IMPLEMENTATION OF A METROLOGY FRAME TO IMPROVE POSITIONING OF MICRO/MESO-SCALE MACHINE TOOLS

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ABSTRACT

Metrology frames have proven to be an excellent tool for improving the accuracy of machine tools. Because of the small sizes and travels involved, metrology frames may provide an excellent method for positioning improvement of micro/meso-scale machine tools. We have developed a metrology frame and incorporated it into a benchtop three-axis milling machine. We have conducted tests to assess the ability of the metrology frame to more accurately measure tool position relative to the workpiece, and we have implemented these measurements for position compensation through two different methods. Linear displacement, straightness, and squareness measurements with and without compensation reveal across-the-board improvements, in one case by as much as 72%.

INTRODUCTION

Significant recent research has gone into the miniaturization of machine tools, and many commercial vendors now offer micro/meso-scale machine tools that industry can use to answer the increasing demand for small parts and features (Dornfeld, Min, and Takeuchi 2006; Ehmann et al. 2005; Honegger et al. 2006; Sriyotha et al. 2006; Lee, Park, and Yang 2006; Takeuchi et al. 2000). These machine tools are significantly smaller and more portable than their traditional-scale cousins, with overall sizes often smaller than 300 by 300 by 300 mm and work volumes as small as 25 by 25 by 25 mm. To meet the high precision and tight tolerances required of micro/meso-scale parts and features, micro/meso-scale machine tools must have very small error motions. Reduction of these errors through precision manufacture of machine

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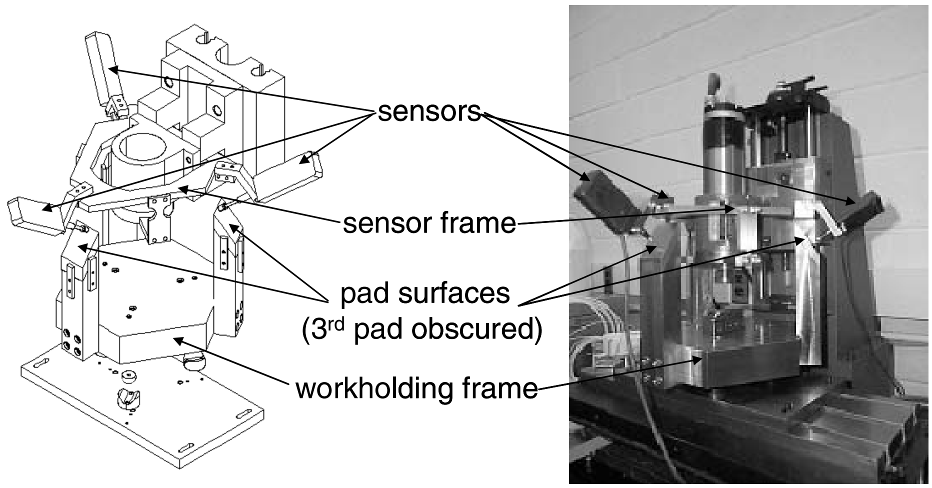

FIGURE 1. DRAWING OF METROLOGY FRAME COMPONENTS AND PHOTOGRAPH OF METROLOGY FRAME MOUNTED ON A THREE-AXIS BENCHTOP MILLING MACHINE.

components is very expensive. Because one of the main objectives in using micro/meso-scale machine tools is cost reduction, a different, more affordable type of error reduction is desirable.

The use of a metrology frame provides an excellent option for accuracy enhancement of micro/meso-scale machine tools. The most common form of accuracy enhancement on traditional-scale machine tools is error mapping (Donmez et al. 1986). However, the measurement systems and tools used to create error maps of traditional-scale machine tools often do not fit or cannot properly operate within the confined spaces of micro/meso-scale machine tools. On the other hand, the smaller sizes of micro/meso-scale machine tools provide an advantage to the use of a metrology frame for more accurate position measurement. The smaller sizes of the machine tools mean that components of a metrology frame are smaller, easier, and less expensive to manufacture.

The concept of improving positioning through use of a metrology frame is by no means new (Bryan 1979; Donaldson and Patterson 1983; Teague 1989; Brand and Kirchhoff 2005; Peggs, Lewis, and Oldfield 1999; Cuttino, Schinstock, and Prather 1999; Slocum 1992). A separate metrology frame is often able to measure the position of the tool relative to the workpiece more accurately than the typical measurement system embedded in the machine tool. Metrology frames accomplish this through two basic premises: they separate the measurement loop from the structural loop, and they eliminate or minimize and account for Abbe offset errors.

The purpose of this study is to demonstrate that the concept of using a metrology frame to improve the positioning of a micro/meso-scale machine tool is viable. This paper primarily discusses the implementation of metrology frame measurements to reduce machine tool error motions. We briefly discuss the design of the metrology frame before discussing tests conducted to characterize machine errors and to investigate the effectiveness of the metrology frame. We present two different methods of implementing the metrology frame position measurements, and the results of machine testing illustrate the relative strengths and weaknesses of each method.

DESIGN OF THE METROLOGY FRAME

A more thorough discussion of the details of the design of the current metrology frame can be found elsewhere (Moylan et al. 2009), but a brief description follows here. The metrology frame consists of two individual frames (see Figure 1). Linear displacement sensors reside in the sensor frame. The sensors use ball-guided plungers that extend to make contact with pad surfaces, which are orthogonal to the sensors and reside in the workholding frame. The sensors are symmetrically distributed around the work volume such that all machine motions displace at least two of the sensors. Most importantly, the three sensors all point directly to the tool tip, thus eliminating Abbe offset errors.

The output of the metrology frame displacement sensors multiplied by a transformation matrix provides the x, y, z position in machine coordinates of the tool relative to the workpiece:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} 0.7175 & -0.6967 & 0.0116 \\ 0.4057 & 0.4043 & -0.8197 \\ 0.5593 & 0.6227 & 0.5495 \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} \quad (1)$$

where s_i represent the displacement readings of the individual metrology frame sensors, and the components of the transformation matrix come from the unit vectors describing the sensor directions. The transformation matrix accounts for misorientations between the sensors and the pad surfaces and between the sensor and workholding frames as a whole. The design of the metrology frame is such that, for a given tool length, error in the position measurement is primarily due to uncertainty in the sensor readings (0.2 µm), and is entirely independent of the machine errors (Moylan et al. 2009).

We followed principles of precision design (Slocum 1992; Schellekens and Rosielle 1998) in the development of the metrology frame and its components. The sensor frame and workholding frame kinematically mount to the machine tool, using flexures and ball and v-grooves, respectively. This eliminates distortions caused by thermal growth of an over-constrained system. The body of the sensor frame, the workholding frame, and the pad surfaces are made from Invar® to minimize thermal growth of the system.

MACHINE TESTING

An examination of linear displacement, straightness, and squareness error motions helps to characterize the effectiveness of the metrology frame. The experimental procedure follows the recommendations set forth in the United States national standard for testing of machine tools (ASME B5.54-2005). We conducted testing over the entire range of the x-axis (8 mm) and the y-axis (7 mm), spacing each measurement by 1 mm (note that the range of axis motion is limited by the range of the metrology frame sensors, and the substitution of longer range sensors would be a simple change). We held the machine at each measurement position for 5 seconds before proceeding to the next position. As prescribed by the standard, we repeated measurements five times in each direction without resetting the zero point of the measurement sensors.

The measurement sensors for machine testing were linear displacement sensors similar to the sensors in the metrology frame. The standard recommends using a laser interferometer for linear displacement testing. However, as is often the case with micro/meso-scale machine tools, the size and shape of the machine testbed along with the presence of the metrology frame made fitting the interferometer optics and conducting laser tests rather difficult. Instead, we mounted displacement sensors outside the machine base such that they were parallel to the machine axes and in contact with an artifact placed in the general position of a workpiece (see Figure 2). These sensors have an expanded measurement uncertainty of approximately 0.4 µm (k = 2).

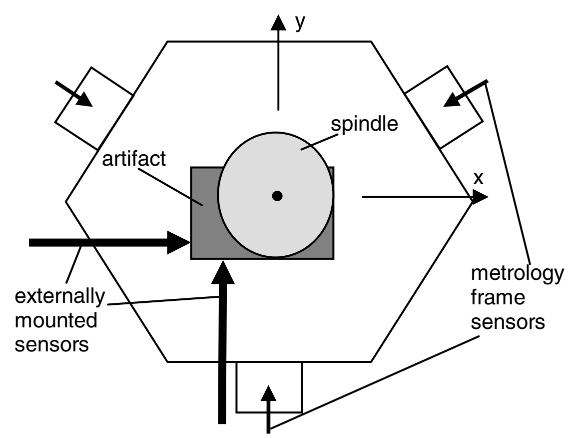

FIGURE 2. SCHEMATIC ILLUSTRATING MEASUREMENT SETUP FOR MACHINE TESTING.

PRELIMINARY RESULTS

The initial experiments were conducted to provide a baseline for machine performance under ordinary operation, but also to assess how well the metrology frame sensors could measure the tool position relative to the workpiece. We carried out the linear displacement and straightness tests described in the previous section without any type of compensation. The external sensors provide information on the error motions of the axes, and Figure 3 shows the results for the x-axis linear displacement error measurements. Table 1 summarizes these results.

TABLE 1. SUMMARY OF RESULTS FROM LINEAR DISPLACEMENT AND STRAIGHTNESS TESTS CONDUCTED WITHOUT ANY TYPE OF COMPENSATION. ALL UNITS ARE MICROMETERS.

Axis	Uni-directional systematic error	Bi-directional systematic error	Bi-directional repeatability	Straightness
x	21.2 (x+) 18.9 (x–)	31.2	8.3	5.8
y	18.6 (y+) 14.4(y–)	22.5	5.8	10.6

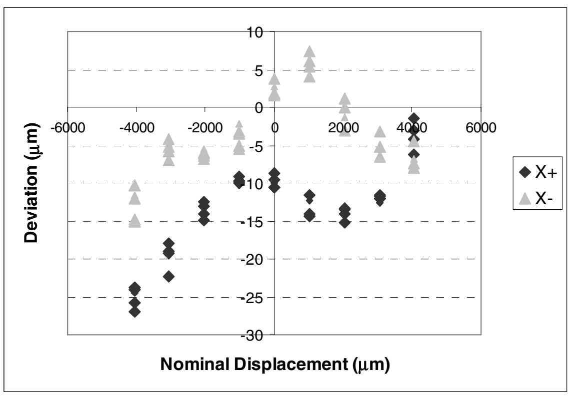

FIGURE 3. X-AXIS LINEAR DISPLACEMENT MEASUREMENTS CONDUCTED WITH NO COMPENSATION.

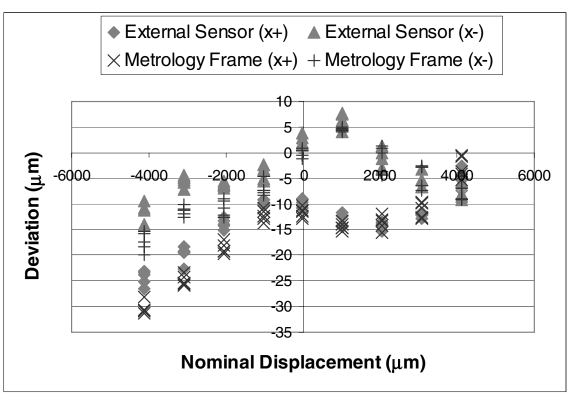

FIGURE 4. COMPARISON OF X-AXIS LINEAR DISPLACEMENT ERROR AS DETECTED WITH EXTERNAL SENSORS AND BY THE METROLOGY FRAME SENSORS.

In addition to measuring error motion through the external sensors, we also monitored the tool position as determined by the metrology frame sensors. The metrology frame position measurements subtracted from the nominal position compare very well with the deviations measured by the external sensors (see Figure 4). These preliminary results indicate that the metrology frame is indeed capable of detecting the linear displacement and straightness errors of the machine tool.

IMPLEMENTATION

A key difference with the use of a metrology frame on a machine tool from the use of a metrology frame on a measurement tool (e.g., a comparator or a coordinate measuring machine) is that the detection of error motions does not suffice; the errors must be corrected for in order to machine more accurate parts. The Delta Tau, Turbo PMAC general-purpose controller used to run the benchtop milling machine in this study allows several options for error compensation (e.g., within the servo loop, using lead screw compensation tables, and using kinematic calculation algorithms). The first approach to servo directly off the metrology frame sensors, however, was not successful. Too much noise in the individual sensor measurements led to servo instability. Other methods of compensation showed better results.

Lead Screw Compensation Tables

Lead screw compensation tables are a common form of compensation for systematic error motions determined during error mapping experiments. The advantage of this method is that the compensation tables are very simple to construct and to implement. We can utilize the metrology frame position measurement to create the error map.

This form of compensation is more primitive than other options. One problem with this type of compensation is that the error maps are created in advance of machining a part with quasi-static measurements, and the errors determined during the mapping are assumed to be systematic. Compensation tables cannot account for non-systematic errors that affect repeatability. Also, PMAC compensation tables are non-directional, meaning table entries are an average of the error detected in the positive and negative directions. Therefore, reversal errors are not fully compensated. It should be noted that many modern controllers allow construction of bidirectional compensation tables.

Kinematic Calculation Algorithms

The PMAC allows changes to the motion trajectories through calculations performed every segmentation cycle. As is typical of machine controllers, linear and circular moves are interpolated by breaking the trajectories down into much smaller segments. The PMAC calculates these trajectories periodically, with the time spacing referred to as the segmentation cycle (the segmentation cycle is set in the PMAC to a value of 5 ms, which is longer, and therefore updated less frequently, than the servo cycle of 442 µs). During each cycle, the PMAC runs through a series of user-defined calculations. PMAC denotes these as kinematic calculations and they allow coordinate transformation of non-Cartesian geometries. We utilize the kinematic calculations not only to perform the transformation of metrology frame sensors to Cartesian coordinates (Eq. 1), but also to adjust the trajectories based on error motions detected by the metrology frame measurements.

The error compensation in the kinematic calculations utilizes a running average of the ten most recent error values. Figure 5 shows the actual kinematic calculation algorithm implemented with the PMAC. The first step in the algorithm is to determine the positioning error. This is done by subtracting the position as determined by the metrology frame (see Eq. 1) from the nominal machine position in the controller determined by the in-line rotary encoders. The second step in the algorithm is to compute the running average of the 10 most recent errors. The running average is necessary to filter out any large error spikes and excessive noise from the sensors that might lead to instability. Finally, we compensate for the errors by subtracting the error values from the theoretical trajectory determined based on the programmed move to adjust the actual trajectory of the motion.

The drawback to this method of implementation is that it will never truly eliminate all of the positioning error. The PMAC kinematic calculations affect future trajectory values. This compensation method uses current error values to adjust future trajectories. As such, if the error in the future position is different than the current error, that total error will not be fully corrected. Additionally, this current algorithm using running averages is more stable but less sensitive to discontinuous errors like stiction or reversals. This simple algorithm is sufficient for the current goal of proving the concept, but more complex algorithms could easily be substituted.

```
; x-axis

;compute positioning error—error equals motor1 (x-axis)
;position (M1) minus metrology frame measured x-position
Q400 = M1 - (S1*0.7175+ S2*-0.6967 + S3*0.0116)

;compute running average of previous ten errors
Q901 = (Q400 + Q401 + Q402 + Q403 + Q404 + Q405 +
Q406 + Q407 + Q408 + Q409)/10

;recalculate next target position (P1) as controller calculated
;trajectory (Q7, based on part program values) minus the
;average error
P1=  Q7 - Q901

;update running average variables
Q409 = Q408
Q408 = Q407
Q407 = Q406
Q406 = Q405
Q405 = Q404
Q404 = Q403
Q403 = Q402
Q402 = Q401
Q401 = Q400
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FIGURE 5. X-AXIS PORTION OF KINEMATIC CALCULATION ALGORITHM USED TO COMPENSATE POSITIONING. Y-AXIS AND Z-AXIS COMPENSATION ARE ACCOMPLISHED IN SIMILAR FASHION LATER IN THE SAME KINEMATIC CALCULATION PROGRAM.

RESULTS

The various implementations of the metrology frame measurements have indeed resulted in improved positioning of the machine's axes. The x-axis measurements provide a good example of the machine performance and improvement by metrology frame compensation. Table 2 and Figure 6 summarize these results. The results of compensation with the lead screw compensation tables demonstrate the effectiveness of the metrology frame measurements, but reveal the weakness of this compensation method. The compensation table consisted of 16 inputs,

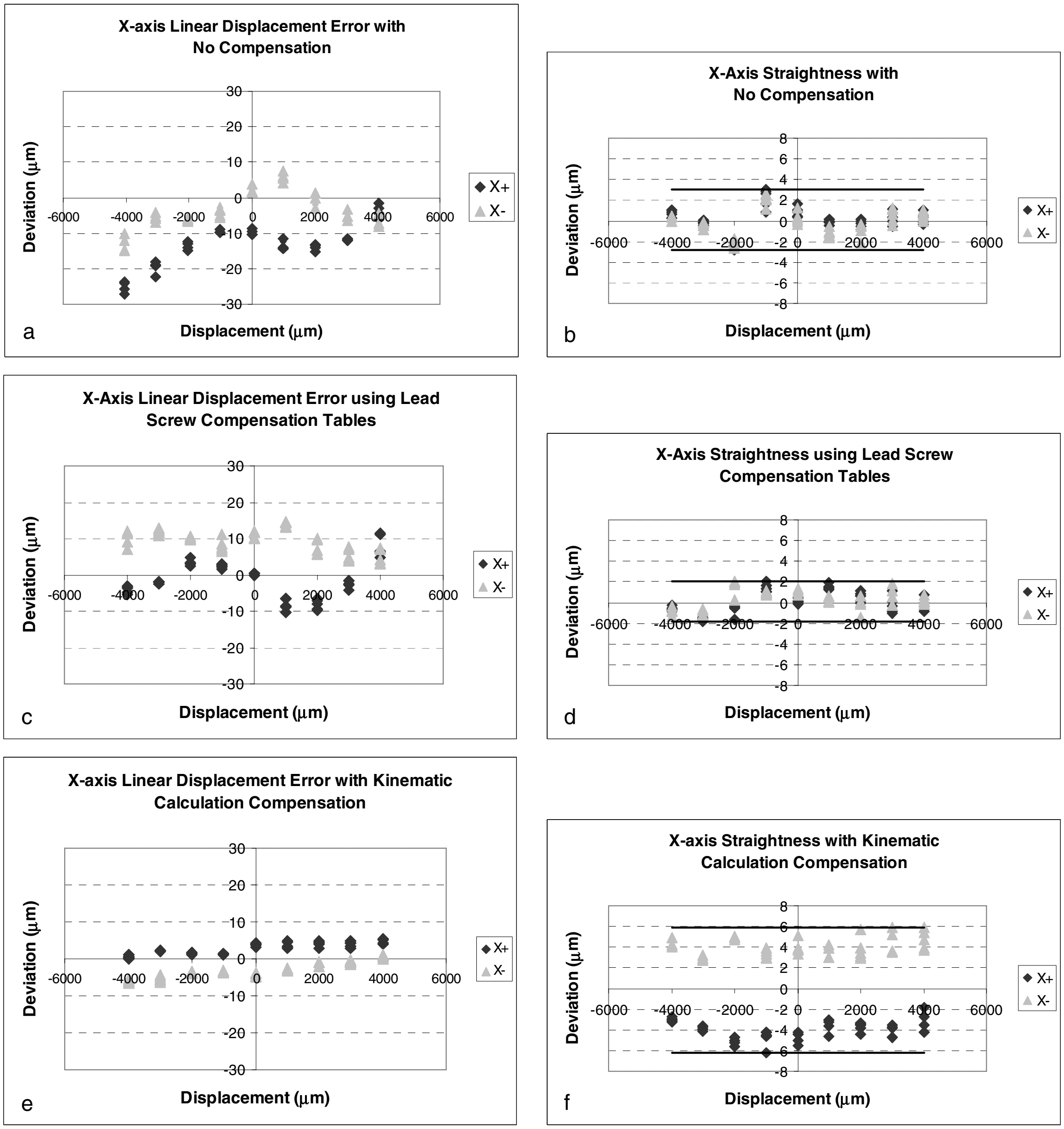

FIGURE 6. SUMMARY OF RESULTS FROM LINEAR DISPLACEMENT AND STRAIGHTNESS TESTING WITH DIFFERENT FORMS OF ERROR COMPENSATION. STRAIGHTNESS ERROR INDICATED BY BOUNDING BARS.

evenly spaced by 500 µm over the entire 8 mm range of motion of the axis (note that, as instructed by ASME B5.54, linear displacement and straightness measurements were at different positions from the inputs into the compensation table). Notice that using the compensation tables improves the systematic deviations, but as expected does not influence the repeatability. In fact, repeatability degraded with implementation of the compensation table.

Results from the kinematic calculation algorithm are much more promising. The systematic deviations improve even more than when using the compensation tables, for an improvement of more than 65%. Additionally, both the repeatability and the reversal error of the axis are improved. The straightness error, however, is worse when using the kinematic calculation algorithms. However, closer inspection of Figure 6f shows that the bulk of this error comes from reversal error. The uni-

TABLE 2. SUMMARY OF RESULTS OF LINEAR DISPLACEMENT AND STRAIGHTNESS MEASUREMENTS WITH AND WITHOUT METROLOGY FRAME COMPENSATION. ALL UNITS ARE MICROMETERS.

	Uni-directional systematic error	Bi-directional systematic error	Bi-directional repeatability	Straightness
x-axis— no comp.	21.2 (x+) 18.9 (x–)	31.2	8.3	5.8
x-axis— lead screw comp. tables	16.2 (x+) 9.1 (x–)	22.3	12.2	4.0
x-axis— kinematic calculation algorithm comp.	4.2 (x+) 6.7 (x–)	10.8	3.4	12.2

directional straightness error of the x-axis is 4.4 μm, an improvement over the uncompensated straightness error.

Finally, compensation with the kinematic calculation algorithm improves the squareness between the x and y axes. Without compensation, the calculated angle between the two axes equals 90.18°. With the compensation, the calculated angle between the two axes equals 89.95°, an improvement of 72%.

CONCLUSIONS

The results when implementing metrology frame position measurement compensation are encouraging. The purpose of this study was to demonstrate the concept of a metrology frame on a micro/meso-scale machine tool and the implementation of the metrology frame measurements to improve positioning accuracy. The large reductions in error motions observed with various methods of error compensation clearly demonstrate the potential. Micro/meso-scale machine tools strive to operate with error motions below 1 μm. Improvements to the metrology frame system will help in achieving this goal. Most notably, better characterization of the misalignments of various metrology frame components will lead to more accurate transformation matrix components (see Eq. 1) and thereby more accurate positioning.

An additional area to address is the significant reversal error with the metrology frame (see Figure 6f). A possible explanation for this issue is the friction between the metrology frame sensor tips and the pad surfaces of the workholding frame causing drag. If indeed this is the cause of the reversal errors, a likely solution is to change materials. A material with lower coefficient of friction, Teflon® for example, could replace the current ruby sensor tips. The Invar® pad surfaces make sense to limit thermal expansion, but coating the surfaces would allow polishing or diamond turning to produce a much smoother surface. Alternatively, the problem of friction could be avoided altogether if we replace the current sensors with noncontact sensors (i.e., laser interferometers). With current technology this is a viable, though expensive, option.

The preliminary results with no compensation reveal the limitations of the testbed on which we mounted the metrology frame. This benchtop machine is of the same size as modern micro/meso-scale machine tools, but was not designed or constructed with precision machining in mind. The implementation of error compensation using metrology frame measurements provides impressive improvement, but questions arise as to the possibility that the testbed is a limiting factor.

In conclusion, the results of this study show that significant improvements are possible with the implementation of metrology frame measurements. Even though improvements to the metrology frame characterization and implementation are still necessary, the concepts that metrology frames are a good fit for micro/meso-scale machine tools and that they can provide improved positioning accuracy is well demonstrated.

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