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Real-time Laser Tracker Compensation of a 3 Axis Positioning System – Dynamic Accuracy Characterization

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ABSTRACT

The concept of integrating metrology systems into production processes has generated significant interest in industry, due to its potential in reducing production time and defective parts. One of the most interesting methods of integrating metrology into production is the usage of external metrology systems to compensate machine tools and robots in real-time. Continuing the work described in our previous paper of a prototype laser tracker assisted 3 axis positioning system [1], this paper describes experimental results of the dynamic path accuracy tests of the machine under real-time laser tracker compensation. Experiments show that the real-time corrections of the machine tool's absolute volumetric error have significantly increased the dynamic path accuracy of the machine. This result is also validated by a ballbar acting as an independent measurement instrument, reducing the 95 percentile error from 60μm to less than 10μm, without any prior calibration or error mapping, showing that the proposed methods are feasible, and can have very wide applications.

KEYWORDS

Machine Tool, Metrology, Laser Tracker, Real-time Error Compensation, Light Controlled Factory

1. Introduction

In our previous paper [1], the static accuracy of a 3 axis machine with real-time laser tracker compensation was analysed, demonstrating dramatic improvements in accuracy and repeatability compared to the machine without compensation. This paper describes the continuation of the research project, specifically the effort to study the dynamic path accuracy of the machine under real-time laser tracker compensation.

Error compensation and accuracy enhancement of machine tools has become a very heavily researched area, due to the increasing demand on the performance of machine tools for precision manufacturing. There are two major categories of error compensation: one approach is to attempt to "calibrate" or construct the error map of the machine before machine operations, which is then applied for the machining operations [2, 3 and 4]; the other approach is to monitor the error during the machine operations, which is then used to alter the machining process while the machine is operating, this is commonly referred to as "real-time compensation". The majority of the body of work on real-time error compensation focuses on minimizing or compensating for the intrinsic and environmental sources of error for each component of the machine tool. Using these traditional methods, in order to achieve complete compensation of all the possible sources of error, all of the individual contributors such as geometric (21 errors for a 3-axis machine) [5], kinematic, thermal [6, 7], and cutting forces must be painstakingly modelled [8, 9], and a large array of sensors such as temperature sensors, load cells, and laser interferometers must be installed to monitor the status of the machine. The complexity of this method means that it is time consuming to setup, and is sensitive to the performance and position of the sensors [10].

In this paper, a simpler and more straightforward real-time method of using an external metrology instrument to directly measure the 3D position of the tool is proposed as an alternative to the traditional real-time machine tool error compensation methods. Similar concepts have been explored by Ruiz et al using their own laser tracking system [11]. They have "closed the loop", but have not yet published results of the performance of the full system. The focus of this paper will be the description and analysis of the dynamic path accuracy experiments at different feed rates, and the validation of the system performance against an independent instrument, a Renishaw ballbar [12]. For detailed descriptions of the system and the static position accuracy, please refer to our previous paper [1].

It is worth noting that the system and methodology described herein is not simply a new machine tool compensation technique, it has greater implications. In such a system, the machine tool accuracy is controlled by a traceable instrument, so that the parts/features produced are in a sense already verified. Since the machine tool gets its absolute position from the metrology system, it can be moved with respect to the part without having to re-datum before starting a new process. This is important as this system can be used to enhance the accuracy of simple, low cost and low rigidity machine tools such as robotic manipulators, delivering positioning accuracies that are associated with the capability of large high precision machine tools.

2. Research Context

The metrology assisted positioning system described in this chapter is now a part of a larger undertaking in the Light Controlled Factory (LCF) research project at the University of Bath [13].

The hypothesis of LCF is that future factories for high value, complex products will realise their requirements for flexibility and re-configurability by increasingly adopting and deploying novel and networked measurement-based techniques; these will provide machines and parts with aspects of temporal, spatial and dimensional self-awareness, enabling superior machine control and parts verification.

A part of the LCF project objectives is to develop a flexible, scalable and low cost assembly cell with integrated manufacturing processes such as machining or material deposition. This technology demonstrator will demonstrate the integration of metrology systems directly into the manufacturing and assembly processes for large and complex aerospace components. The integration of metrology instruments has the potential of reducing the cost of the tooling and of the processing machines, and because the parts are measured while they are being manufactured, inspection time can be reduced if not eliminated, and the probability of rejecting parts is also reduced. The LCF demonstration cell will use metrology instruments and reconfigurable tooling rather than the traditional heavy and expensive jigs and fixtures to solve the problem of locating the part and the fixtures. The LCF research is relevant to and will benefit other researchers in the fields of manufacturing systems design and development, large volume dimensional metrology, measurement-enabled assembly and in the related fields of composites, industrial applications of photonics and process automation.

3. Experimental Equipment

3.1. 3 Axis Positioning System

The hardware system consists of 3 THK linear slides, with 20µm positioning repeatability, an extruded aluminium frame and custom parts for mounting the slides to each other in a bridge configuration (Figure 1), with a designed payload of 5kg. The machine is assembled by hand, therefore has high inherent geometric errors. It also does not have any error mapping, or backlash compensation.

Figure 1 - Picture of the 3 axis machine performing a ball-bar test

The integration of the laser tracker and the machine is handled by the main control software. The main control software runs on a Windows 7 PC, and is written in C#. Communication with the motion controller is achieved using the serial port, and communications with the laser tracker is handled through the laser tracker Software Development Kit (SDK) provided by Faro. The main control software also provides an easy to use user interface to control the machine manually, plot position information of the machine and the tracker, loading and executing G-Code files, enable or disable compensation and record and save measurement results.

The overall layout of the connections and data flows is illustrated in Figure 2. The laser tracker is connected to the PC via a 100Mbps Ethernet, and the PC is connected to the motion controller through a 38400 Baud RS232 serial connection. The Motion controller drives the servos through the proprietary OMRON Mechatronlink-II connection.

The real-time compensation starts with locating the 6DOF position of the 3-axis machine in the laser tracker coordinate system. This is accomplished using the main controller software, which moves the machine through a series of three points, the positions of which are measured by the laser tracker. This provides enough information to compute an Euler rotation matrix and an offset vector to convert the machine coordinate system into the tracker coordinate system and vice-versa. If error compensation is enabled, a compensation vector is sent to the motion controller, which then performs a synchronized 3-axis move command on 3 “virtual axes” using the compensation vector. The movement of the virtual axes are then added to the physical axes. For a detailed explanation of controls, communications and calculations for the correction vector please refer to our previous paper on the static performance [1].

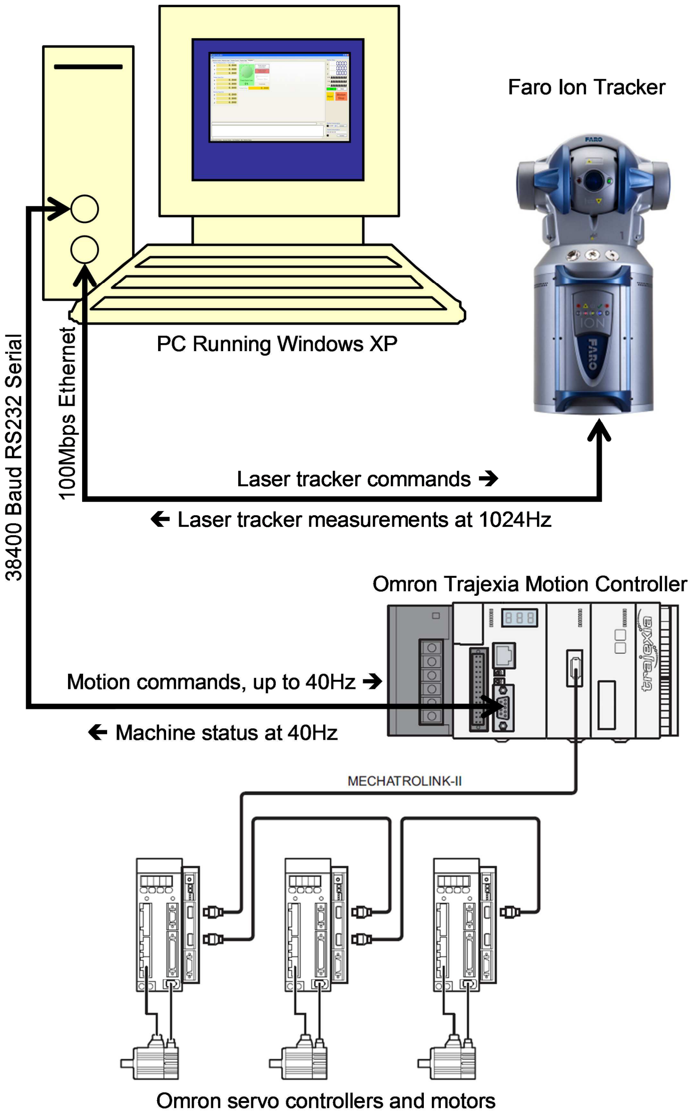

Figure 2 - Layout of physically connections and data flow

3.2. Measurement Equipment

3.2.1. Laser Tracker

The Laser Tracker (LT) is the instrument that provides the absolution coordinate information to the machine. It utilises interferometry for measuring length and a pair of high resolution angle encoders to measure the horizontal and vertical angles of the laser beam. (Figure 3) shows a schematic of the internal components of a typical laser tracker. In the interferometry technique a coherent laser beam of known wavelength passes through a beam-splitter. One beam is reflected back within the system while the other is aimed at a Spherical Mirror Reflector (SMR) that is a sphere with an embedded corner cubed reflector. When the two beams combine, constructive and destructive interference at the laser wavelength can be observed by the detector. The number of the bright and dark patterns is counted by the relevant electronics to calculate the distance. The SMR is used as the instrument probe, thus the laser tracker is a contact measurement system.

Laser trackers are considered to be one of the most reliable and well established metrology systems. An international standard exists for the system's performance evaluation [14]. Their main drawback is that the line of sight between the laser tracker head and the SMR must be maintained at all times, and only one SMR at any time can be tracked.

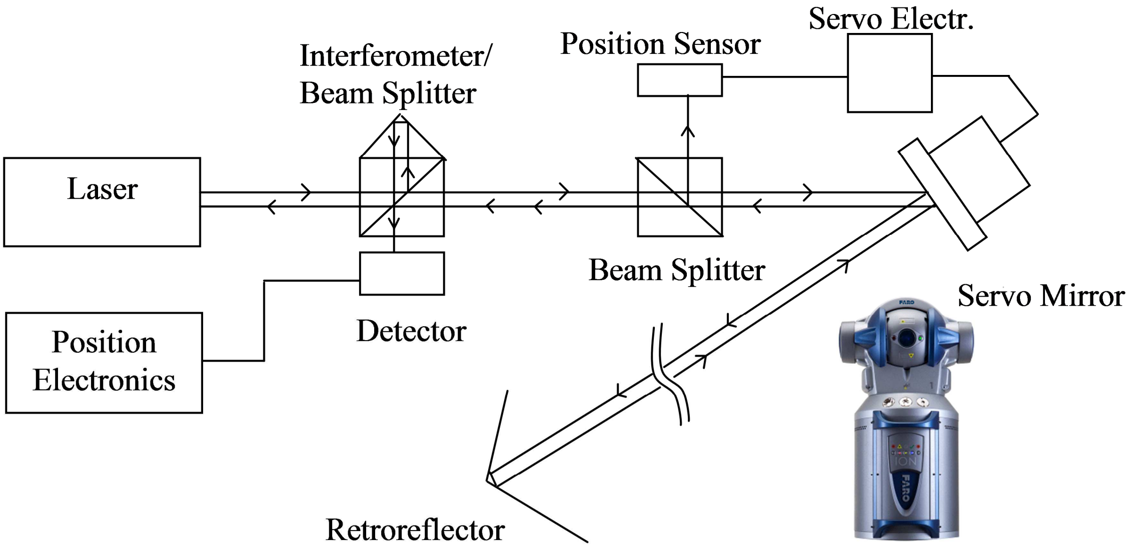

Figure 3 – Interferometry in Laser Trackers [15].

Some laser trackers provide an Absolute Distance Measurement (ADM) system, which modulates the laser beam and detects the phase of the returned light [15]. By gradually reducing the modulation frequency, the absolute distance of the target can be determined with a high degree of accuracy. ADM enabled laser trackers are more user friendly, since when the line of sight is broken, the tracker can reconnect with the SMR without homing the SMR to the tracker's initial position, as is required for an interferometer system. The ease of use however, comes at the cost of a slight decrease in accuracy [16].

The laser tracker used to compensate the 3-axis actuator is an ADM only FARO ION. It has a Maximum Permissible Error (MPE) [14] of 10µm + 0.5µm/m for distance.

3.2.2. Renishaw Ballbar

The Renishaw ballbar (Figure 3) is a linear measurement device that is typically used for quick machine tool performance checks and the diagnosis of potential problems, such as axis scale, squareness, and backlash.

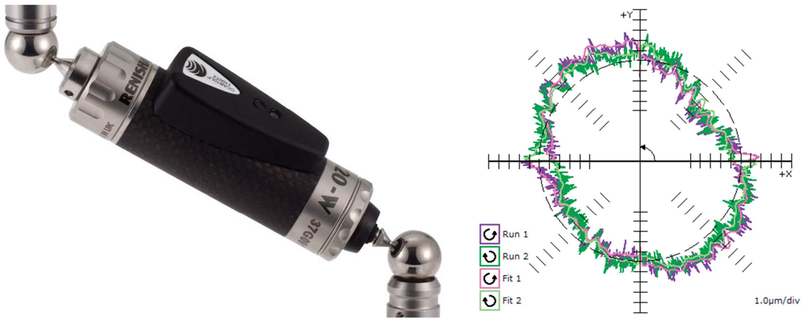

Figure 3 – Renishaw QC20-W Ballbar and typical test results [12]

It consists of two precision tooling balls attached to a telescoping linear transducer. Two kinematic mounts, one placed on the machine bed and one attached to the spindle, holds the ballbar in place as the machine performances a series of programmed circular paths about the centre of one of the spheres. The distance between the two balls (deviation from the nominal circle) is recorded during the operation, and can then be used to analyse the accuracy of the machine tool according to ISO 230-4, ASME B5.54 standards or Renishaw's proprietary diagnostic tools.

The QC20-W ballbar used in the paper has a resolution of 0.1µm and measurement uncertainty of 0.7µm + 0.3% L (i.e. for a 100µm measured circular deviation the uncertainty is 1µm) [12]. Since the ballbar is able to make dynamic measurements, and is at least an order of magnitude better than a laser tracker for the purposes of the experiments described in this paper, it is a very useful tool to independently validate the dynamic performance of the system.

4. Experimental Setup

4.1. Path Accuracy Experiment

To study the dynamic path following performance of the machine at different feed rates with and without laser tracker feedback, a set of three linear paths is programmed (Figure 4). The machine comes to a full stop at the end of each linear segment before continuing.

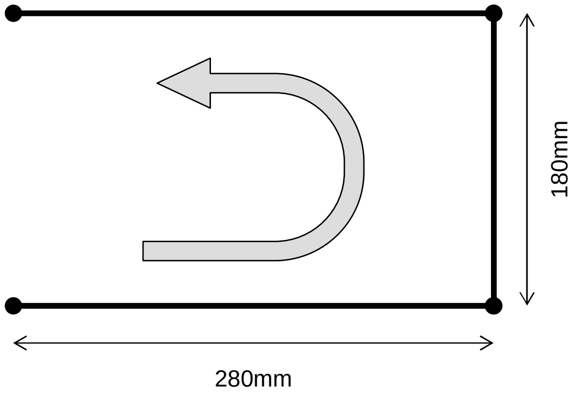

Figure 4 – Programmed path for path accuracy test

The experiment is performed three times at increasing feed rates (2000mm/min, 4000mm/min and 6000mm/min) with real-time feedback enabled, as well as one time at 2000mm/min without feedback for comparison. The position of the SMR as measured by the laser tracker is recorded for analysis. The positions of the end of line segments points are also recorded to be used for best fitting the result to the nominal path.

4.2. Ballbar Test

Since the ballbar's measurement uncertainty is at least an order of magnitude lower than that of the laser tracker, it is used as an independent measurement instrument to validate the system performance. The ballbar also measures from the end of the tool, which is offset from the SMR, such that it will be able to record any orientation errors which cannot be compensated by the laser tracker.

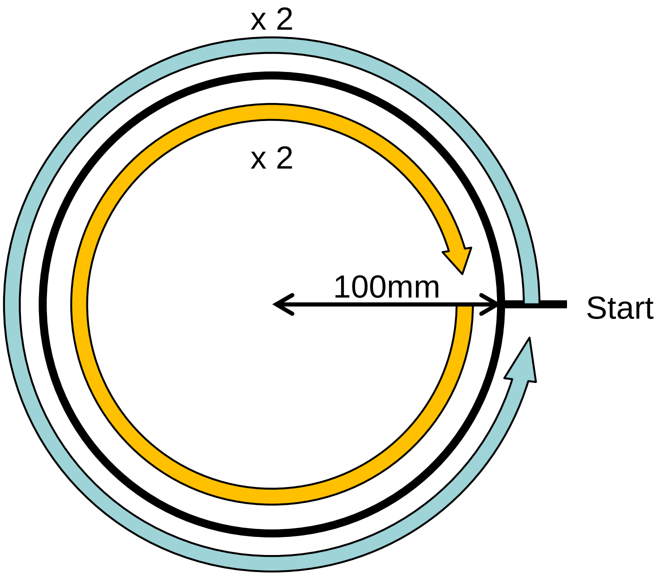

Figure 5 – Programmed path for ballbar test

The ballbar test consists of two circular moves 100mm in radius in the X-Y plane, each repeated twice (Figure 5) at 1000mm/min. The test is performed with and without compensation for comparison. The Renishaw ballbar software records the result and saves the deviations from the nominal circle as an .xml file.

5. Experimental Results and Analysis

5.1. Laser Tracker Measurement Uncertainties

The measurement uncertainties of the laser tracker can be estimated using a mathematical model of the instrument. The group at the University of Bath has access to the tracker model developed at the National Physical Laboratory [17] by Forbes et al, which allows the simulation of tracker measurements.

Using the NPL model and the manufacturer's specifications, the measurements in the experiment are simulated using a single tracker station. The model produces covariance matrices for each of the measured points, which can be visualized as uncertainty ellipsoids as shown in Figure 6.

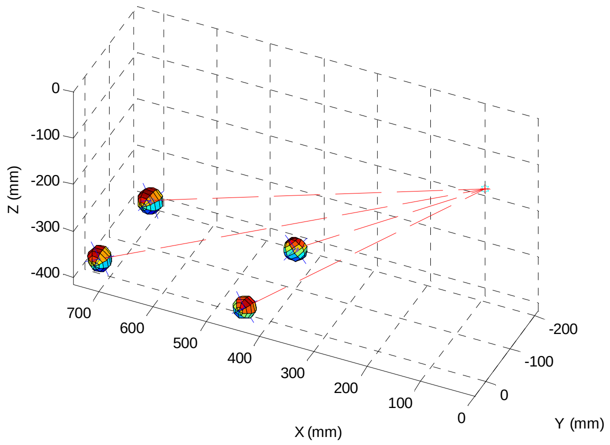

Figure 6 - Simulated tracker measurements using NPL code

The simulation shows that the laser tracker measurement uncertainty for the path accuracy experiment is on the order of 7 to 8µm. Since the ballbar test is within the same volume, the measurement uncertainty will be similar.

5.2. Path Accuracy Results

The path accuracy experiment is specifically designed to study the effect of feed rate on the machine path accuracy when laser tracker compensation is enabled. To compute the path deviation, the recorded path needs to be compared to the nominal path. A transformation matrix is calculated using a simple least squares best fit of the 4 path vertices of the end of the line segments to the nominal points. The transformation matrix is then used to move the recorded path measurement.

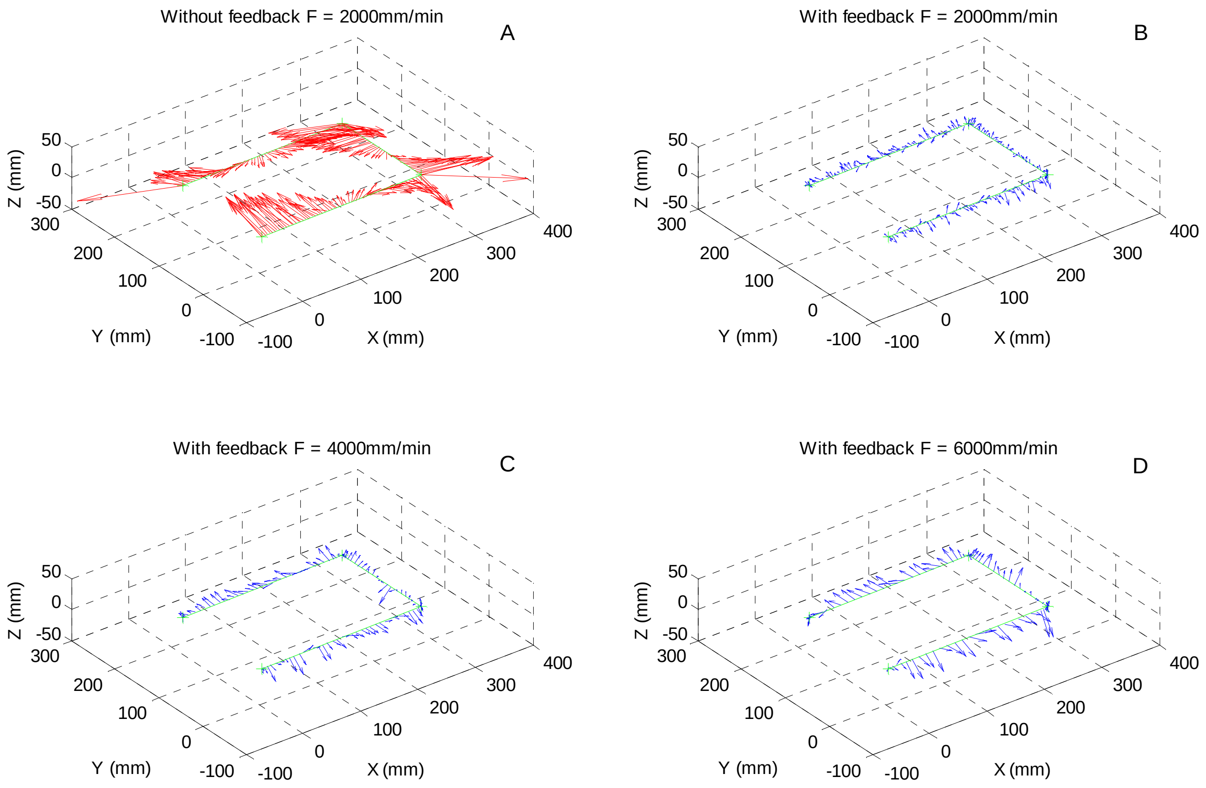

Figure 7 - Exaggerated (x1000) deviation from nominal path. A) Without feedback 2000mm/min, B) Without feedback 2000mm/min, C) With feedback 4000mm/min, D) With feedback 6000mm/min

Figure 7 shows a qualitative plot of the deviation vector exaggerated 1000 times, showing large error in the path in the X-Y plane without error compensation and significant reduction of path error when real-time compensation is enabled. The differences can be seen more quantitatively in Figure 8, where the absolute deviation from the nominal path is plotted against distance along the path. It is clear to see that real-time compensation reduced the path error at all feed rates. With compensation, the error at 6000mm/min is still much lower than the error at 2000mm/min without compensation. The discontinuities in the graph are the result of projection of the position error to the end of the line segments.

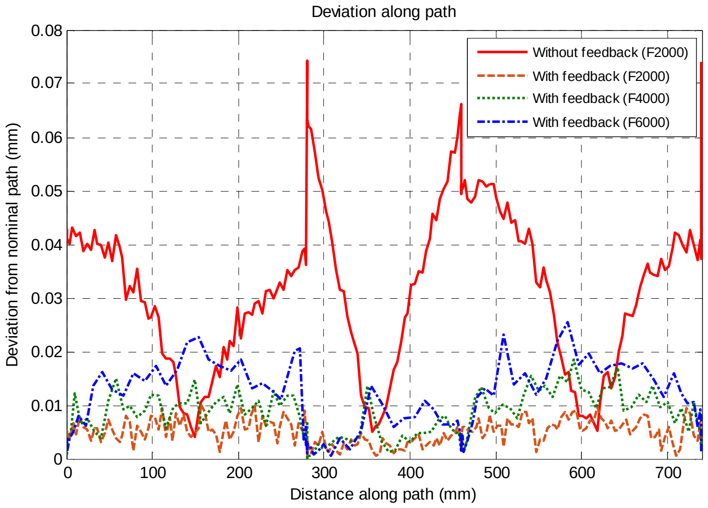

Figure 8 - Absolute deviation from nominal path for different feed rates

The path deviation can be analysed statistically by comparing the cumulative distributions (Figure 9), showing that as the feed rate increases, the path accuracy decreases. The 95 percentiles path deviations with real-time compensation for 2000, 4000, 6000mm/min are 0.009mm, 0.015mm, and 0.022mm respectively, compared to 0.058mm at 2000mm/min with no compensation. The increasing feed rates reduces the effectiveness of the compensation, since the compensation loop operates at the same rate regardless of the feed rate, therefore at faster feed rates the system has less time to respond to detected errors. This results in an apparent change in the slope of the cumulative distribution.

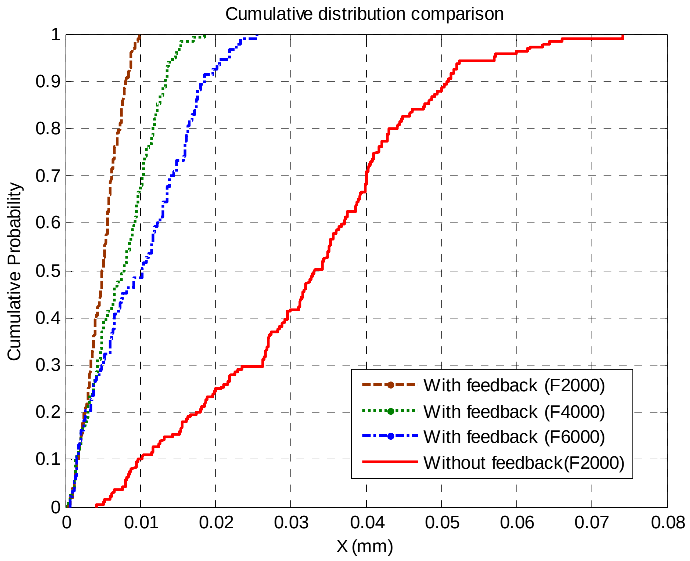

Figure 9 - Cumulative distribution of path deviation for different feed rates

5.3. Ballbar Test

While the path accuracy test demonstrates the effectiveness of real-time laser tracker compensation, it is never-the-less based on the measurement from the laser tracker. It is therefore important to have an independent instrument that can verify the performance of the system without having to rely on the laser tracker.

While the Renishaw software does not allow direct comparisons between sets of ballbar measurements, it records the deviation from the nominal circle in an .xml file which can be parsed extracted and processed. Using these files, the circular deviation comparisons between tests with and without real-time compensation is plotted in Figure 10 (polar plot) and Figure 11 (linear plot).

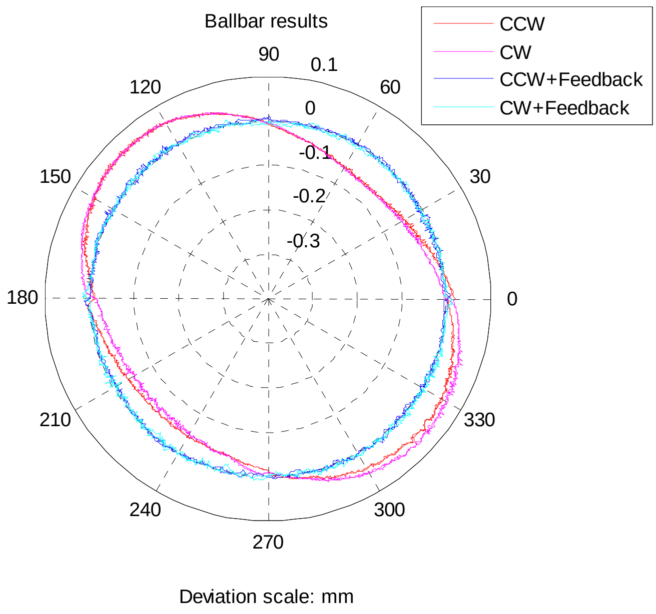

Figure 10 - Ballbar test comparison (polar plot) for 1000mm/min feed rate

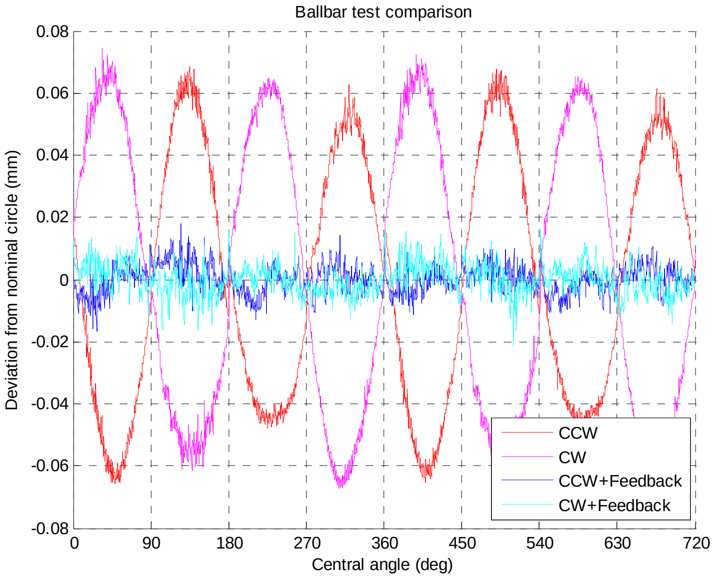

Figure 11 - Ballbar test comparison for 1000mm/min feed rate

From the Figure 10, without compensation, it is possible to see that the machine has a large X-Y axis squareness error, which causes the deviation to be elliptical, and back lash causes offsets between the clockwise (CW) and counter-clockwise (CCW) deviations. The accuracy of the machine is significantly better when real-time compensation is enabled. The quantitative difference between the two tests can be easily seen in Figure 11, in which the squareness error appears as a sinusoidal deviation.

The comparison in cumulative distribution form is shown in Figure 12. The 95 percentiles path deviations with real-time compensation is less than 0.01mm, compared to > 0.06mm with no compensation. The differences in the CW and CCW for the uncompensated experiment show that there is a hysteresis effect affecting the path accuracy, likely caused by backlash. The result in Figure 12 is very similar to the laser tracker measurements in Figure 9. Therefore it has independently confirmed the previous results.

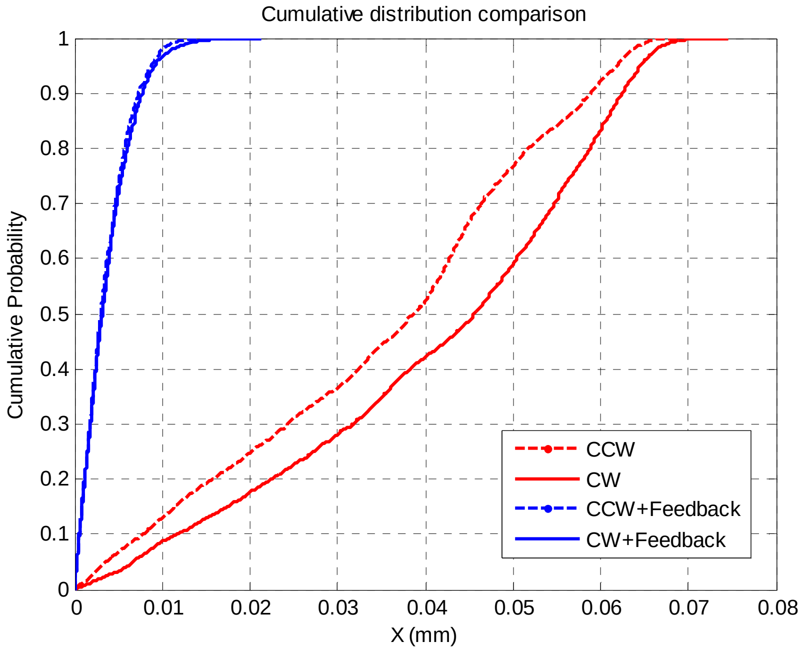

Figure 12 - Cumulative distribution of path deviation comparison for 1000mm/min federate

6. Summary and Discussions

This paper has described the working principles and dynamic performance assessment of a prototype 3-axis machine tool with real-time laser tracker error compensation. This metrology assisted machine tool can be thought off as an accurate end-effector for use within a Measurement Assisted Assembly cell, delivering localised, high accuracy tool control within large working envelopes of tens of meters.

The dynamic path accuracy experiments have demonstrated that the laser tracker real-time compensation produced extensive improvements in accuracy. This experiment showed that at 6000mm/min feed rate, there is a nearly 3 times lower path deviation when real-time compensation is enabled, and considerably more when the feed rate is lower. Using a Renishaw ballbar, we have independently confirmed the dynamic performance of the machine, showing nearly the same results as the laser tracker measurements in the path accuracy test.

The novel research described in this paper is a significant technical development that demonstrated the feasibility of the proposed methods, and can have wide scale industrial applications by enabling low cost and structural integrity machine tools to achieve positional accuracies that were the preserve of expensive machines. The outcomes of the research and the overarching concept of measurement-enabled production has generated significant interest in industry, due to the potential to increase process capability and accuracy which in turn reduces production times and defective parts.

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