Investigation into the accuracy of a proposed laser diode based multilateration machine tool calibration system

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Abstract. Geometric and thermal calibration of CNC machine tools is required in modern machine shops with volumetric accuracy assessment becoming the standard qualification in many industries. Laser interferometry is a popular method of measuring the errors but this, and other alternatives, tend to be expensive, time consuming or both. This paper investigates the feasibility of using a laser diode based system that capitalises on the low cost nature of the diode to provide multiple laser sources for fast error measurement using multilateration. Laser diode module technology enables improved wavelength stability and spectral linewidth which are important factors for laser interferometry. With more than three laser sources, the set-up process can be greatly simplified while providing flexibility in the location of the laser sources improving the accuracy of the system.

1. Introduction
Calibration of CNC machine tools is required in modern machine shops with volumetric accuracy assessment becoming the standard qualification in many industries employing large machine tools. Laser interferometry is a popular method of measuring the errors and new multi-degree of freedom laser systems, such as the API 6D laser [1], have reduced the measurement times considerably. The majority of these systems employ a stabilised Helium Neon laser to produce a stable wavelength for accurate interferometry over long measurement distances, which usually makes these systems expensive. The measurement strategy required for volumetric compensation is considerably different to calibration. Measurement times remain high because of the need to validate the effect of compensation by multiple linear or straightness measurements [2]. For a 5-axis machine, there are nine angular errors to measure and validate. These measurement requirements are time intensive even using multi-degree of freedom lasers.

Measurement systems that can measure three-dimensional error at arbitrary positions throughout the volume without the need for measurement-specific set-up offer significant time savings for calibration and even more dramatically for compensation. Schmitz [3] uses a triple Laser Ball Bar technique to achieve trilateration and describes many static and dynamic measurements that are made possible with the system but only over a limited volume. Triangulation, trilateration and multilateration techniques have been successfully employed as calibration methods using equipment such as laser trackers but accurate tracker systems are very expensive and accurate measurements can remain time consuming with limited measurement sources.

This paper investigates the potential accuracy of a laser diode based measurement system utilising multiple measurement sources for fast error measurement using multilateration. A measurement
strategy is implemented through simulation that includes all the significant errors and uncertainties likely to affect a practical system.

Laser diode technology has progressed considerably, improving wavelength stability and spectral line-width which are important factors for laser interferometry. With more than three laser sources, the set-up process can be greatly simplified while providing flexibility in their location, improving the accuracy of the system and efficiency of volumetric error measurement.

This paper shows that an accurate system for medium sized machine tools is feasible and proposes a measurement methodology that highlights the potential efficiency improvements from a multi-reference based system.

2. Laser diode measurement accuracy

Laser diode based measurement has been widely used for precision stages and other smaller measurement applications but rarely where measurement ranges are several metres as they are on machine tools. A combination of advances in laser diode technology and methods of applying the devices for distance measurement are enabling high accuracy measurement over ranges applicable for machine tool error measurement [4] [5]. The potential errors that could affect the accuracy of such a system will depend on the way the technology is implemented. This investigation assumes that a Michelson interferometer and homodyne set-up will be used as described by Takaaki [5].

The wavelength of a diode laser varies in the short term due to thermal distortion of the diode housing, the spectral linewidth and power supply fluctuations. In the long term the wavelength drifts whether in use or not due to minute structural changes. Table 1 considers the individual error sources to determine the overall accuracy (using a minimum nominal lasing wavelength of 635nm).

| Error source       | Discussion                                                                 | Error  |
|--------------------|-----------------------------------------------------------------------------|--------|
| Temperature        | Laser diode modules are complete units that can be bought as an off the shelf item. High specification modules designed for stability have inbuilt temperature compensation and stabilized power input. For a typical high specification laser diode module, the temperature control can be as good as 0.002°C using a PID temperature controller. Experimental work carried out by MESO [6] shows the effect is approximately 0.25 nm/°C. | 0.8µm/m |
| Power              | Current control of the power supply is important for a stable wavelength. The affect on wavelength is approximately 0.05 nm/mA. A typical diode driver unit should have current stability and noise level less than 5µA. | 0.4µm/m |
| Environment        | Most metrology lasers include environmental compensation to correct for the dominant environmental factors affecting accuracy. Air temperature, humidity and pressure measurement of the same accuracy gives an uncertainty of the system. | 0.1µm/m |
| Spectral linewidth | The spectral linewidth is the frequency range over which lasing will occur. For diodes this is much greater than helium neon lasers. Short term linewidth can be less than 2MHz resulting in negligible error, however, a normal diode can drift excessively over days and years. Only through careful design of a diode has Takaaki [5] been able to minimise the drift to just 6µm/m over 20000 operating hours. A 2000 hour period representing annual usage is used for this simulation. | 2µm/m |

Like many metrology devices, the system would be regularly calibrated to eliminate the long term drift error of the diode and the environmental compensation sensors. The remaining short term errors in the table that would affect normal calibration give an approximate uncertainty of 3.3µm/m per unit.

3. Multilateration

A useful form of multilateration for this application is quadrilateration, which uses four measurement
references. This provides redundancy for self calibration and flexibility in the location of the fourth reference. In practice, it would be extremely difficult to place the references in known positions with sufficient precision, therefore self calibration is required. The calibration and measurement Methodology described in the following sections is based on simulating the machine and lasers.

3.1. Optimisation
Upon installation of the lasers, a calibration procedure is required in order to determine an initial absolute position of the tool from which subsequent incremental measurements can be made. Calibration involves moving the tool to a number of different positions during which the incremental data from the four lasers can be recorded. Figure 1 shows an example arrangement of the four lasers P0 to P3. A cost function $E$ is calculated using equation 1 which compares the beam lengths $l_i$ and the calculated diagonals. The diagonals are calculated from the coordinates of the reference positions $x_i$, $y_i$ and $z_i$ and the coordinates of the calibration points $x^k$, $y^k$, and $z^k$, where $i$ is the number of lasers and $k$ is the number of calibration points. The only values known accurately at this stage are the incremental changes in the beam lengths as measured by the lasers therefore $l_i$ is split into its known part $m^{k}_{i}$ and the unknown absolute beam length for the first tool position $l_1$. Random errors are added to the nominal reference and tool coordinates to simulate a real system. A non-linear least square optimisation is used to find the parameters.

$$E^K = \sum_{k=0}^{K-1} \sum_{i=0}^{3} \left[ (x^k - x_i)^2 + (y^k - y_i)^2 + (z^k - z_i)^2 - (m^k_i + l_i)^2 \right]$$

An exact match between the simulated machine and optimized beam lengths $l$ is achieved consistently and rapidly using a minimum of 16 measurement positions as this provides more equations than variables for the least square optimisation function used.

For fast implementation, manual placement of the lasers would be ideal although the uncertainty of location could be in the region of many millimetres. Simulating this level of uncertainty results in significant errors during measurement at arbitrary positions throughout the volume. To overcome this, an initial calculation of the reference positions is made using the accurate initial beam length value found from the first optimisation and the superior accuracy of the machine (relative to the reference positions). The calculation uses simultaneous equations similar to equation 2 transposed to give $x_i$, $y_i$, and $z_i$ for each measurement position. The number of unknowns requires that a non-linear least-squares optimisation is run to get the reference coordinates. A second full optimisation is then run using improved initial estimates. The accuracy of arbitrary position measurement throughout the volume is now significantly improved, typically from several hundred $\mu$m/m to approximately 5$\mu$m/m.

3.2. Coordinate measurement
Kim [7] uses assumptions relating to the reference positions in order to arrive at a deterministic equation for calculating position. Unfortunately, the equation requires that certain relationships between the reference positions are without error. In practice this simplification is not achievable due to uncertainty of the position of lasers. Accurate coordinates for the measurement points can only be calculated using equation 2 which requires optimisation similar to that previously used.

$$x = \frac{1}{4} \sum_{i=0}^{3} \left[ x_i + (y_i^2 + 2.y.y_i - y_i^2 + 2.z.z_i - z_i^2 - z^2 + r_i^2)^{1/2} \right]$$

4. Measurement Methodology
The measurement time for geometric error measurement for calibration or compensation is very important where machine tools are used; therefore the ability of a measurement system to be set-up and acquire the data efficiently is desirable.
To some extent progressive errors that affect the lasers in the same direction can be minimised by arranging the references symmetrically. For example, the measurement of Y axis vertical straightness can be enhanced by positioning reference P3 above reference P2 as shown in Figure 1. At this X and Z location, the x, y and z errors will include linear positioning and horizontal and vertical straightness errors, the Y axis angular errors are considered zero here. Taking another measurement at a different X axis position as shown in Figure 2 provides a high resolution and accurate measure of angular errors.

![Figure 1. Set-up position for linear and straightness error measurement](image1)

![Figure 2. Set-up position for yaw and roll error measurement](image2)

Presuming that the time between the two measurements will be in the order of minutes and that the progressive laser errors affect each measurement in a similar manner, then the change in accuracy during each measurement will be negligible.

4.1. Mechanical arrangement
Implementation of tracking technology using the received signal from the reflected beam would be a significant additional cost. An alternative mechanical method is being investigated that uses a taught wire system attached between the laser and the reflector. Each of the reflectors must have two motion axes that intersect in the same place with minimal run-out. Precision planar bearings can be made with sub-micron errors that should not adversely affect system accuracy. Similarly this precision motion will also be required at the laser source. The use of corner cube reflectors ensures high accuracy even if the laser beam entry to the reflector changes due to sag variation in the taught wire.

5. Conclusions
The theoretical accuracy of a laser diode based machine tool calibration system has been determined using research data and measurement simulation. Results give an uncertainty in the region of approximately 5µm/m for position measurement. The measurement methodology enables improved accuracy for straightness and angular error proving that the proposed system is suitable for calibration and compensation. An overall system design is briefly described that should be cost effective, practical and accurate. With the feasibility studied, work is now underway to develop a practical system.

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