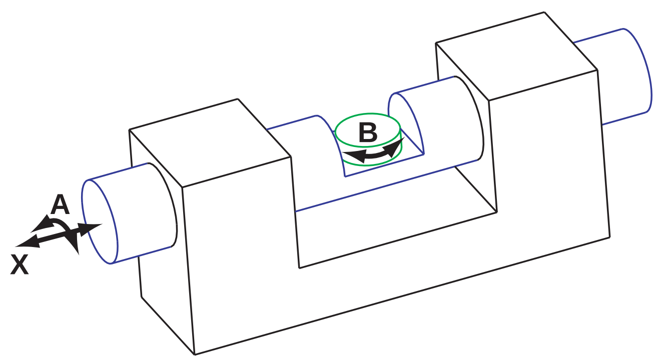

Figure 2: Our rotary-linear (A-X) axis eliminates the conventional stacking of axes.

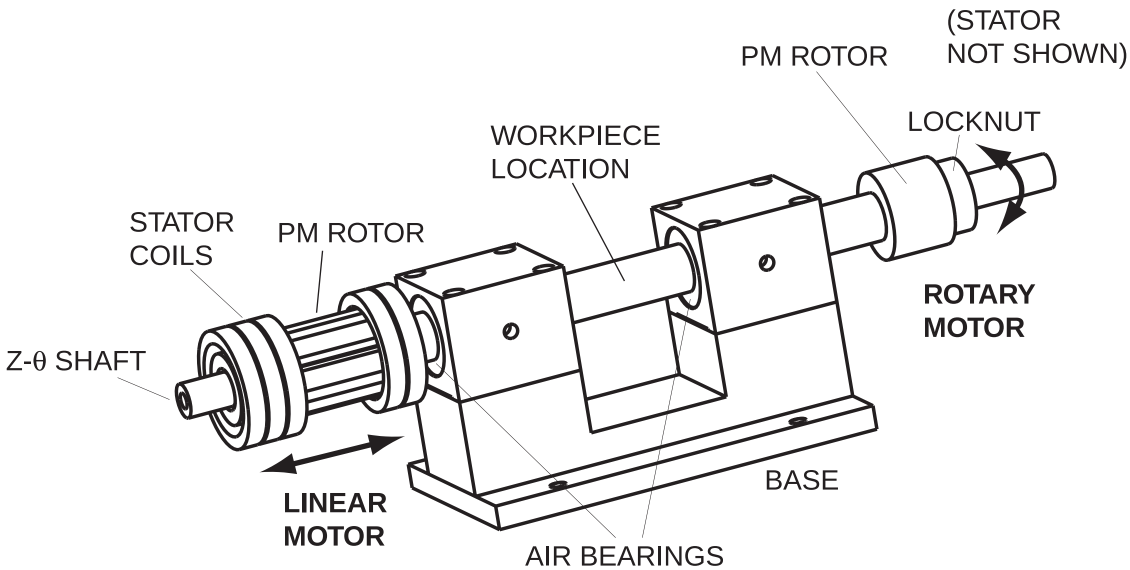

Figure 3: A rotary-linear hybrid axis. The central shaft is mounted in air bearings and has permanent magnet rotors for linear and rotary motors attached to it.

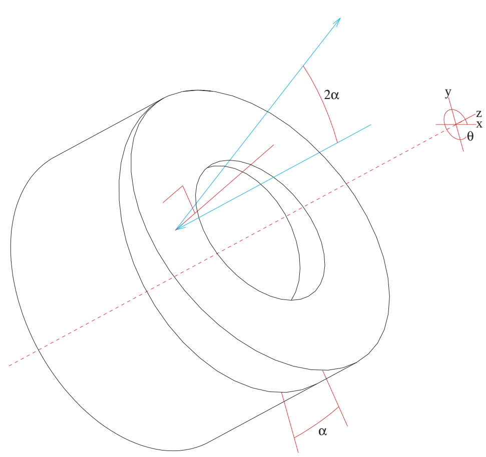

Figure 4: Plane mirror interferometry off a tilted mirror maps rotation into displacement. The angle α is limited by the angular acceptance of the light detector.

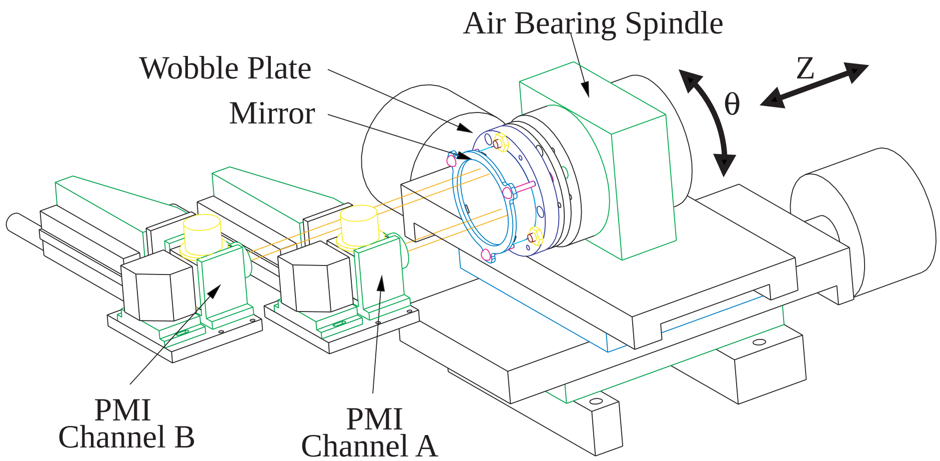

Figure 5: Experimental setup for testing the tilted mirror sensor.