A Laser Speckle Sensor for Compound Rotary-linear Motion Metrology

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1 Introduction

In previous work [1], our group implemented a tilted-mirror interferometric sensor that can measure rotation of a hybrid rotary-linear axis as part of a 5-DOF machine tool intended for fabricating centimeter-scale parts. Attached to the shaft of the hybrid axis is a tilted mirror rotary sensor, which uses two laser interferometers to measure the orientation of a tilted 3-inch diameter mirror attached to the shaft. The sensor has a resolution of 1,336,000 counts/rev (4.6 μrad) corresponding to a linear resolution of 0.046μm at a 1cm radius. However, the tilted-mirror's inertia dominates the rest of the axis, limiting accelerations, and its mass causes a cantilever resonance, limiting the controller bandwidth.

A promising alternative sensor that can be used for cylindrical motion metrology is a laser speckle based machine vision sensor. We have implemented such a prototype metrology system for a 4-inch diameter air bearing spindle. Off-line measurements from the experiments performed on our setup show that images obtained from the spindle surface can be used to measure angular displacements of the spindle with sub-pixel resolution. Real-time implementation on our prototype setup is expected to be able to run at update rates of 10 Hz, thus allowing for closed loop control with a bandwidth of the order of 1 Hz. Further, we predict that the sensor can achieve resolutions of 0.1 μm for translation and 5 μrad for rotation.

Yamaguchi [2] developed a laser speckle rotary encoder achieving a resolution of 35 μrad for angle of a 115-mm diameter metal cylinder. However, the encoder is based on measuring relative displacement across images. Measurements based on relative registrations are prone to significant drift, which cannot be tolerated for high precision measurements. In our implementation, we intend to eliminate drift by referencing all our image registrations to global images retrieved from a library generated over the range of motion.

2 Design of the Laser Speckle Sensor

Figure 1 shows the schematic of our prototype laser speckle based sensor. A laser beam is directed at the cylindrical surface of a rotating shaft. Parts of the reflected beam interfere in the space surrounding the illuminated spot on the spindle surface, creating a three-dimensional pattern, referred to as a speckle pattern [3].

An analog monochrome CCD camera captures, at a frame rate of 30 Hz, a two-dimensional slice of the pattern (see Figure 2) obtained at a fixed point in this space. When the surface is displaced laterally, the speckle pattern is found to shift accordingly, while slowly changing in the distribution of spatial intensity. Laser speckle can therefore be viewed as a way to recover displacements of surfaces from displacements across images.

A video frame grabber interfaced with the camera feeds the images to PC-based image registration algorithms that recover angular displacements of the spindle from the offset between images. We perform preliminary experiments with the sensor over small displacements given by rotating a micrometer head mounted on a cantilever arm fixed to the spindle as shown in Figure 3. We compare our measurements with those obtained from an auxiliary sensor consisting of an incremental optical rotary encoder indexed by a custom-built photo-interrupter unit mounted on the spindle.

To implement the sensor for feedback control of position, the video frame grabber is interfaced with a real-time operating system with an embedded real-time engine that implements the image registration algorithms. We provide low torque inputs to the spindle from a brushless DC motor via a belt drive. An optical encoder mounted on the back of the motor is used to measure angle and the difference between its successive counts is used to determine velocity.

3 Results

Off-line measurements obtained for small angular displacements of the spindle conform well with those obtained from the auxiliary sensor. Figure 4 shows on the 640×480 pixel plane the locus of the center of a pattern built from a reference image and detected across the images obtained when spindle is given small displacements with the micrometer totalling to 50 μm displacement along its surface. The repeatability of our measurement is within a pixel. The straight line locus lies along the direction of the speckle shift.

For large displacements of the surface, the speckle patterns de-correlate. To tackle this, we initially store a global library of reference images spread uniformly throughout the range of motion of the surface. Given the current image, we perform the image registrations with respect to the reference images retrieved from the library. The added advantage of this method is that we eliminate drift in our measurements, since our registration is based on global images. In our implementation, the library images are spaced at a 20-100 μm pitch. Further, we refine the estimate of the current position of the surface by averaging the results of image registrations performed on the current image with respect to the nearest neighboring reference images in the global library.

We have implemented closed loop position control of the air bearing spindle using feedback of position and velocity of the shaft of the brushless DC motor obtained from the optical encoder. The minor loops on the motor for velocity and position feedback from the encoder are constructed in dSPACE, a PC-based rapid prototyping controller, for cross-over frequencies of 150 Hz and 20 Hz respectively.

Further, we have implemented the feedback of angle estimates given by our laser speckle based sensor. We have observed that the jitter in the loop times for the image registration is bounded at 4.85 ms for images spaced 5 μm apart, thus allowing for real-time determinism. We expect the sensor to run at update rates of 10 Hz, thus enabling it for use in closed loop position control for bandwidths of the order of 1 Hz.

4 Conclusion

We have experimentally verified that the image sensor can be used to achieve sub-pixel resolutions. The measurements conform well with those obtained from an auxiliary sensor. With the existing setup, we predict that the sensor can achieve resolutions of 0.1 μm for translational and 5 μrad for rotational motion. However, the limitation of this metrology technique is the time and memory intensive nature of the image registration algorithms. By using localized search, we should be able to achieve higher update rates of around 30 Hz. We plan to continue to improve on the sensor and further, develop a similar version for measuring the rotation and translation of a hybrid rotary-linear axis.

References

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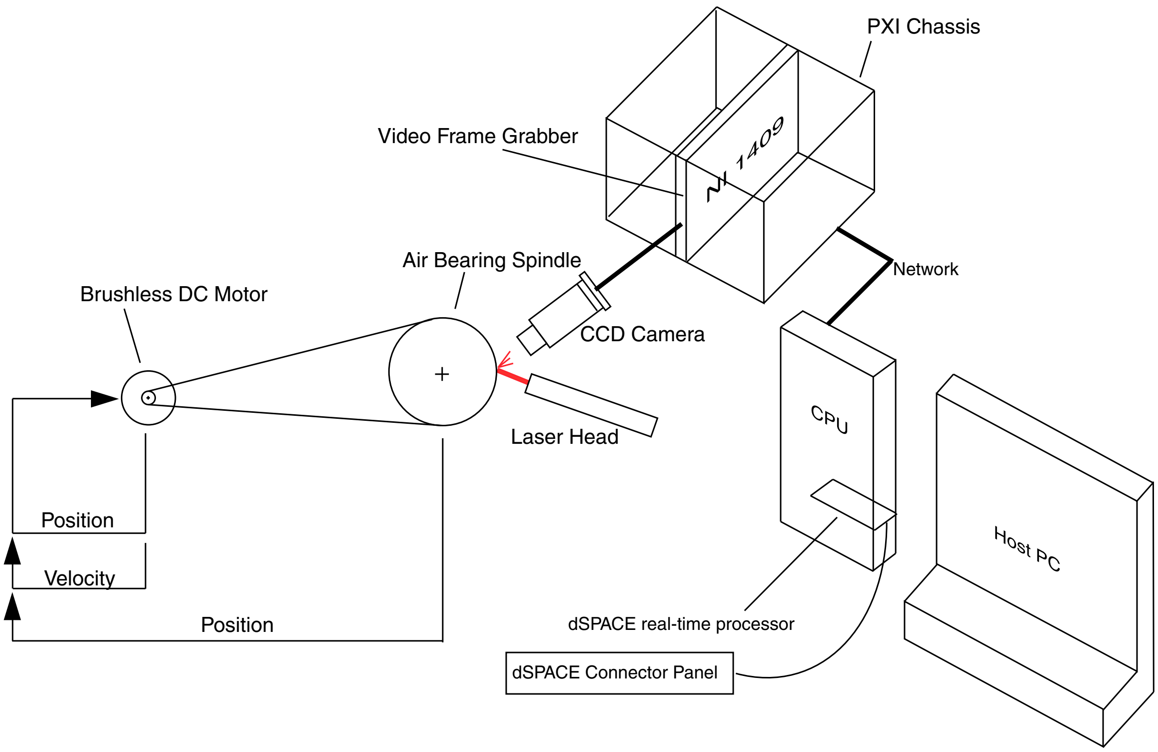

Figure 1: Schematic of real-time setup.

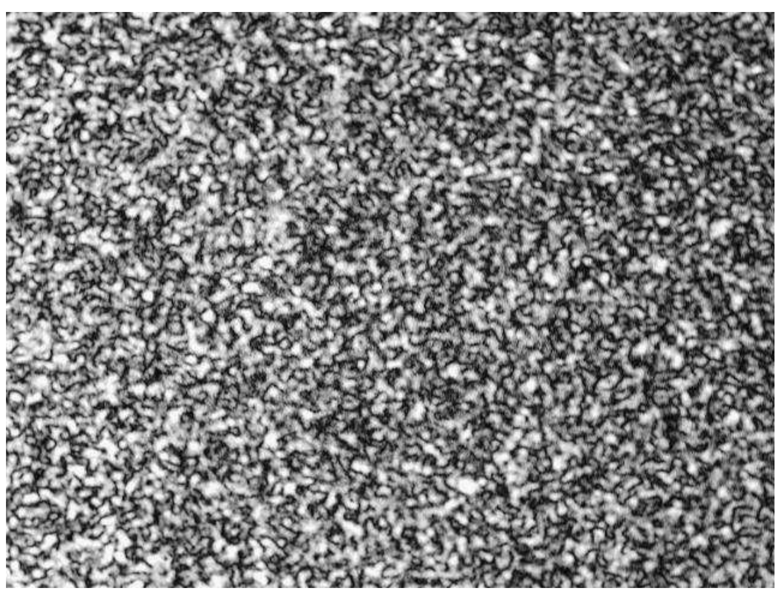

Figure 2: Speckle pattern captured by an image sensor placed at a fixed point in the space surrounding a laser-illuminated spot on the target surface.

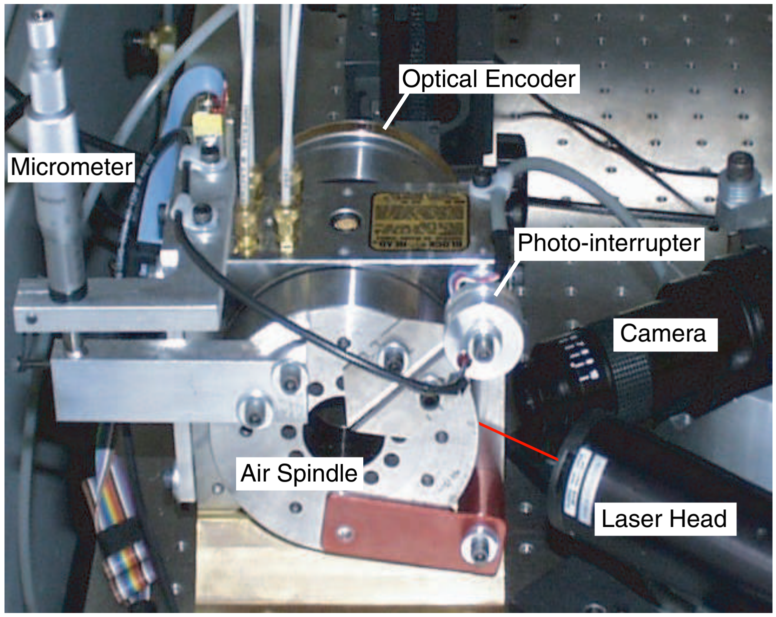

Figure 3: A laser speckle sensor for motion metrology of a precision air spindle. An optical rotary ring incremental encoder indexed by a custom-built photo-interrupter unit is used to compare results obtained from the speckle sensor.

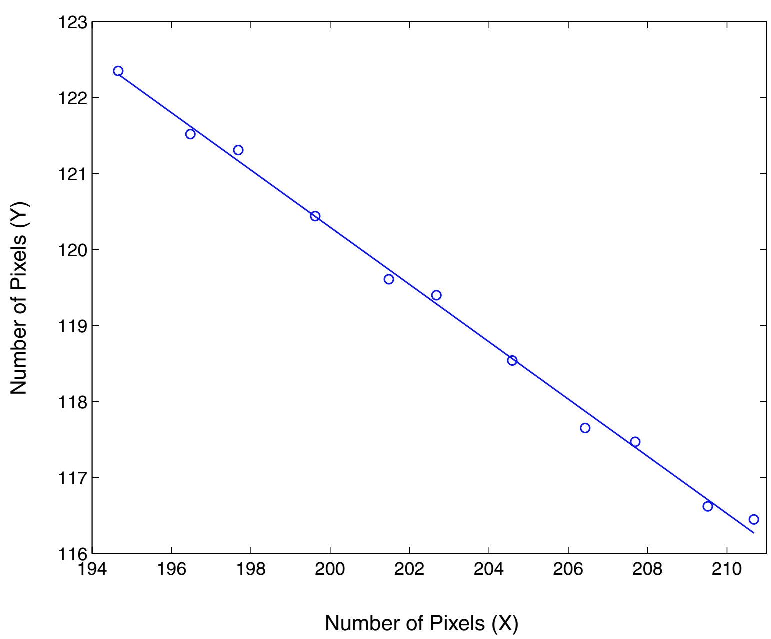

Figure 4: Line of motion of the centers of a pattern window matched across the images obtained for small rotations corresponding to a 50 μm displacement along the surface of the spindle.