Application of Laser Feedback Metrology to a Hexapod Test Strut

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1. Introduction

Figure 1. Hexapod Machine at NIST

A laser position feedback system has been designed to improve the accuracy of strut positioning for the prototype Ingersoll[2] Octahedral Hexapod machine installed at National Institute of Standards and Technology (NIST) (Figure 1). Strut laser feedback metrology experiments are conducted on a test strut, which duplicates one of the Hexapod's struts but is positioned in a test stand. The Octahedral Hexapod machine is based on a Stewart platform [Ref. 1], with 6 ballscrew-driven struts that support and move a cutting spindle. The position and orientation of the spindle are determined by the lengths of the struts, which extend from 2150 mm to 3600 mm. For Hexapod machines; accurate, strut-length metrology is essential to achieving the accurate spindle platform motions necessary to take advantage of the Hexapod's speed and stiffness for various machining applications. Currently, a rotational resolver on the back of each direct drive motor is used for position feedback to the machine's controller. This configuration has significant disadvantages in measuring strut length due partly to leadscrew errors, backlash errors, friction in the spherical joints, and especially thermal errors. Therefore, there is "a need for closed-loop thermally invariant metrology that addresses the length of the total strut". [Ref. 2] Direct measurement of the strut length using laser interferometry seems a promising approach to significantly increase the accuracy of the machine. The goal of this project is to develop a laser strut length metrology system that is accurate to within 5 µm. In the Conclusions, we discuss other metrology techniques under investigation.

2. Experiments

Experimental Apparatus

Test Strut All the tests were done on the single independent strut. Figure 2 shows a schematic of the test strut in the horizontal test position with the Pentaprism Retroreflector (PR) positioned vertically.

Lasers Two HeNe laser systems were used in experiments with the test strut. One was used to measure the distance between the large and small ball joints of the strut, and is referred to as the strut laser. It uses a single beam path, returning the measurement beam along the same path as the source. With this system there is also no separate reference beam outside the laser head. The interferometer is integrated into the laser packaging and is very close to the laser source making attachment and alignment of the optics much easier than a typical laser system [Ref. 3]. The second laser served as reference, measuring the displacement of the test stand's carriage. It has a separate interferometer package, but its operation is similar to the strut laser. The A quad B output signal from the strut laser is given to the reference laser's software as an encoder signal for comparison to the reference laser. Critical to achieving optimum system accuracy and repeatability [Ref. 4], both systems are compensated for environmental conditions using a

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weather station, which is part of the reference laser's system. Environmental precautions will be required when implementing this system on the Hexapod including protecting the laser path with telescoping tubes.

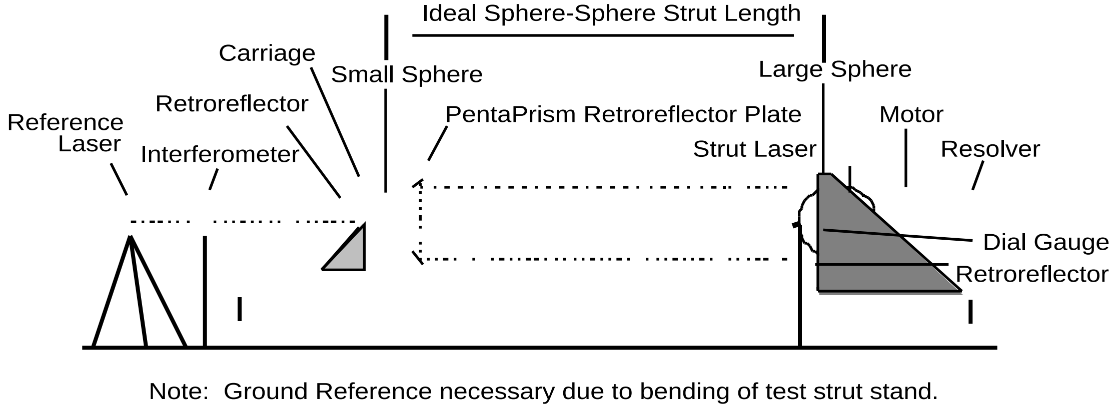

Figure 2. Schematic of Test Strut with experimental Pentaprism Retroreflector before application of a commercial Lateral Transfer Hollow Retroreflector (LTHR) and redesigned laser mounts.

Dial Gauge Two displacement transducers, as shown in Figure 3, were used to measure the displacement of the large ball joint bracket due to the sagging of the test strut stand as the strut moved throughout it's range. The sagging and distortion of the test-strut-base-frame is the reason why the foundation is part of the metrology loop for the reference laser. Especially for (thermal) drift experiments, a different solution will be adopted.

Mounting Hardware A simple clamp was designed to hold an adjustable mount for the strut laser. The clamp was attached to the strut near the large ball joint. The retroreflector, for the measurement of the strut length, was located at the bottom of the clamp to return the signal from the "wrapped" laser beam. This system was later redesigned for easier laser adjustments with kinematic mounting supports and features for attaching telescoping tubes to protect the laser beam. Additional coupling brackets for the smaller tube of the test strut were designed to accept the commercial LTHR as shown in Figure 4.

Lateral Transfer Hollow Retroreflector (LTHR) A commercial Lateral Transfer Hollow Retroreflector (LTHR) shown in Figure 4 was purchased to replace the prototype pentaprism retroreflector described in the following sections and shown in Figure 5. The LTHR system functions similar to a very large thermally stable corner cube and allowed us to "wrap" the beam around and through the strut [Ref. 5].

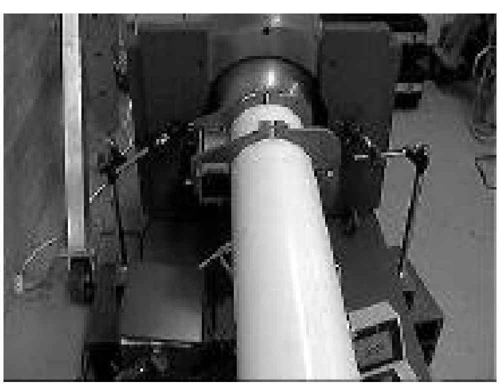

Figure 3. Test Strut showing Dial Gauges, Strut Laser and Laser Mounting bracket.

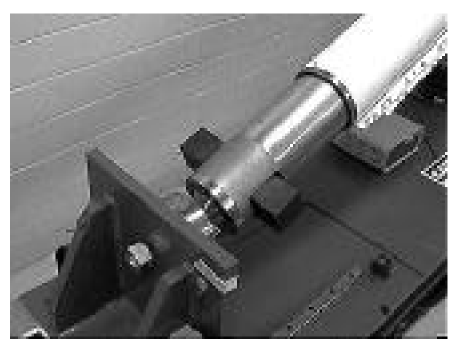

Figure 4. Lateral Transfer Hollow Retroreflector (LTHR) installed horizontally on the Hexapod Test Strut.

Background The first approach for applying laser position feedback to the strut involved a beam path through the center of the test strut. A 10 mm diameter hole was made through the center of the ballscrew and motor, with the laser head attached to the motor end of the strut. (Eventually the laser was to be mounted on a low expansion structure connected to the large sphere, thus taking the motor out of the structural loop.) The retroreflector was mounted on-axis at the small ball joint end. The beam's signal was uninterrupted for all lengths of the strut when the strut was stationary. However, under high velocity motions, the beam's signal was lost. Commercial hexapods now employ a similar technique with a larger diameter hole, which could not be done easily on NIST's Hexapod because it would require replacing the struts. One such application is Patent #5604593 by McMurty [Ref. 6].

Initial Experiments The first step was to verify that the Strut laser could be used for reliable measurements on the test strut. Many sources of error were found that caused different displacements to be measured by the strut laser and the reference laser. As they were discovered, they were eliminated if possible, or measured by other means and included in the comparison of displacement values. These preliminary results lead us to believe that it will be possible to achieve a target value of 5 μm for the uncorrected values between laser measurements. One important conclusion from these experiments was that compensation for Abbe errors [Ref. 7] due to the bending of the test strut was critical to good measurements of the strut length. Then, the solution is to take measurements on both sides and take average of the measurements.

Experiments with Wrap-around Laser Setups to Reduce Abbe Errors Once the experiments with the strut laser showed good results, a prototype system was designed to reduce the Abbe error and to allow the measuring of both paths concurrently. A slotted steel plate (Figure 5) was designed to route the measurement beam through the strut. The design uses a pentaprism to reflect the incoming beam 90 degrees to send it through the strut and then to another pentaprism to bring it parallel to the incoming beam headed back to the large ball joint end of the strut. The bottom half of one of the clamps supporting the strut laser was modified for mounting the strut laser's retroreflector. Alignment was difficult. This is because the pentaprisms create a perfect right angle deflection in one plane, but, being 2-dimensional prisms, act as plane mirrors in another plane. It was possible to maintain sufficient signal strength over the full range of position and acceleration of the test strut. In order to assess the validity of using this laser path and mounting scheme to accurately measure strut length, measurements were performed. The reference laser was used to measure the position of the test strut carriage, while a displacement transducer was used to measure the displacement of the large ball joint bracket towards the strut. The contribution of the bracket's movement was subtracted from that observed by the reference laser, and the result was compared to half the distance measured by the strut laser. This same approach was used in a small number of preliminary experiments covering a variety of speeds and roll angles of the strut. The speeds, horizontal strut position and the roll angles are representative of the worst case scenario on the measurement system regarding the different strut orientations encountered on the hexapod. The prototype optics caused the alignment to be very sensitive, but the prototype system proved out the concept and the reason to proceed with a commercial as shown in Figure 4.

Figure 5. Pentaprism Plate

3. Conclusions

Summary Previous attempts to apply laser strut length measurement through the center of the test strut installed at NIST were not successful under dynamic conditions. An externally mounted system has been described that minimizes Abbe error by measuring along parallel paths on opposite sides of the strut. With this arrangement, bending and cocking of the extensible strut tubes have a minimal effect on the total laser path length. Tests using the laser with the pentaprism retroreflector prototype instead of the rotational resolver for position feedback confirm that the method designed decreases positioning error to around 5 μm, even as the strut, ballscrew and other components undergo considerable thermal expansion due to friction heating. In a test performed after repeated rapid motion, the steady state position error is reduced from 50 μm with the rotational resolver to less than 5 μm with the laser, over a strut travel of 1200 mm. The laser signal is maintained for all speeds and accelerations of the test strut. The prototype optics were replaced with a commercially available Lateral Transfer Hollow Retroreflector (LTHR), and new mounting clamps to bring the laser beam as close as possible to the strut centerline. Compared with the prototype pentaprism-based optics, the LTHR reduces the sensitivity to bending and cocking of the strut in the transverse plane and facilitates alignment. Telescoping tubing will be used to protect the laser beam and optics from the flying chips and cutting fluid on the Hexapod. A sample of the tests performed with the LTHR system is shown in Figure 6. The LTHR system performed well in the horizontal position with results under 4 μm, but in the vertical position the range of errors was up to 10 μm. These preliminary sets of data will be replaced by thorough testing following an accepted standard such as ANSI/ASME B5.54 [Ref. 8]. This initial data set may indicate a roll problem for the measurement system

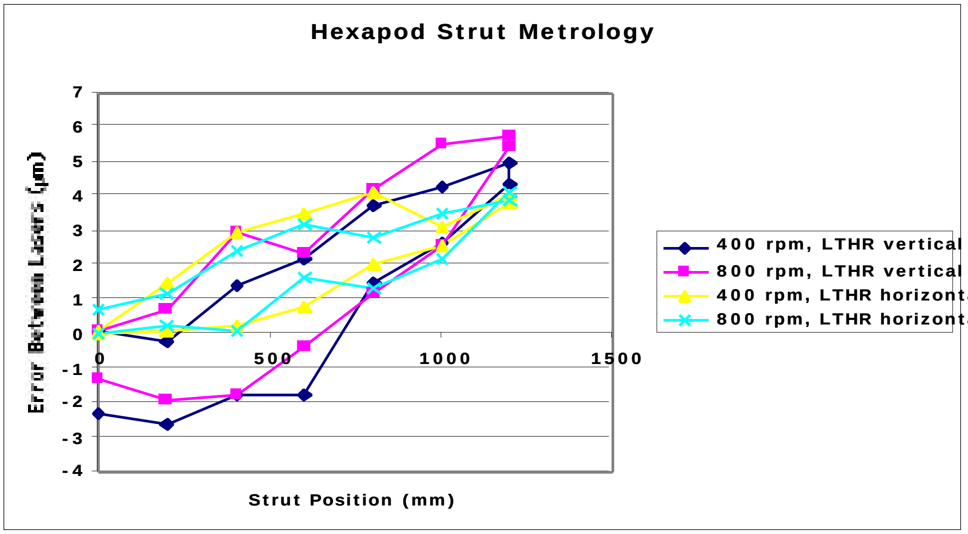

Figure 6. Preliminary and Unconfirmed Errors between the strut laser and a reference laser over the 1200 mm range for strut speeds of 8000 and 16000 mm-per-min (20 mm per revolution).

due to poor alignment of the retroreflector plate and laser bracket. The mounting hardware for the laser will need to be improved before full implementation to the Hexapod.

Alternative Metrology Systems Alternative metrology systems to determine the strut lengths to within 5μm are being explored. One design is based on an internal, on-axis interferometer system by using fiber optics. Another system under consideration are linear optical encoders. One or two encoders will be attached to the external strut. This system would be very compact and eliminate the need for telescoping tubes. Laser interferometric systems will be compared to linear encoders on our test strut, while also considering other published studies conducted. [Ref. 9]

4. References

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