Introduction

Since its first appearance in the early 1980s, interest in offline programming (OLP) has grown steadily as its benefits have become apparent. OLP offers the robot programmer a number of key benefits, most notably a reduction in the time it takes to design and program an automated robotic system. With traditional teach pendant methods the robot must be taken out of production when modifications or new programs are being generated. A demonstration by Chrysler has shown that by utilising OLP the time a robot is out of production can be reduced from between 12-18 hours to 6.5 hours for each robot. Additional figures suggest that programming using OLP can reduce programming time by up to 85 per cent for small batch programs (Wittenberg, 1995). However, due to problems associated with accurately modelling both the robot workspace and the robot itself, OLP is often still used as part of a two part programming methodology utilising traditional teach pendant methods for “on the job” moves.

When considering the robot, the main problem with respect to OLP is in creating an accurate kinematic model. Factors such as machining tolerances in the robot linkages, compliance and elasticity in the robot arm, encoder resolution, and the lack of repeatability during calibration serve to give each robot a unique signature (Van Brussel, 1990). The term calibration in this respect and throughout this paper, unless otherwise stated, refers to the method of commissioning the robot. Typically robots are factory calibrated using a fixture to determine absolute joint positioning. These positions are then marked on the robot arm linkages to aid in future re-calibration on the shop floor.

Re-calibration may be necessary during maintenance or when calibration data have been lost due to power failure. When calibrating in this environment, the marks are aligned, possibly in conjunction with a fixture, and the absolute joint position set. The robot is then considered to be calibrated.

Whereas it is accepted that industrial robots exhibit good repeatability, robot accuracy is rarely quoted and is generally believed to be quite poor, errors commonly being several
orders of magnitude worse than the robot repeatability (Mooring et al., 1991). In addition, it will usually be found that robot repeatability remains within its tolerance throughout the working envelope whereas the accuracy of the robot may deteriorate significantly towards the boundaries of the envelope.

Although this situation is far from ideal, it has in the past been accepted. By utilising the traditional “teach and repeat” method of programming, these accuracy errors have no influence on the positioning of the robot, repeatability being the important factor. Unlike OLP, this method does not require a precise Cartesian co-ordinate system. Moving the robot to its desired position using the teach pendant and recording this position will generally guarantee that the robot will return to this “taught” position to within a fraction of a millimetre.

By programming this position offline it is likely that the final position, due to the signature effect and lack of precise co-ordinate system, may be a number of millimetres away from the position that is desired. Based on these factors, it is clear that relying solely on OLP methods utilising a nominal kinematic robot model alone can result in serious positional errors.

One recent solution to this problem has been the development of calibration tools (Owens, 1994; Schroer, 1994), which result in a more advanced method of calibrating the simulation model. These calibration tools generally involve mapping the accuracy errors inherent in the real robot working envelope and using the measurement data to produce a more accurate kinematic model for use in OLP. While the claims behind these systems are impressive, it can be argued that they are bypassing the fundamental problems associated with real robot accuracy, that is, those associated with the calibration of the robot during commissioning and maintenance.

A recent study at Warwick Manufacturing Group (WMG) based at the University of Warwick has measured and compared the accuracy of a number of industrial robots. This has been conducted with a view to assessing their suitability for use in OLP.

Method

A total of three six-axis serial linkage robots have been measured, namely the Cloos Romat 310, The ABB IRB 6400S, and the KUKA KR125 (Figure 1). All three robots are measured in their unloaded state, and are commissioned using the manufacturers calibration methods.

With reference to the relevant UK and ISO standards (BS 4656, 1986; ISO 9283, 1998) a testing framework has been established. Using a Renishaw laser interferometry system, accuracy and repeatability measurements are made within a tolerance of ± 0.001mm. Each measurement is taken as part of a bi-directional run. These are conducted a total of five times with a minimum of five points. An overrun point is programmed at the end of each measurement to remove the effect of backlash when changing direction. However, due to the limitations of this measurement system only static measurements in a particular area of the envelope are taken. The measurements taken are as follows:

- Linear positional accuracy in both the X and Y axes. These are represented by raw data plots showing relative positional measurements. A system datum is taken at the axis zero point for the robot co-ordinate system.

Figure 1 The measured points for a sample run on the Kuka robot
• Straightness measurements showing deviation in the X-axis and deviation in the Z-axis when travelling in the Y direction. These are represented using the least squares fit approach. Due to difficulties in aligning the laser system with the robot co-ordinate system a correct datum line is not possible. The least squares fit approach involves defining a datum such that the sum of the squares of the distances from the data points to the line (graphically measured parallel to the Y-axis) is at a minimum. Graphically this approach is represented showing the mean straightness error for both positive and negative runs, in addition to the standard deviation for both sets of run.

Results

Cloos Romat 310
The linear positional measurements for the Cloos Romat 310 are shown in Figures 2 and 3. Both measurements have similar characteristics for the X and Y-axis. While the repeatability is within the tolerance of 0.1mm specified by the manufacturer, positional accuracy deteriorates quite significantly in one half of the measured envelope for both sets of measurements. Errors for both axes are within an error band of 1.7mm although for one side of the measured envelope this error is within a 0.5mm band.

The straightness measurements for the Cloos Romat 310 are shown in Figures 4 and 5. Deviation in the X-axis when travelling in the Y direction is within an error band of approximately 0.7mm across the measured envelope. In a similar way to the linear positional measurements, however, the accuracy deteriorates in one half of the working envelope. This error band is approximately twice that for the opposing envelope. In contrast, deviation in the Z-axis when travelling in the Y direction is similar for both sides of the envelope, this error band being in the region of 0.4mm.

ABB IRB 6400S
The linear positional measurements for the ABB IRB 6400 robot can be seen in Figures 6 and 7. Accuracy in the Y direction lies within an error band of approximately 0.5mm, this being roughly constant in both sides of the envelope. The error band is almost entirely due to backlash with an indication that this may be improving towards the boundaries. Due to limitations in the workspace for this robot, caused by its proximity to a wall, a reduced envelope has been measured in the

Figure 2 Linear positional accuracy in the Y direction for the Cloos Romat 310
X direction. Although direct comparison cannot be made with the measurements taken in the Y direction because of this, similar characteristics are evident. Measurements in this direction show an error band within 0.5mm although most of the envelope exhibits a constant error within a 0.3mm band with deterioration towards one side of the envelope.

The straightness measurements for travel in the Y direction for the ABB IRB 6400S are shown in Figures 8 and 9. Both exhibit similar characteristics but deviation in the X-axis has a larger error band than deviation in the Z-axis. This is roughly four times that of the Z-axis, maximum error being within bands of 0.4mm and 0.1mm respectively.
KUKA KR125

Linear positional accuracy for the KUKA KR125 is shown in Figures 10 and 11. Accuracy in the $Y$ direction is within an error band of 1.8mm with much of this error being evident in one side of the envelope. The error for the $X$ direction is slightly less, being within a band of 0.8mm although like the measurements for the $Y$ direction, the error band is greater in one half of the envelope. Repeatability is within the manufacturer’s stated tolerance of 0.2mm.
Straightness measurements when travelling in the Y direction for the KUKA KR125 are shown in Figures 12 and 13. Deviation in the X-axis is within an error band of 0.7mm and is almost symmetrical about the centre of the measured envelope. In a similar way, deviation in the Z-axis is almost symmetrical about the centre of the envelope although with a smaller error band, this being within 0.2mm.

Discussion of results

The results from this trial show that of the three robots measured, none exceeded a
1.8mm error band in any of the three dimensions measured, with repeatability being within the specified tolerance. While the Cloos Romat 310 and the KUKA KR 125 exhibited similar error bands, the ABB IRB 6400 appears to be the most accurate, never exceeding a 0.5mm error band in any of the three dimensions measured. It is notable that for the linear positional measurements for the Cloos Romat 310 and the KUKA KR 125, robot accuracy deteriorates significantly in one half of the measured envelope, while the same measurements for the ABB IRB 6400 have an almost constant error band throughout the envelope. The likely reasons for these errors are calibration errors on one or more joints.

Figure 9 Straightness showing deviation in the Z-axis when travelling in the Y direction for the ABB IRB 6400

Figure 10 Linear positional accuracy in the Y direction for the KUKA KR125
When considering the calibration errors responsible for the accuracy errors evident in this trial it is important to analyse the effect of each joint in turn. Analysis of the effect of a small angular error in any of the joints shows that errors in joints 1-3 make the major difference for positional errors, with joints 4-6 mainly affecting the orientation. Any error introduced into joint 1 has the effect of rotating the robot coordinate system without affecting the overall accuracy of the robot as measured in this manner. It is therefore apparent that the errors found in these results are due to errors being introduced by poor calibration on joint 2 and joint 3. Errors in these two joints tend also to introduce errors which show up as straightness errors centred on the centre of the axis system. These errors are evident in Figures 6, 12 and 13.

Conclusions and recommendations

This trial has established the accuracy and repeatability errors inherent in the modern industrial robot. While the trial is somewhat limited in that only static measurements are taken in a particular area of the envelope, it does serve to give an indication of these errors. The errors are not large and are less than those recorded for older robots (Mooring et al., 1991) and significantly lower than expected when the trials began. The results show that OLP can in fact be a viable method of programming for certain tasks where this level of accuracy is acceptable. Any improvement in robot accuracy, however, would be welcomed when utilising OLP. Whereas certain signature errors like backlash can only realistically be rectified by increasing the cost of manufacture, much of the accuracy error, it is felt, can be reduced by a more accurate method of calibration when commissioning the robot.

The serial link robots used in this trial use one of two methods of calibration. This is either by defining the axis absolute position datum using a calibration fixture, or by lining up scribe lines on each axis to achieve the same aim. The KUKA KR125 measured as part of this study for example utilises a calibration fixture. The accuracy in spite of this is comparable to the two robots calibrated using the scribe line method. This would indicate that both the tolerance inherent in the fixture and its method of fixing to the robot are introducing an error into each joint axis. In a similar way, it is doubtful that the scribe line method used on the Cloos and ABB robots is repeatable.
Accurate and repeatable positioning of these lines by the manufacturer is unlikely, as is a repeatable method of aligning these scribe marks during later calibration. It is notable that whereas the Cloos robot has a very basic series of scribe lines, the ABB robot exhibits far greater accuracy. This could indicate the importance of a precise method of absolute positioning of each robot axis during calibration.

Future work in this area will investigate the repeatability of using the scribe line method of calibration and see if by careful...
adjustment of each joint axis during calibration the accuracy of the robot can be improved.

References
