DEVELOPMENT OF A DEDICATED ROBOTIC SYSTEM FOR STRAIGHTNESS ERROR MEASUREMENT WITH DATA REDUNDANCY

Benedito Di Giacomo
Escola de Engenharia de São Carlos – USP – Av. Trabalhador São Carlense, 400 – 13566-590 – São Carlos – SP
bgiacomo@sc.usp.br

Roberto Hideaki Tsunaki
Escola de Engenharia de São Carlos – USP
rtsunaki@sc.usp.br

Fabricio Tadeu Paziani
Escola de Engenharia de São Carlos – USP
fpaziani@sc.usp.br

Abstract. *This work presents the development of a dedicated robotic system aiming at straightness error measurement with data redundancy. The proposed system consists of an industrial robot that operates a scanning device containing three displacement transducers. Measuring systems and instruments present errors that deteriorate the measurements result. Furthermore, it is known that industrial robots do not allow reliable measurements with high accuracy and good repeatability. That asks the application of error separation techniques for error decoupling, permitting to estimate part error without the likely degrading influence of system errors. Here the Three-Probe Method was used to separate part straightness error from system error. An issue arises as the method is extremely sensitive to the presence of zero-adjustment errors of the probes. Previous tests have shown that probe position cannot be easily adjusted even with the help of a sufficiently accurate reference flat surface. In this work, a self-calibration procedure was developed to minimize the influence of probes zero-adjustment errors. Computer simulation and experimental tests were performed and proved the efficiency of the proposed technique.*

Keywords*: Straightness error, error separation, multi-probe method, automated measurement and dedicated measurement.*

1. Introduction

Permanent enhancement of manufacturing processes has motivated the development of more efficient and more accurate measurement techniques. Most mechanical industries currently aim at the production of mechanical parts within small tolerances. So as to ensure product dimensional quality, industries must invest on research and construction of measurement systems that comply with the required precision levels.

Dedicated measurement instruments are employed when it is necessary to repeat a measuring procedure several times. The coordinate measuring machines (CMM) technology allows measurement of complex parts in short periods of time with high accuracy. However, in repetitive measuring runs of relatively simple parts, CMM may not be so effective and adequate as dedicated instruments. In this case, questions about utilization and convenience of CMM may arise, for example, concerning the number of parts to be measured (Hocken, 1995). Alternatively, dedicated measuring instruments can be used to evaluate individual characteristics on large lot size, providing efficiency and quality to the measuring process.

Instruments commonly used in measuring procedures, such as straightedges and reference gauges, present systematic errors (Whitehouse, 1976). Additionally, measuring procedure itself is influenced by random errors due to environmental changes and vibration. Therefore, data sets originated from a measuring process present a degree of degeneration due to the influence of errors from the measuring process itself. So, error separation methods were developed to minimize such damaging influences.

Error separation methods can be categorized as either multi-orientation or multi-probe techniques. Reversals are multi-orientation methods that allow separation between part error and instrument error by means of the manipulation of one degree of freedom of the system, except for the transducer sensitive direction (Bryan and Carter, 1989). A comprehensive review of several reversal techniques that can be applied to a wide range of situations in industry can be found in (Evans *et al.* 1996).

Multi-probe methods require the acquisition of redundant data on the part and besides, depending upon the type of the measured error, a specific sensorial arrangement is needed. Several multi-probe methods were proposed to accomplish straightness error measurement and the most prominent are the two-probe technique (Tanaka *et al.* 1981; Gao and Kiyono, 1996) and the three-probe (Tanaka and Sato, 1986; Gao and Kiyono, 1997).

This work presents an automated multi-probe measuring system dedicated to the purpose of measuring straightness error. The instrument is composed of an industrial robot that operates a dedicated measuring device containing three inductive sensors. Analogue communication between the robot and a microcomputer was established using an electronic interface to allow data acquisition and proper control of manipulator movements. Simulated and experimental results are presented.

2. Automated and dedicated measuring system

Importance has always been given to the statement that robots can perform long-term activities more rapidly than human operators, being more consistent and reliable. Robots can also operate in insalubrious environments.

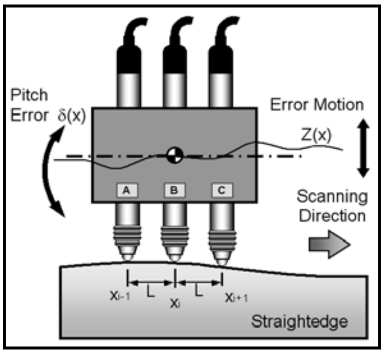
The utilization of robots on the execution of dedicated and repetitive measuring work presents some advantages over human labour, namely, enhanced efficiency, exclusion of operator influence, quick execution of programmed tasks and quick reprogramming for several tasks.

Nevertheless, the majority of robots currently in operation in industrial environments are position-controlled machines. Friction, backlash, vibration, clearance in drive systems and deflections of the robot arms are responsible for the poor absolute positioning accuracy of most of the present-day robots (Van Brussel, 1990). Accuracy is hardly ever quoted by the companies and it usually is much worse than the robot repeatability. The production of high repeatability and high positioning precision robots is limited and very expensive. Despite these important drawbacks, robots can still be used for high precision tasks.

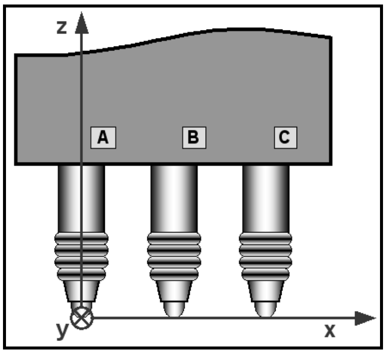
To make measurements independent from the robot accuracy, the application of some error separation technique becomes necessary to decouple workpiece errors from the motion errors of the robot system. According to Whitehouse (1976), the distance y between an observed profile and a given reference can be expressed by the equation $y=d+mx+cx^2$, where d, m and c correspond to separation, inclination and curvature between part and reference, respectively. Four probes are needed to allow the identification of all variables and, from the point of view of measurement with redundant data, using four probes provides improved redundancy and, consequently, better results from the error separation processes. However, studies have showed that second order terms of the evaluated error component on a machine tool do not cause significant variation of the error (Di Giacomo et al, 1997). Thus, the utilization of three probes is sufficient to allow straightness error estimation with good accuracy.

The *Two-Probe Method*, which provides separation of tool motion straightness error from artefact straightness error, is the simplest multi-probe method. Two displacement sensors are moved along the motion direction of the tool, scanning the straightedge in regular intervals that correspond to the distance between probes. However, the two-probe method is unable to eliminate possible deleterious influences from rotational movements of the machine carriage.

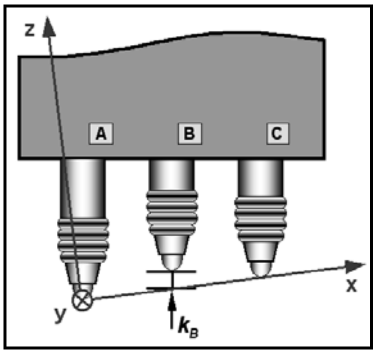
The *Three-Probe Method*, described next, is capable of eliminating the influence of rotational errors and straightness errors of the probing system, allowing detection of part straightness free from the deterioration caused by the measuring system. Figure 1 (a) shows the operational principle of the three-probe method.



(a)



(b)



(c)

Figure 1. (a) Three-probe method for straightness measurement; (b) Ideal reference system; (c) Proposed system

The readings of sensors A, B and C, represented by DA, DB and DC, can be expressed as a function of system errors, at position i: Let X_i be the straightness error of the workpiece to be evaluated, Z_i the probing system error motion, $-\delta_i$ and δ_i respective displacement at the probes A and C tips due to pitch on the scanning direction of the probing system and k_B the axial positioning error of probe B related to a reference system with origin in probe A zero-reading. The extension of axis X was set to intercept probe C zero-reading. The difference between probe B zero-reading and axis X cannot be determined by any practical means (Gao et al, 2002). In the proposed method, probe B zero-difference, k_B, is self-calibrated and its effect on the profile result is minimized. Fig. 1 (b) shows the ideal reference system, which is unattainable, and Fig. 1 (c) shows the proposed reference system that accomplishes the real aspects of probe positioning in multi-sensorial straightness measurement. We propose that probe readings can be individually written by:

$$\begin{aligned} DA_i &= X_{i-1} + Z_i - \delta_i \\ DB_i &= X_i + Z_i + k_B \\ DC_i &= X_{i+1} + Z_i + \delta_i \\ i&=1,\dots,n \end{aligned} \tag{1}$$

where n is the number of points sampled by the measuring system. The system above can be represented by a matrix arrangement as follows:

$$[A] \cdot \{e\} = \{d\} \tag{2}$$

where $\{e\} = \{X\ Z\ \delta\ k_B\}^T$ is an array that contains the variables to be identified, $\{d\}=\{DA\ DB\ DC\}^T$ is the measured displacements array and $[A]$ corresponds to the coefficient matrix of the system.

Solving (2) yields decoupling between part straightness error, measuring system motion error, probing device pitch error and axial positioning error of central probe.

3. Simulation and experimental tests

The ability of the method to separate and fit the part straightness error, the robotic arm error motion and probing system pitch was evaluated by means of computational simulations and validated by experimental tests.

Simulated readings were generated by the combination of individual errors and consist of discrete values. By hypothesis, probe *B* is not influenced by pitch errors of the probing system, so that rotation happens always around the central point, and data perceived by probe *B* is given by the sum of part straightness error and robot error motion. Data from probes *A* and *C* were generated by summing straightness error of part, robot motion error and sensor tip displacement due to pitch of probing system. Fig. 2 shows simulated readings *DA*, *DB* and *DC*.

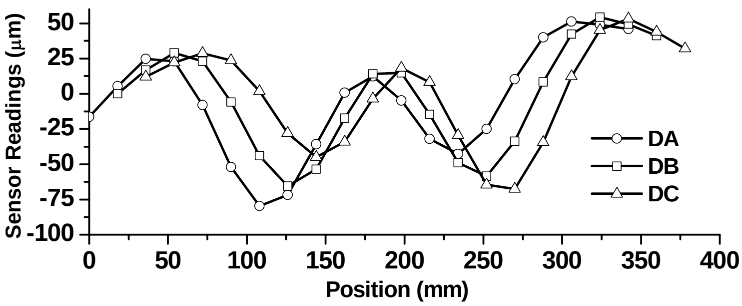


Figure 2. Simulated sensor readings

By means of the application of the proposed error separation method to the simulated data, individual errors were determined and displayed in Fig. 3.

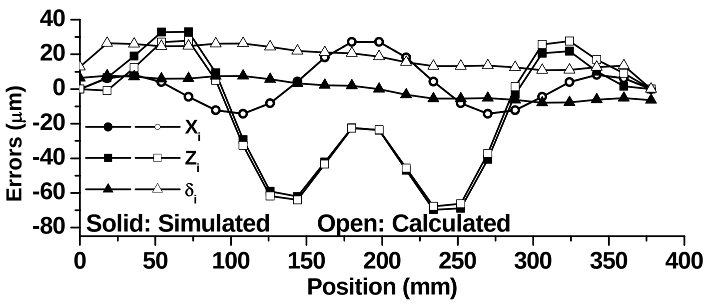


Figure 3. Simulated and calculated errors

It can be noticed that the amplitudes of robot and part errors calculated by the proposed error separation method are in accordance with the simulated values. Simulated and calculated part error curves are almost superimposed to each other, and appear to be the same curve on the graph. Robot simulated and calculated errors present minor differences, which do not change the overall error value. It must be observed, however, that there are differences between simulated and calculated pitch errors. The difference, that was already expected, can be credited to the smaller data redundancy of initial and final points. It must be emphasized that our main concern resides in accurately identifying part error, instead of robot and pitch errors.

Although simulation results demonstrated very promising applicability of the proposed method, sets of experimental testing on previously known profiles were accomplished in order to evaluate the efficiency of the method in practical situations.

The measuring interval was set to 18 mm, which is the distance between probes. The LVDT type displacement transducers present resolution of 0.2 µm over a measuring range of ± 2 mm and tip radius of 1.5 mm. The probes were connected to the measuring interface and to a microcomputer by means of a 12-bit resolution AD/DA acquisition board to provide conversion of the analogue signals from probes into digital signals to the microcomputer. Fig. 4 shows the complete measuring system.

Two steel artefacts were employed in the experimental tests. Both artefacts had been machined to present pronounced straightness error. The intentional deviations were accomplished as follows: firstly, the steel part was shimmed with thin pieces of plastic film on the magnetic table of a grinding machine. When turning the magnetic table on, the steel bar would bend due to the attractive force. Then, the part was ground as usual and became straight within the limits of the grinding process. After machining, the magnetic table was turned off and the artefact was released from the attractive force and restored to its original tensional state. Since the artefact was straightened when tensioned, it exhibited smooth straightness error after the release. Both artefacts were previously evaluated by means of the reversal technique on a coordinate measuring machine.

The measuring procedure began with the activation of the robot arm through the AD/DA communication in order to place the probing system at the artefact at the starting point of the measurement. Fig. 5 shows the probing system located on the measuring surface.

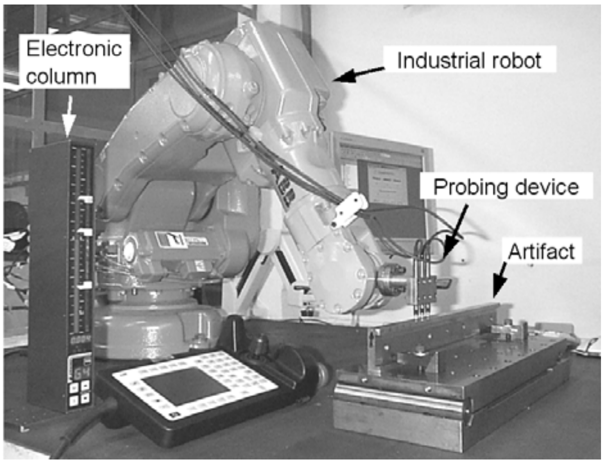


Figure 4. Measuring system

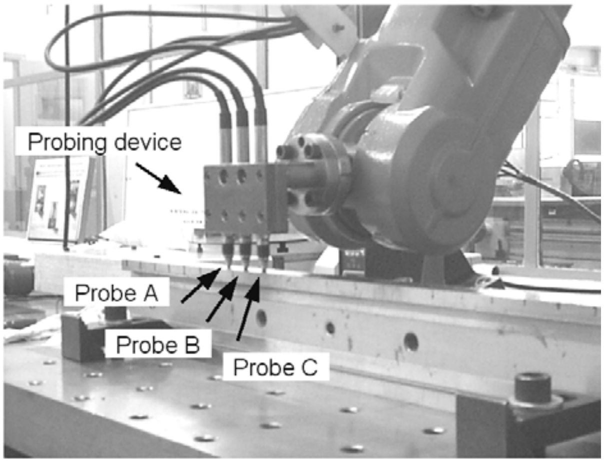


Figure 5. Probing device and artefact

The probing device was then moved along the length direction at intervals of 18 mm. Sensors readings were collected at each step via AD/DA interface. Measurements can be performed either on step-by-step mode or on the fly. Fig. 6 shows readings DA, DB and DC.

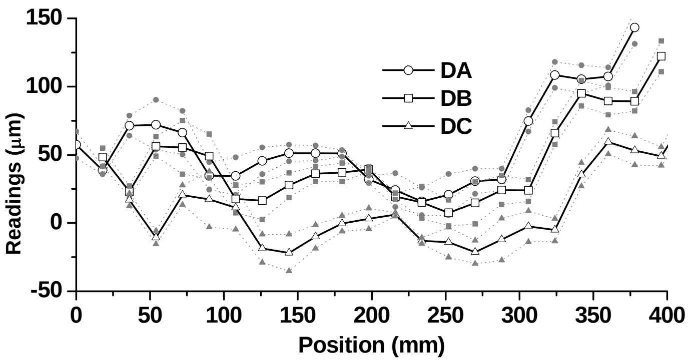


Figure 6. Sensors readings

The proposed error separation method was applied to the data of five forward and five backward measurements. Elapsed time for the execution of the whole procedure was 12 minutes. It must be mentioned that the process still demands a moderately long time to be completed. The authors expect that run time can be considerably reduced by means of the process optimisation.

4. Results and discussion

The obtained results from the application of the proposed error separation method are shown next. The straightness error of the measured artefact was evaluated over 378 mm of measuring length. Fig. 7 shows the error values both by the proposed system and by reversal technique in the CMM.

It can be seen that the results produced by the proposed multi-probe method are consistent and compatible with the results obtained by the reversal technique. The measured straightness errors of the steel artifact by means of the proposed system was about 37 μm, roughly the same value as obtained by the reversal method, despite the fact that there is a slight difference between the profile curves.

Standard deviation using the proposed method was nearly 3 μm of magnitude and standard deviation of the reversal result was approximately 1.5 μm although is was not shown for aesthetic reasons.

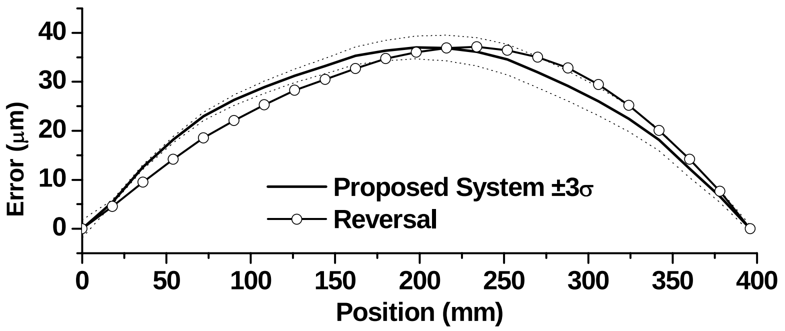


Figure 7. Straightedge straightness error

Figure 8 shows the robot motion error as separated by the proposed method compared to the one provided by a laser interferometer calibration.

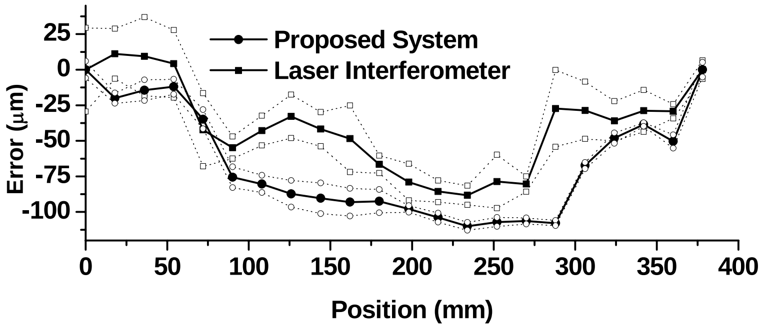


Figure 8. Robot error motion

It can be observed that the curves of Fig. 8 present similar behaviour along position axis. The observed discrepancies may be due to measurement on slightly different lines of action.

Probing device pitch errors by the proposed technique and laser interferometer is shown in Fig. 9.

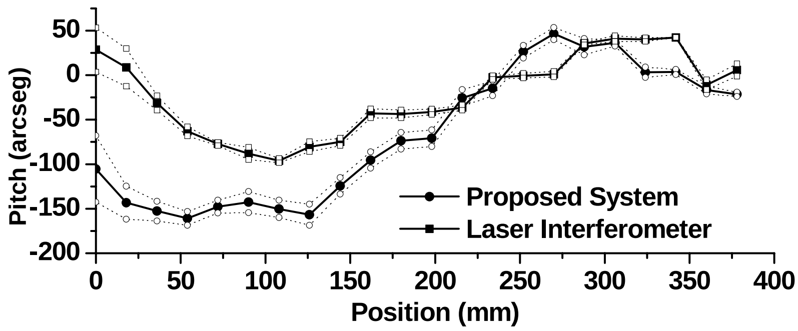


Figure 9. Probing device pitch errors

The difference between lines in Fig. 9 can be ascribed to probing device rotational attitude at the starting point of the measuring process.

Supplementary experiments were carried out so as to explore the method capabilities.

A second artefact, which was manufactured to present a more pronounced straightness error, was evaluated and the result is presented in Fig. 10.

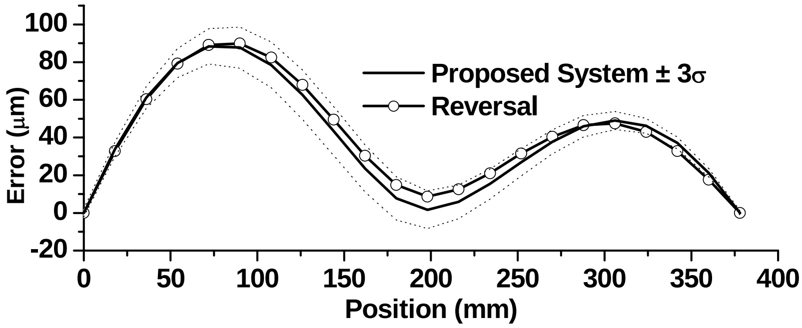


Figure 10. Straightness error of second artefact

It can be seen in Fig. 10 that the results produced by the proposed system are in good accordance to the ones provided by the reversal method. The measured straightness errors of the second steel artifact using the proposed system was about 88 μm, whilst the reversal technique yielded approximately 90 μm. Standard deviation for the proposed method was about 2.5μm and standard deviation of the reversal result was approximately 1 μm, which is not shown in the graph.

5. Conclusion

This work presented an automated measuring system that consists of an industrial robot operating a device that encloses three displacement sensors. An error separation method, based on the three points method, was developed. Separation of part straightness error from the out of straightness of the robot motion and probing device pitch error was attained by means of the proposed system. Computational simulations ensured the applicability of the method.

Experimental testing was carried out to evaluate the proposed system at the specific task of estimating straightness error of some test artefacts. Achieved results for straightness error by the proposed method were consistent with the ones obtained from the application of the reversal method on a CMM. Robot motion error and probing device pitch error were compared to the respective laser interferometer measurements and they were proved consistent. The results were considered of good quality.

It was shown that consistent straightness error measurements can be achieved with the use of the proposed measuring system. Although the industrial robot presents large motion errors, accurate measurements were achieved and the system may only be limited by the resolution of the probes themselves.

Several associated aspects are still being studied and shall be dealt with in future works. Other practical applications such as estimation of flatness and roundness errors, as well as measurement uncertainty analysis are also being studied.

6. Acknowledgements

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8. Responsibility notice

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