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3-D Cartesian Co-ordinate Laser Interferometer Tracking System

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Abstract

This paper presents a simple approach to construct a 3-D laser tracking system based on Cartesian co-ordinates. This system employs a laser interferometer for displacement measurement as well as a reference datum to perform the automatic tracking of a moving object, a Co-ordinate Measuring Machine (CMM) as the tracking mechanism and an analogue PID controller to control the tracking system.

1. Introduction

The accuracy of a machine tool determines the quality of products produced and also the ability for economic productivity. A machine can be operated to meet the designed accuracy only under the specified working conditions. However, in the real world it is often difficult to achieve the desired accuracy due to the complexity and interactions of various factors involved. Error sources in the machining process are greatly influenced by the mechanical and thermal loading generated from the cutting process and the operation conditions. These error sources may be divided into two categories i.e.,

- Quasistatic errors, which are defined as " *the errors of relative position between a tool and a work-piece and these errors are varying slowly in time and are related to the structure of machine tools itself* " [1]. The error sources include; the geometric/kinematics errors of the machine, the errors due to static and slowly varying forces such as the dead weight of the machine's components and over-constrained slides and those due to thermally induced strains in the machine tool structure.
- Dynamic errors, which are caused by sources such as the spindle error motion, self-induced and forced vibrations of the machine structure, controller errors and deflections under inertial forces.

The quasistatic errors, which are related to the geometric and kinematics variations of the machine tool, vary slowly with time and dominate nearly 70% of total errors of numerically controlled machine tools [1]. Among the machine error sources, stationary geometric errors and thermally induced errors of machine linkages are known to be key contributors.

The calibration techniques guided by usual standards [BS3800, Part 2 (1991): ISO 230-2, Part 2 (1988)] use static measurement cycles. In general, a machine axis is moved to the target position and measurements are recorded. Errors are estimated by a generalized geometric error model. For a 3-axis machine tool, there are 21 error components from the geometric error model consisting of six error components along each axis and three squareness errors. The model of movement errors (translation errors and rotation errors) of each axis, and squareness errors between each two axes are derived by using the homogeneous transformation metrics based on the assumption of small angle approximation. Most of the error components can be measured using a laser interferometer system except for ROLL errors.

The static measurement technique offers good results for compensation but it is obviously very time-consuming and labor intensive. For the last few decades, many efforts have been made to improve the calibration efficiency by error modeling techniques to identify error parameters with a minimum number of measurements. The positions of a standard artifact are measured to compare with the nominal positions of machine tool and then error parameters are determined from a set of model equations. Ferreira et al. [2, 3] introduced the quadratic model for the geometric error of machine tools. They further extended the model, generalized the concepts to Nth order of quasistatic error model and verified the first order model on a three-axis CNC machining center (see references of Kiridena et al. [4, 5, 6]). Recent advances in the laser interferometer technology used for machine calibration allow data to be captured dynamically. Dynamic calibration overcomes the inherent problems of static calibration, being quick to perform and providing detailed information on the machine performance. Dynamic machine calibration on one axis movement has been reported by Postlethwaite et al. [7].

Laser tracking technology has been developed in recent years and has already had an impact on robot calibrations. There are three types of laser tracking systems based upon three metrological principles, triangulation, multi-lateration and spherical co-ordinate. In common, all systems have a tracking mechanism to lock a laser beam onto a moving retro-reflective target. Then, the position of the robot is calibrated by either known linear scales or a laser interferometer or the combination of the two. Gilby and Parker [8] in 1982 described the principle of a laser tracking triangulation system in which two identical tracking heads follow a common target attached to a robot. Each head has two distinct mirrors mounted on two orthogonal rotation axes. The positions of the mirrors are servo-controlled to maintain the retro-reflected laser beam aimed at the center of the target. The knowledge of the mirror angles and tracking offsets allows the determination of one line of sight. Combining two lines of sight, one from each head, with the knowledge of the relative location between the heads provides a means to calculate the position of the target by triangulation. With this method there is no laser interferometer involved and Mayer and Parker [9] reported an application of such a system. The multi-lateration method, on the other hand, defines a 3-D position of a robot by the intersection of three or more surfaces such as spheres. It usually requires more than one interferometer system to measure the position. Greenleaf [10] used four single mirror laser tracking interferometers and a common cat's eye target to provide µm accuracy. Lau et al. [11] reported a LITS where a laser interferometer is accurately pointed, by means of a two-angle servo-system, to a reflector attached to the robot's wrist. The measurement of the length of the laser beam and the two angles of the positioning device gives the position of the retro-reflector in spherical co-ordinates. Shirinzadeh [12] recently reported a laser-interferometer-based tracking system to follow a retro-reflector target in spherical co-ordinate. In this system, a CCD camera is employed to capture the return-beam for dynamic measurements.

All laser-tracking systems offer a continuous measurement in a large volume. Systems based on interferometer techniques are sensitive to the loss of tracking. With the spherical co-ordinate systems, the measuring process has to be reset if the tracking beam is interrupted/blocked accidentally. This involved moving the target back to the pre-calibration position to repeat measurements. The accuracy of this pre-calibration will affect greatly the accuracy of later measurements. This is not the case with the triangulation method where absolute readings can be taken as soon as tracking is restored. But those systems generally require more than one laser stations which are more difficult to manipulate and control. Both the triangulation and spherical approach have the ultimate precision based on their angular measurement systems.

In an attempt to overcome the necessity for the pre-calibration process, a laser interferometer tracking system based on Cartesian co-ordinates has been developed. The origin of the co-ordinate system can be set anywhere convenient for the working volume of the measuring system. The linear axes of the tracking mechanism provide a good datum to align the laser beam and thus facilitate the ease of integration or removing. Moreover, the tracking mechanism offset and the beam misalignment are static errors which can be compensated via calibration. These benefits however, are at the expense of the measuring volume and possibly the dynamic performance. Tracking in Cartesian co-ordinates has the lowest ratio of measuring volume to size in comparison with other systems. The measuring envelope is limited by the active size of the X-Y stage, which has to be optimized among the accuracy, dynamic response and portability of the system. However, these factors tend to favor small and compact size systems, which are more attractive to the machine tool calibration in shop-floor situations.

2. Cartesian Co-ordinate 3-D Laser Tracking System

2.1 Configuration and Principles

As shown in Fig.1, the system consists of a laser interferometer (HP5528A) for dimension measurement, a Coordinate Measuring Machine (CMM) as a tracking mechanism for X-Z movement, a servo-controller and a host computer. Details of the optical-layout configuration are given in Fig.2. The LIS measures the accumulated distance of a target and the movement of the tracking system. A two-axis position sensor, the four-quadrant-detector (4QD), monitors the movement of target. The circuit that is shown in Fig.3 amplifies the position signal of laser spot on 4QD: An analogue PID controller controls the tracking mechanism, the CMM, to follow the target. The target movement will cause the laser beam to move as shown in Fig.2 by arrows at the return beam. If the target moves in positive direction of X-axis, the laser spot on the 4QD will be shifted to negative direction of X-axis and the servo-loop control will move the CMM in positive direction of X-axis to follow the target. The direction of the laser spot movement due to the target movement is summarized in Table 1.

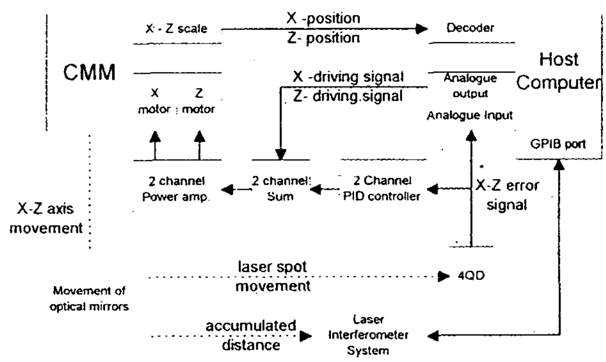

Fig. 1 Configuration of 3D-LITS

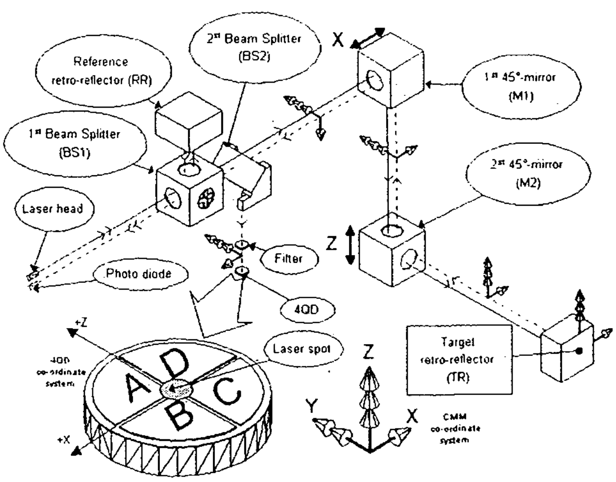

Fig. 2 Optical layout of 3D-LITS

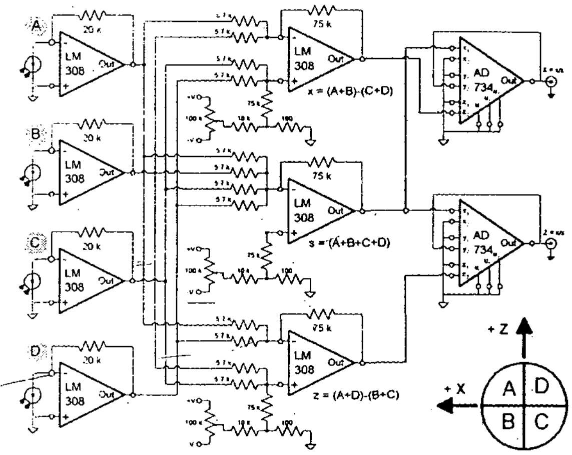

Fig.3 Amplifier circuit of 4QD

Table 1. Summary of laser spot movement direction

Target Movement	Laser Spot Movement on 4QD	CMM Movement
+X	-X	+X
-X	+X	-X
+Z	+Y	+Z
-Z	-Y	-Z
+Y	No	No
-Y	No	No

The host computer controls the system operation and reads the position of tracking mechanism and accumulated distance from LIS. The target position is measured in space by using two 45°-mirrors (M1 and M2) which reflect the measuring laser beam along the three axes (X, Y and Z) of Cartesian coordinate system. Each mirror can be moved along one linear axis, the coordinate of target is determined from the position of these two mirrors and the accumulated distance. The X and Z positions of the target are the X and Z positions of mirrors and the Y position of the target is determined by the accumulated distance minus X and Z positions. Because the measuring beam travels along X, Y and Z-axes, the dead-path of LIS is the accumulated dead-paths of the 45°-mirror movement in X and Z-axes, which are 150 mm and 50 mm respectively. The LTS monitors the return beam by using the 4QD. When the target moves, two movement signals from 4QD are used to control two 45°-mirrors to follow the target. Since the tracking system is a part of LIS, which is in Cartesians co-ordinate configuration. This system is called *'Cartesian 3D Laser Interferometer Tacking System'* (Cartesian 3D-LITS). With this configuration, there is no need for the pre-calibration process and any point in the measuring space can be reset to act as the reference point, which is the same as three-axis CNC machines.

2.2 Measurement and Control Configuration

Fig.4 shows the detail connections of the hardware for the measurement and control system. There are three cards on the expansion slot inside the host computer. The HP 5528A is connected to the host computer via GPIB ports on both sides. The address of the GPIB on HP 5528A is set to 1. The data collection and control commands are sent through the GPIB port. The maximum data reading rate from the HP 5528A is dependent on the data measuring type but for displacement measuring, the maximum speed is 40 data per second.

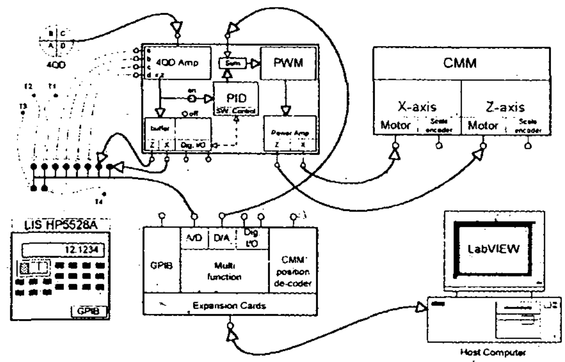

Fig.4 The layout of Measurement and control system

The decoder card counts the changing position of the CMM's linear scale in real time and collects the accumulated results in its buffer memory, which is on the decoder card (1 count equal 1 μm). The computer can read the CMM position from the buffer memory at any desired time, the resolution of the CMM position is 1 μm. The data acquisition card, PC30FA, is used to control and measure many signals.

The analogue input is used to read each segment voltage of the 4QD, X and Z-axis error signals from the 4QD and four temperature sensors. Each of the analogue inputs is connected as single ended, sharing the common analogue ground. The 4-segment voltage of the 4QD, A, B, C and D, are read into analogue channels 2, 3, 6, 7. Error voltages of X and Z-axis are read into channels 4, 5. The temperature sensors, T1, T2, T3 and T4, are read into channels 9, 10, 11 and 12.

The digital I/O port_1 is used to read the status of the PID control circuit and the command to control the PID controller is sent through the digital I/O port_0. The PID controller can be selected to switch on/off the I-mode and D-mode, separately.

There are two control modes for the tracking system of the 3D-LITS, one is manual mode and the other is tracking mode. Manual mode can move the CMM to any position by using the button on the motor control box in the main screen. Tracking mode is used to perform automatic tracking. In manual mode, the X and Z-axis motors of CMM are driven by the signal from the analogue output channels 0 and 1 of the multi-function card, respectively. The analogue signals from the multi-function card pass to the pulse width modulator circuit (PWM), so the amplitude of the analogue signal is changed to the width of a square wave. It is sent then to the power amplifier and on to the motor. In tracking mode, the error signals from the 4QD pass to the PID controller and the PID controller will send the driving signals to control the X and Z-axis motors for tracking the target.

2.3 System Software

The measurement and control systems were controlled by host computer. The software program for operating the whole 3D-LITS has been developed based on a commercial package LabVIEW (Laboratory Virtual Instrument Engineering Workbench). LabVIEW is a powerful and flexible instrumentation and analysis software system which includes all tools for data acquisition (DAQ), data analysis and result presentation. The program uses the concept of graphical programming language which is called G-Program. Each function is created as a block module which is called 'VI' and is presented as a graphic block. The main program graphically assembles the VI blocks then compiles them into machine code. It is the LabVIEW version 4 that is used to develop the whole of this application program. The tracking system and measuring system can be controlled through the main program by selecting the desired button on the computer's screen which is shown in Fig.5.

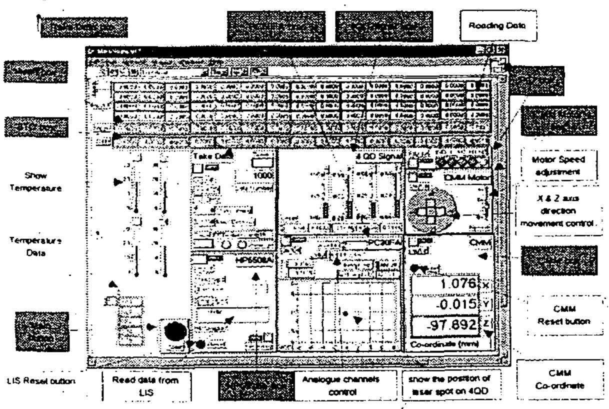

Fig.5 Main control screen on host computer

3. Conclusions

A 3-D Cartesian co-ordinate LITS has been designed and built. It consists of a laser interferometer for displacement measurement as well as a reference datum to perform the automatic tracking of a moving object, a Co-ordinate Measuring Machine as a tracking mechanism and an analogue PID controller to control the tracking system. This 3-D Cartesian co-ordinate LITS offers the following advantages:

- No need for a given reference position, which means any position can be reset to be a reference point;
- No need for the pre-calibration process prior to measurement and during the calibration process when the beam is blocked;
- The system can be performed automatically;
- The tracking mechanism is an X-Y stage, which consists of linear scale;
- The system can be constructed to be portable so that it can be used in the workshop floor for machine tool calibration;
- With a given number of measuring points, 20-30 points, 21 error parameters of a 3-axis machine can be determined by software and these parameters can be updated into the machine controller to improve the machine accuracy.

4. Acknowledgement

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