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Calibration and correction methods of spatial errors found in Cartesian manipulators

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Abstract

The paper suggests how the manufacturing process can be improved by the use of off-line programming of robots in the production line. Calibration is necessary for this strategy. Some calibration methods are noted and their limitations discussed.

Knowledge gained from research in geometric error compensation in machine tools is applied in principle to the compensation of errors in Cartesian manipulators. The method devised makes use of a compensation algorithm based on results obtained from a deviation error map. Data derived from laser measurement techniques is used for the generation of algorithms that can be integrated through the manipulator control system.

Introduction

The quality and reliability of working assemblies can be improved by manufacturing parts to closer tolerances. A possible method of achieving this is to improve the performance of robots involved in the production process.

The manufacturing potential of a company can be improved by increasing overall flexibility in the production line. This allows the company to change production quickly to suit the needs of its customers. To reduce downtime, and so become more flexible, robot programming should be performed off-line, using simulation models.

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To achieve these objectives the robots involved must be calibrated. This paper suggests some methods by which this can be achieved.

Robots in Manufacturing

Many robots in a manufacturing environment are instructed by a teaching pendant method. The operator defines all the positions and orientations of the manipulator hand required for a process. Robots intended to be taught in this way can be designed to perform with excellent repeatability values. However this method of robot programming can be inflexible; precluding small batch jobs, or imposing costly production downtime. Off-line programming can be used to reduce downtime and improve the flexibility of the production process.

Some robot simulation applications which can be used to achieve this are GRASP (Graphical Robot Applications Simulation Package), IGRIP (Interactive Graphics Robot Instruction Program), Workspace, etc. which enable an operator to test and run cycles prior to actually using the robot.

In order to gain satisfactory results from the simulation packages accurate dimensional data from the robot in question is required. This means that accuracy is of much greater importance when using off-line programming than when adopting the teaching pendant methodology. It is therefore important to calibrate and correct factors affecting accuracy. These factors are often classified into three categories:

Geometric errors have a constant effect on accuracy for a specific robot. Many of these errors can be sourced back to the manufacture of the machine. It is inevitable that the more complex the configuration of the machine, the greater the potential for compound errors.

Load compliance errors occur as a result of varying payloads acting on the manipulator structure. The payload weight and its distribution can vary widely depending upon the range of duties performed.

Load compliance errors can occur both statically and dynamically with the latter being more complex to analyse, particularly in multi-link structures.

Numerical errors occur as a result of limitations in control resolution and programming resolution. Although the individual errors may appear insignificant they can compound to create a major error source. This is of particular concern in high accuracy systems such as in the control of high specification machine tools and Co-ordinate Measuring Machines (CMMs).

A fourth type of error has often been overlooked in the fields of robotics. High cutting forces mean thermal effects are generally more

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significant in machine tools than robots, however a robot operating under heavy loads may generate significant induced heat from the motors.

Previous research into thermal errors in machine tools by Allen *et. al.* [1] resulted in a novel, indirect method utilising two separate thermal and distortion models. This could equally be applied to Cartesian manipulators such as gantry robots and CMMs for the correction of thermal errors.

Approach To Robot Calibration

The field of robot calibration exemplifies the diverse nature of research. Many different methods for directly measuring the spatial position of a robot end effector have been developed. These can be broadly divided into two categories; contact and non-contact sensors.

Jiang, *et. al.*, [2] review several measuring techniques, ultimately providing a table listing the advantages and disadvantages of several calibration methods. Some of the systems discussed are the dial indicator, ball-bar, LVDT, acoustic sensor, optical scanners, expert vision systems, theodolites and proximity transducer system.

Also discussed are the five techniques which Brown [3] stated can be used to calibrate using a laser: time of flight, phase modulation, triangulation, optical encoding and interferometry.

Of these methods Brown suggests that the first two give low measurement resolution. The optical encoder method suffers measurement error, in the same way as all contact sensing methods, by artificially constraining the movement of the machine.

The remaining two methods of laser measurement have both been adapted into commercial systems. A single tracking interferometer can be used to derive polar co-ordinates (e.g. SMART) or several such systems can be used to take measurements. The redundancy of the data can then be used to check the results.

A triangulation method using laser beams without interferometric capabilities, but resolving spatial co-ordinates using the angular data has also been developed by Mayer [4].

The above methods rely upon the ability of the sensor to track the manipulator hand throughout the robot working volume. Direct measurements are taken throughout the working volume of the manipulator which can then be used to create an error map.

In the laser-based systems a potential problem is the need for the line from the sensor to the manipulator to be unobstructed throughout the working volume. If, for example, a supporting strut impedes the direct line from the sensor to the manipulator hand, data for that position cannot be taken.

The University of Huddersfield (UoH) has created a novel technique for machine tools where measurements are taken using a laser interferometer in a single line for each axis. The data can then be extrapolated using an appropriate algorithm. Attempts will be made to adapt this technique to robot systems. Initially this will be directed towards the bridge/gantry robot configuration, but work to cover non-Cartesian robot configurations such as polar, tripod and hexapod configurations is intended.

Current Calibration Methodology

The device used for calibration must be chosen while bearing in mind the way in which it will be employed. Current commercial methods for calibrating robots are limited in that they only partly correct geometric and load compliance errors.

Pathre [5] used a pair of electronic theodolites for calibrating a system which was modelled using the IGRIP simulation software. The robot was calibrated for geometric and non-geometric errors in two separate tests:

A. The manipulator is commanded to move through a sequence of movements whilst the tool centre point (TCP) is commanded to stay in one position. Any movement of the TCP is due to joint offset errors.
B. The TCP is commanded to move away from a zero reference point and then returned to the reference point. Any deviation between the initial and final position is said to have been caused by backlash. This test is repeated for each of the joints.

The accuracy of this calibration is limited insofar as a complete representation of these errors cannot be seen throughout the whole working volume. The calibration method is simplistic in that it assumes a linear relationship of inaccuracies between measured points.

GRASP follows a similar technique to that used in IGRIP. In this case the robot's TCP is commanded to several points within the working volume. These points are then measured and compared to the simulation model. No mathematical correction algorithm is used.

Machine Tool Calibration

Much work has been performed in an attempt to identify and compensate for systematic errors in machine tools. Ford, *et. al.*, [6] illustrated that a universal approach to error compensation in various types and configuration of 3-axis machines could be covered by a common

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geometric algorithm. This algorithm can be simplified for some configurations of machine as terms become redundant. The correction signals generated by the algorithm could then be applied through the control system of the appropriate axis.

The error compensation system can be adapted to consider factors such as load compliance and thermal effects. Such a system has the capability to compensate, in real time, for systematic positioning errors produced by all major sources of geometric inaccuracy.

This method only requires the measurement of error components of each of the machine's axes in a single line. The time for calibration will consequently be less than methods such as the space grid direct measurement technique discussed by Bury [7] and Hutley [8] and is therefore more cost effective. The above technique can equally be applied to Cartesian manipulators.

Other analytical methods [9] for gantry robot structures offer useful guidance for improvements during the design process but are unsuitable for real time error corrections. This is because they are limited to structural analysis in identifying payload errors.

The ongoing research at The University of Huddersfield (UoH) applies the principle of error mapping. The method can be used to measure and account for errors found in Cartesian robots of gantry or bridge configuration where compensation algorithms are created to resolve geometric errors.

Investigation and Correction of Geometric Errors in a Bridge Type CMM Application

The configuration of a Cartesian manipulator and that of a bridge-type co-ordinate measuring machine (CMM) is the same. Figure 1 illustrates the typical structure. The following discussion of calibration of a CMM can therefore be applied to such a robot.

The measurement scale on each axis is some distance away from the measurement point of the probe. This construction will lead to errors due to the Abbé offset principle.

As the CMM probe moves its position is influenced by a six degrees of degrees of freedom associated with each axis of motion. These are: linear positioning, pitch, yaw, roll, side to side straightness and up and down straightness. In addition to these degrees of freedom errors also arise from lack of squareness between axes. These are termed orthogonality errors.

The 6 degrees of freedom for each axis together with the 3 orthogonality errors constitute the 21 sources of error. All of these error components will contribute to an overall error between the actual probe position and that indicated by the 3 co-ordinate scales.

The error components produced by the geometrical inaccuracies of the CMM structure can be considered to be made up of 2 components; systematic and random errors.

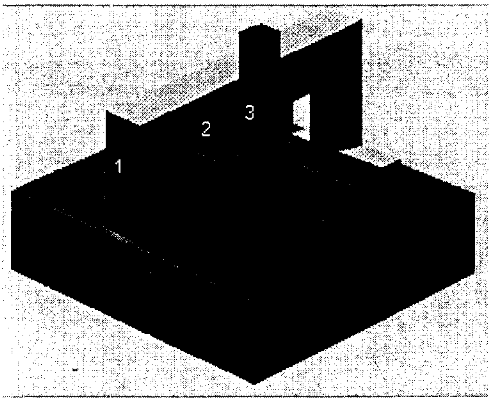

Figure 1: Bridge Type Co-ordinate Measuring Machine

Systematic errors can be measured and can be used to characterise the accuracy of the CMM. Such measurements may also be used to develop error compensation algorithms either within the CMM host computer or via an external processor. The systematic errors can be further subdivided into three more specific error components. These are non-cyclic error, cyclic error and hysteresis or backlash.

Random error components cannot be quantified directly, nor can they be compensated for by the CMM software or external processor. Such errors can, however, be represented as statistical averages and such representations can give a guide to the overall accuracy of the CMM.

The following equations give the error components in each of the three axes which interact to produce the composite systematic error.

$$\left.\begin{aligned} X_{error} &= X_{lin} + Y_{strt(X)} + Z_{strt(X)} + (X_{Pitch} \cdot Z) + (Y_{Roll} \cdot Z) + (X_{Yaw} \cdot Y) \\ &\qquad + (XZ_{sqr.} \cdot Z) + (XY_{sqr.} \cdot Y) \\ Y_{error} &= Y_{lin} + X_{strt(Y)} + Z_{strt(Y)} + (X_{Roll} \cdot Z) + (Y_{Pitch} \cdot Z) + (YZ_{sqr.} \cdot Z) \\ Z_{error} &= Z_{lin} + X_{strt(z)} + Y_{strt(Z)} - (X_{Roll} \cdot Y) \end{aligned}\right\} \quad (1)$$

Changes in the environmental temperature together with heat generated within the CMM can obviously have a significant effect on the accuracy of the machine. Ambient temperature variations can cause the machine structure to distort which can have a marked effect on the

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squareness of the axes. Linear errors can occur when there is a difference in the expansion between the CMM scales and the workpiece being measured. Thermal compensation issues are not within the scope of this paper.

The most effective current method of measuring the accuracy and identifying the errors within a CMM is to use a laser interferometer. A laser system enables position, velocity, pitch, yaw and straightness to be measured directly. Squareness can be measured using the laser system or by using a precision square. Roll measurement may be undertaken with an electronic level such as a Talyvel. Measurements can be taken uni-directionally or bi-directionally, the latter enabling hysteresis to be evaluated.

Figures 3-9 illustrate typical laser plots for a single axis of a CMM.

Research recently completed at the UoH has resulted in the development of error compensation systems which will cope with geometric, thermal and non-rigid body induced error [10]. Whilst this research is largely aimed at machine tools it is equally applicable to CMMs, and so to gantry-type robots. The research has shown that significant error reduction can be made.

Further Calibration Under Investigation

The technique described above utilises data from laser interferometry equipment, electronic levels and artefacts in order to derive a volumetric accuracy model of a machine. However the time required to fully calibrate a machine is about 3-5 days, depending upon accessibility, the size of the machine, etc.

Other work at the UoH is directed towards the use of tracking laser equipment in an effort to provide an accurate, automated calibration system. A potential benefit over the laser interferometer system is the expected reduction in calibration time and the benefits of automated calibration.

The system is very similar to one developed at the University of Surrey by Mayer, *et. al.*, [11]. Each pod can track the movement of a reflector (usually corner cube or cat's eye) by using a quadrant error detector to measure deviation of the return beam. The signal is transformed into a command to the actuated mirrors in the laser pod which adjust in order to compensate for this deviation.

The LaserTrace system (figure 2) which is used for this research employs two laser tracking pods. The position of the targeted reflector can then be found by triangulation. A comparison of the position to which the robot is commanded and the actual position will give the error at that point. An error map, assuming a linear relationship, can then be made for the machine.

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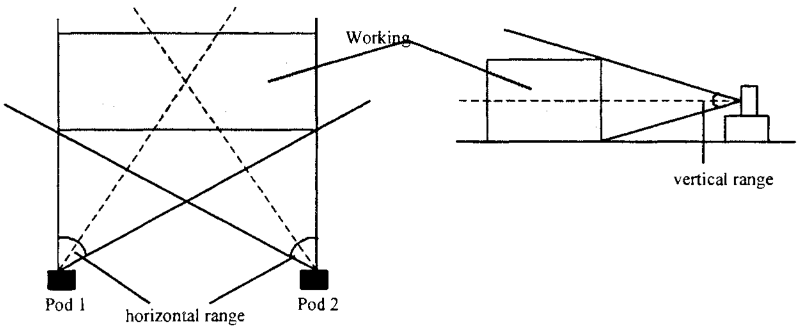

Figure 2: Configuration of a LaserTrace system

This will be compared to the volumetric error derived from equations (1) to determine its accuracy. Any reduction in calibration time will then be set against the loss in accuracy when deciding the most appropriate method to employ for each individual machine.

Conclusion

Research carried out at the UoH has shown that significant geometric correction is achievable with the limiting factors being the resolution and uni-repeatability of each axis of the machine.

Laser interferometry, electronic levels and precision squares can be used to determine the error components that make up a typical 3-axis system. From these figures the volumetric accuracy can be determined using a novel algorithm.

In an attempt to produce a calibration technique which can be implemented in a shorter time a tracking laser is being investigated. It is expected that this instrument will prove less accurate when compared to the above method.

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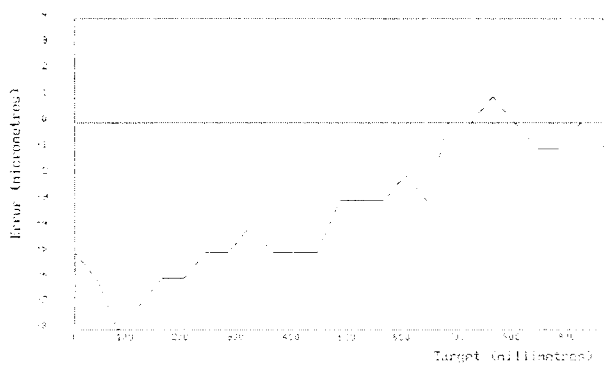

Figure 3: X Axis Linear Measurement

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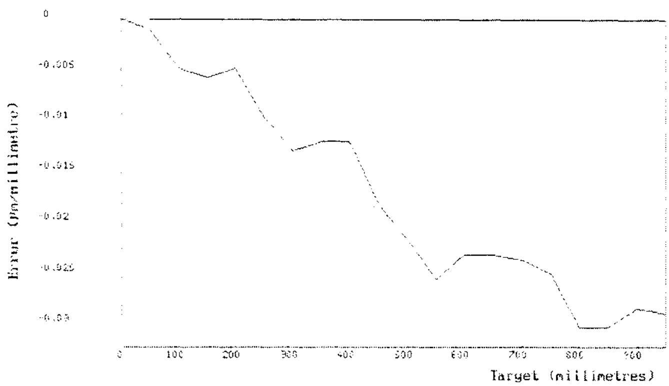

Figure 4: X Axis Pitch

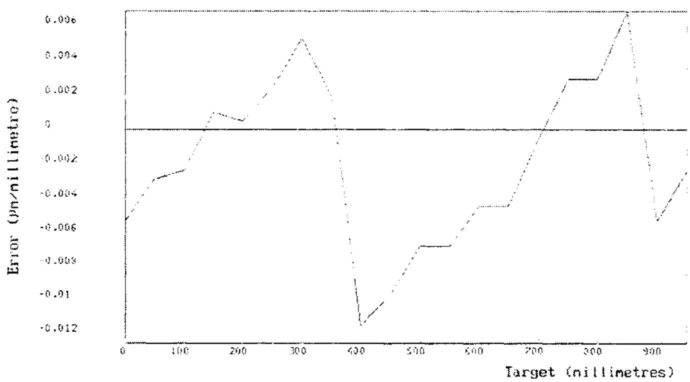

Figure 5: X Axis Yaw

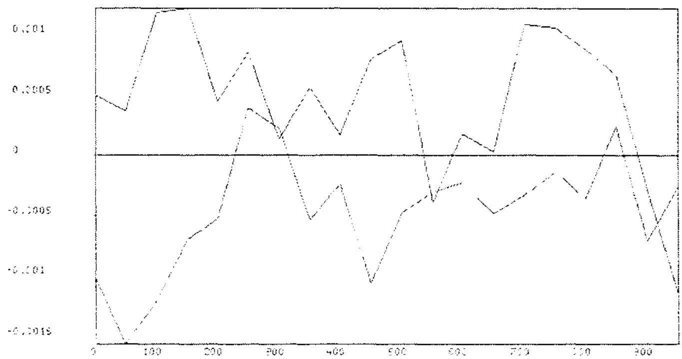

Figure 6: Bi-Directional Horizontal Straightness of the X Axis

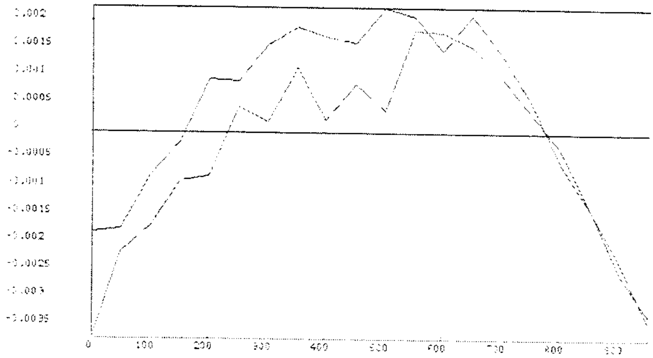

Figure 7: Bi-Directional Vertical Straightness of the X Axis

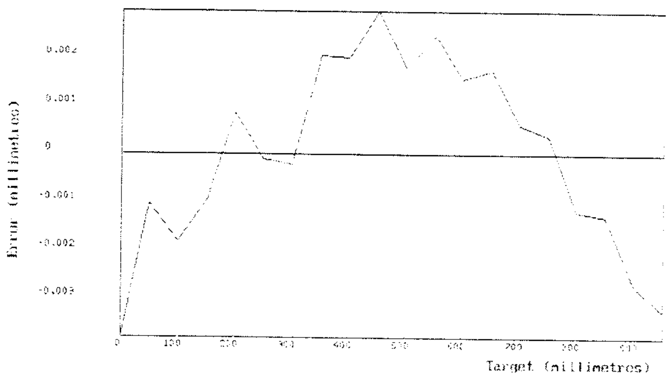

Figure 8: Z to X Squareness

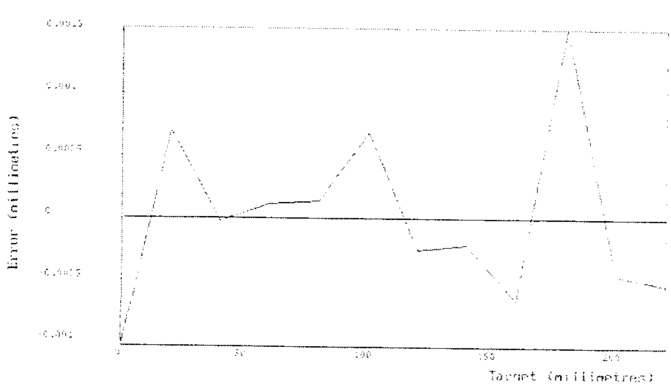

Figure 9: X to Z Squareness