Int. J. Engng Ed. Vol. 9, No. 5, pp. 414–421, 1993
Printed in Great Britain.

Introducing Robotics through Demonstration and Performance Evaluation*

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This paper describes the development of an undergraduate laboratory to teach students about repeatabilty and statistical process control in manufacturing using an industrial robot and a specially designed repeatability measuring instrument (RMI). The RMI is described as a simple device which can be easily manufactured and used by students on any actual manufacturing facility. It provides immediate hard-copy records of an experiment and gives the student an opportunity to interpret the results into a control chart format. The experience gained with the system, including the Cincinnati Milacron T3 robot and the RMI, is described and some of the results obtained are discussed with illustrations of how warm-up drift influences robot end-effector positioning.

INTRODUCTION

AS competitiveness grows in manufacturing industries, so does the need for increased productivity, product quality and product consistency. In order to meet these growing requirements, many industries are turning to automated manufacturing processes. Since robots often play an integral role in automation, we are seeing a rapid increase in their development and use. As with many rapidly growing technologies, the problem arising in robotics is that people often fail to understand how robots fit into manufacturing and what they are capable of doing and not doing.

The recent acquisition of an industrial robot at the Department of Mechanical Engineering at Queen's University gave the perfect opportunity to introduce undergraduate students to robotics and their role in automated manufacturing. Within two years of acquiring the robot, two undergraduate laboratories have been developed and implemented: a second-year demonstration laboratory in automated manufacturing, and a third-year laboratory to explore and evaluate the performance of the robot.

The second-year laboratory utilizes the development of a manufacturing cell by two undergraduate students in their final year. The cell contains the industrial robot, a three degrees of freedom vertical mill, a programmable logic controller (PLC) and a double acting pneumatic vise. With the robot controlled by its own Acramatic control unit and the mill controlled by a personal computer, the PLC was implemented to coordinate the actions of the cell components. The students learn first hand, through demonstration and lecture, about the programming requirements and limitations of the robot and the mill and the difficulties in coordinating their actions to produce a working manufacturing cell.

The third-year laboratory utilizes a specially designed device to measure the repeatability of the robot. Repeatability is one of many important performance criteria used to evaluate the performance of a robot. As an extension of the second-year laboratory, students now learn how robots are evaluated and how statistical process control can be used to monitor their performance. Covered in the laboratory are the various sources of error in a robot and a robot system that can account for poor performance, and the many ways that have been developed to measure robot performance including the recent development of a few draft standards on performance evaluation. Specifically introduced is the specially designed repeatability measuring instrument (RMI) and its use to demonstrate the capability of the robot to position its end-effector.

The third-year laboratory is described in detail here, including a description of the RMI and some results that have been obtained with its use.

BACKGROUND

Robot

The robot used is a hydraulically driven, six degrees of freedom articulated industrial robot (see Fig. 1). Manufactured by Cincinnati Milacron in 1981, this all-revolute joint manipulator stands

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* Paper accepted September 5, 1993

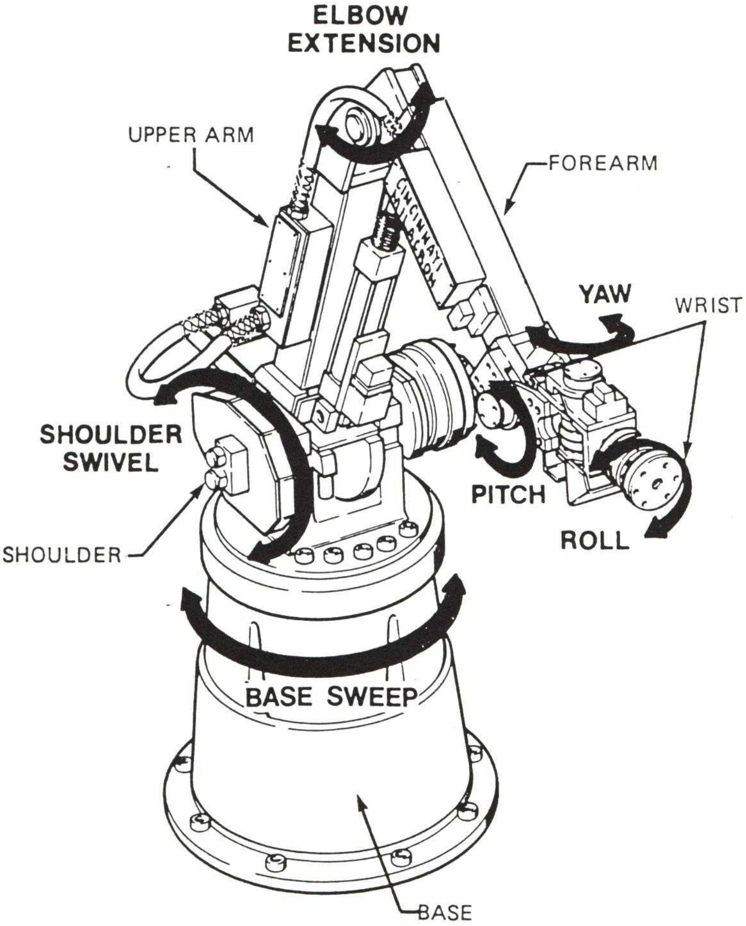

Fig. 1. Cincinnati Milacron T3 industrial robot.

about 2 m and weighs over 2300 kg. It is programmed on-line and utilizes point-to-point control. The arm is capable of carrying a 40 kilogram payload at over 1200 millimeters per second. Its size and simple programming strategy make it ideal for introducing students to robotics and demonstrating fundamentally how a robot system works (configurations, feedback control, etc.). Since the robot is programmed on-line, accuracy is really unimportant and most of the attention of the laboratory is paid to measuring its repeatability [1].

Performance Criteria

Performance parameters such as repeatability and accuracy are often confused and misused. For clarity, the following definitions will be adopted [2]:

Repeatability. Closeness of agreement of repeated position movements, under the same conditions, to the same location. Note that 'location' refers to a 3D position vector x,y,z, pointing from the robot base coordinate system's origin to the tcp (tool-centre-point) and the orientation of the tool, O,A,T, as typically described by the so-called Euler angles.

Accuracy. Degree to which the actual location corresponds to the desired or commanded location.

Accuracy is a measure of how well a robot moves to the absolute position and orientation of the taught location every time it is commanded to do so, whereas repeatability measures how well the robot returns to the taught location time after time.

Repeatability Measuring Instrument (RMI)

In order to measure repeatability, the robot being tested must be programmed to cycle its end-effector through a known path (or known set of positions) as many times as deemed necessary. At some predefined point in the program, the actual location of the end-effector will have to be recorded during each cycle. The RMI, once calibrated, attains a permanent record of the location of the end-effector for each cycle.

The RMI consists of two main components: the marker, which is rigidly attached to the robot end-effector; and the recorder, which is fixed in the robot working space at some predefined location. Fig. 2 shows a schematic of the device.

The marker consists of a 6 × 32 mm bar stock mounting bracket with holes for attaching it to the robot end-effector. Bolted to the mounting bracket is a 22 mm inside diameter tube capped at one end. Inside is a spring and a free-running plug with a needle and guide pin. The guide pin ensures that the plug does not rotate inside the tube, and the

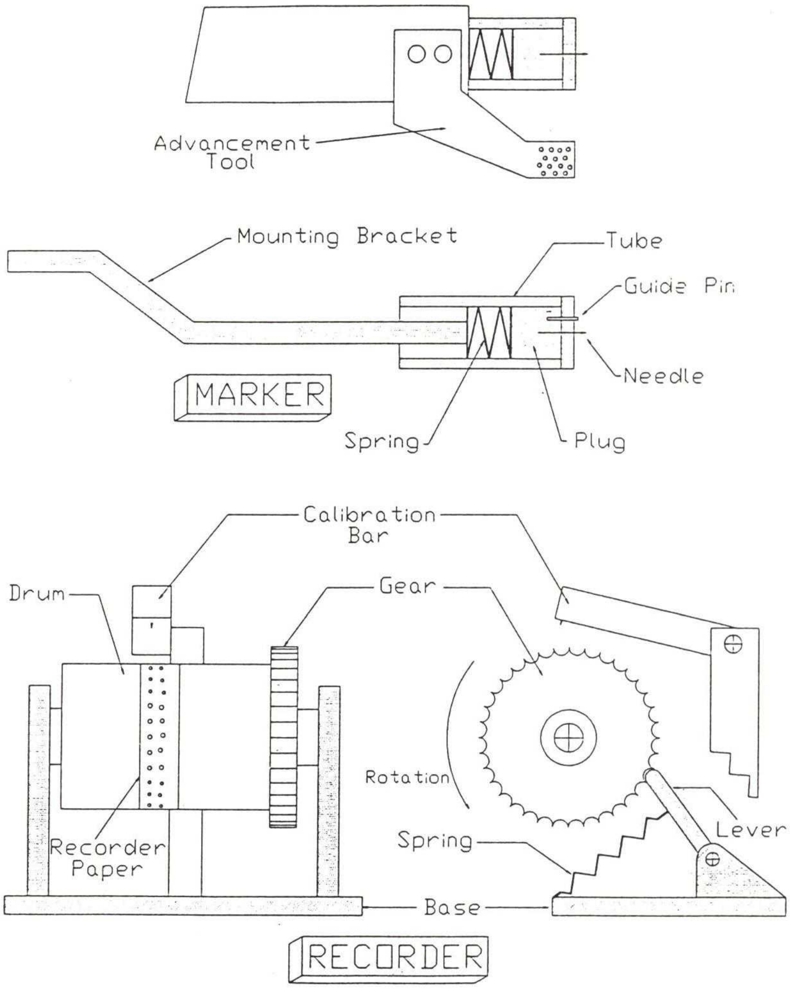

Fig. 2. Schematic of the RMI. Shown is a cut-away of the marker and the working detail of the recorder. Some components are not shown for clarity.

spring offers compliance to the plug when subjected to the forces necessary under testing. Also attached to the tube is an advancement tool which, when engaged with the outside of the drum of the recorder, rotates the drum to the next recording position. Critical features include smooth, tight motion of the plug and rigidity in the mounting bracket.

The recorder consists of an 84 mm diameter drum assembled onto a 13 mm diameter shaft fixed to two support brackets. The fit between the drum and the shaft has been specified to within 0.025 mm to prevent looseness in the drum rotation as well as brass washers and rubber O-rings between the drum and support brackets to prevent movement along the shaft. The only degree of freedom essentially left in the drum is rotational. To control how far the drum rotates consistently, an 80 tooth spur gear has been bolted to one end of the drum and a spring-loaded lever mounted to the base (see Fig. 2). With the spring in tension, it acts to 'drive' the lever forward much like a watch mechanism. With the centre of rotation of the lever and the centre of rotation of the drum brought close enough together, the two bind into each other, effectively locking the drum into position. The configuration is such that the drum can be rotated in one direction only, shown in Fig. 2 as counterclockwise, and when advanced enough for the lever to engage with the next tooth on the gear, the lever will bring the drum back and lock it into the next position. The resulting ratchet arrangement allows for 80 drum positions to be achieved consistently.

To calibrate each position, a calibration bar has been bolted to the base of the RMI. With the calibration bar effectively fixed in space, it represents a perfectly repeatable position which is recorded with a needle in the end of the bar that marks the paper at each position. The paper is fixed onto the drum which has a small diameter rubber sleeve stretched over it to prevent slippage between the drum and the needle. The 'holes' generated by the calibration bar then become the reference positions for each drum position that the robot locations (produced by the marker) will be measured from.

Critical features include constant radius in the drum, rigid calibration apparatus and no slip in the recording paper during testing. Limitations of the

RMI include 2D positional repeatability only, contact-type instrumentation and laborious data acquisition.

EXPERIMENT

Procedure

To capture the end-effector locations during each cycle, the robot is programmed to mark the paper with the marker needle held as close as perpendicularly as possible to the recorder drum. After each mark is made (or each robot end-effector location captured), the advancement tool is used as described to advance the drum one position. The robot program continues to whatever other points are necessary and the process is repeated. With the robot marks made in the vicinity of the calibration marks, the resulting recorder paper will appear as in Fig. 3.

Although there are many ways of measuring the displacements of the robot points from the calibration points, a simple and inexpensive method was developed utilizing a Nikon Shadow Graph machine and transparent graph paper. Placing the recorder paper on the Shadow Graph generates an image magnified 20×, whereupon the measurements are taken manually. This effectively makes the measuring procedure easier and increases the accuracy of the measurements by 20×. A resolution on the order of 0.05 mm can be obtained with reasonable effort.

The measurements are taken as shown in Fig. 3. With the X-axis and Y-axis drawn on the transparent graph paper, it is overlaid onto the magnified image and aligned as shown. The origin of the

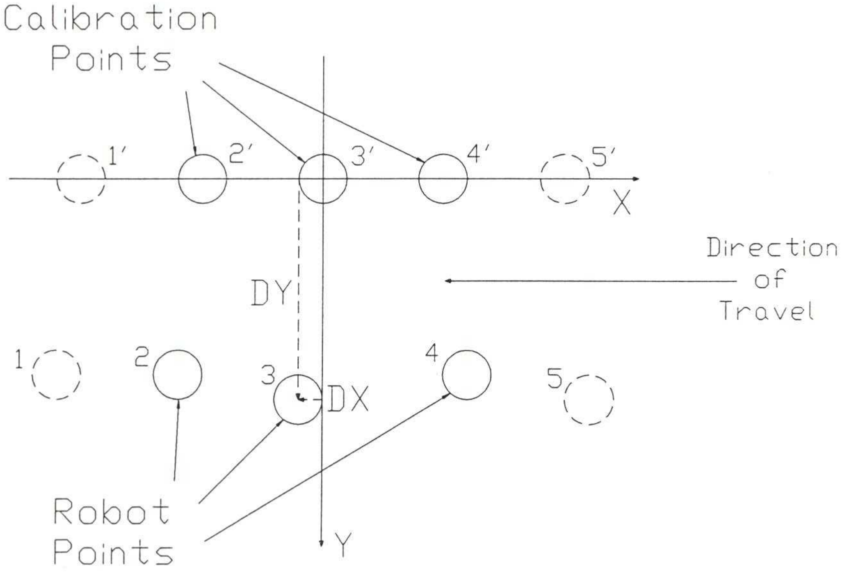

Fig. 3. Schematic of the RMI output and measuring procedure. To be recorded for each point is the displacement in both the X and Y directions of the robot points (1, 2, 3, 4, 5) from the calibration points (1′, 2′, 3′, 4′, 5′).

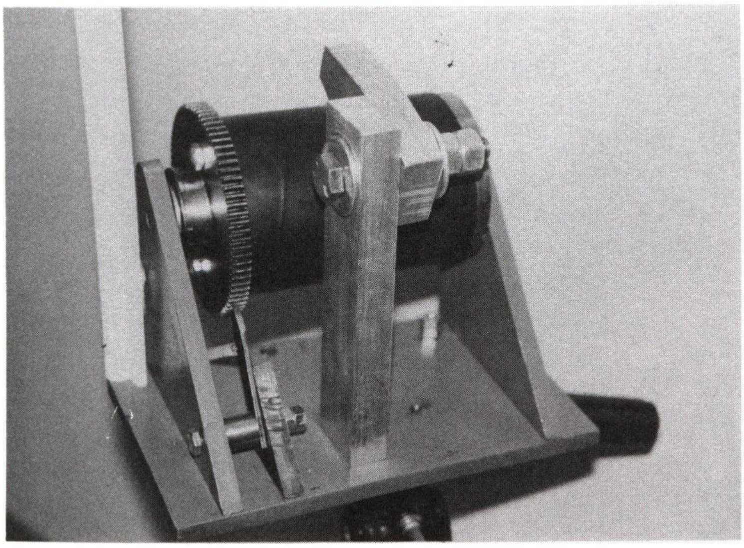

Fig. 4. Rear view of the RMI.

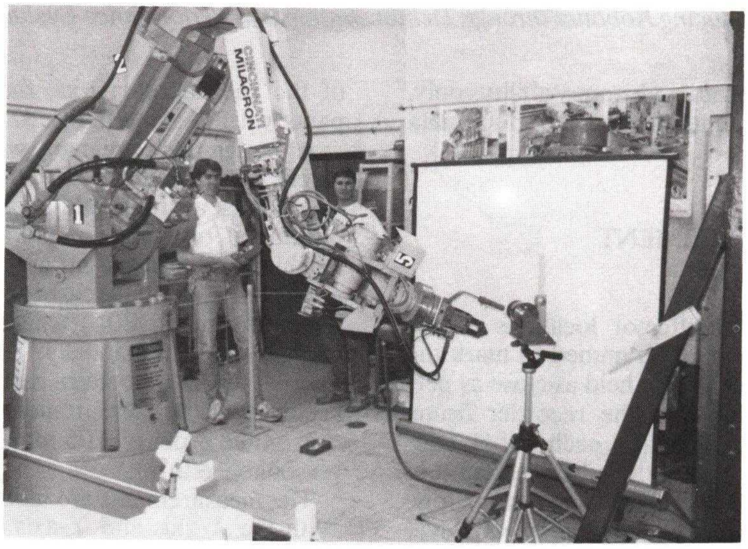

Fig. 5. Programming the robot.

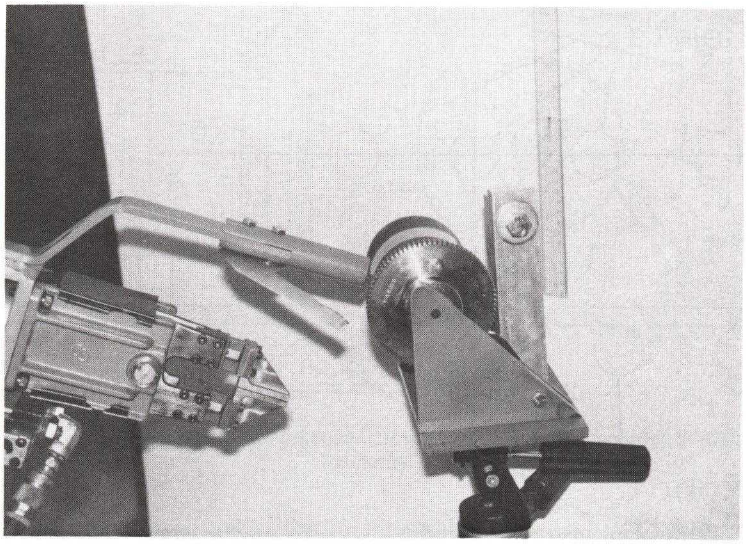

Fig. 6. Recording the end-effector position.

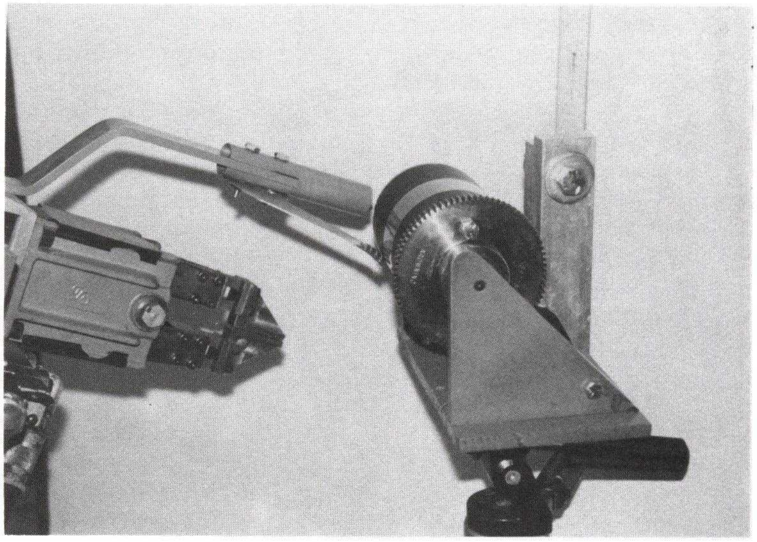

Fig. 7. Advancing the drum position.

axis is positioned as close as possible to the centre of the calibration hole being used and the X-axis is aligned through the centre of the neighbouring calibration holes. This ensures that the measurement X-axis remains tangential to the 'line' formed by the centres of the calibration holes. With the axis properly aligned, the centre of the robot hole is measured using two coordinates, DX and DY. Each robot point must be measured relative to each calibration point. It should be noted that the magnitudes of DX and DY will not be important here, but rather their respective variances.

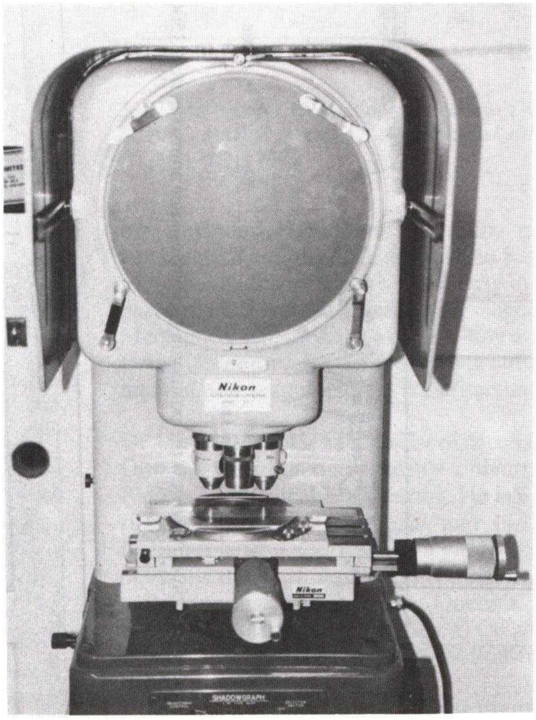

Fig. 8. The Nikon Shadow Graph.

Figs 4–9 shows pictorially the experimental procedure and apparatus used in the laboratory.

Analysis/results

The two-dimensional repeatability may be found as follows:

$$R_2 = 3\sqrt{\sigma_{DX}^2 + \sigma_{DX}^2} \qquad (1)$$

where σ^2 is the variance in the DX and DY values, and the 3 multiplier specifies 99.7% confidence. The magnitude of R_2 will then represent the radius of a circle within which 99.7% of the robot positions will be found.

The values of DX and DY can also be plotted against time (or cycle number) to allow quick visual assessment of how the robot behaves during continuous cycling and to observe the behaviour during warm-up.

Figure 10 shows the results of the robot positioning from a cold start measured with the RMI. For this test, the last two joints of the robot were not programmed to move (i.e. the yaw and the roll). The orientation of the RMI was such that the first joint (i.e. the base sweep) was primarily responsible for positioning in the Y-direction, and joints two, three and four were primarily responsible for positioning in the X-direction. The graph of Fig. 10 subsequently shows the warm-up characteristics of the base sweep as DY-values, and the coupled warm-up effect of joints two, three and four as DX-values. This is consistent with the results seen in the graph with the drifting in the DY-values being relatively smooth and continuous and the drifting in the DX-values exhibiting unpredictable and discontinuous behaviour. Furthermore, the positioning of the end-effector can be seen to stabilize after approximately 3500 s. It could be concluded then that to utilize the robots' best performance, the robot system should be allowed to warm-up for approximately one hour in this instance before using it.

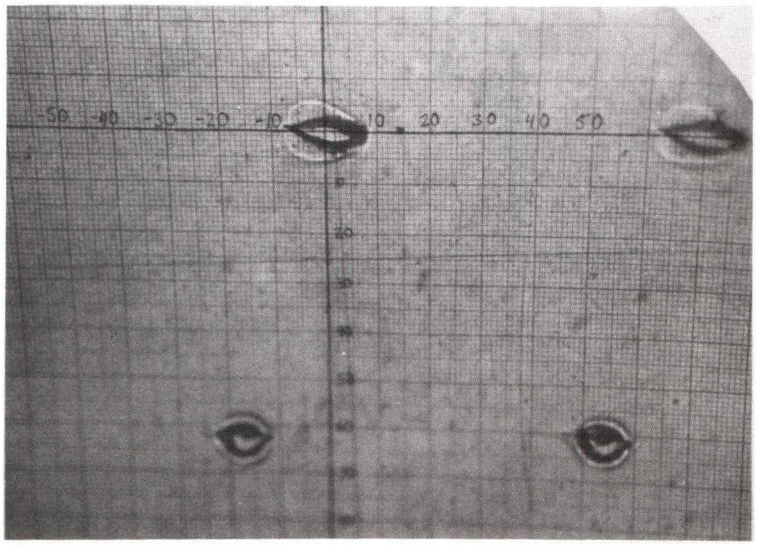

Fig. 9. Measuring the displacements.

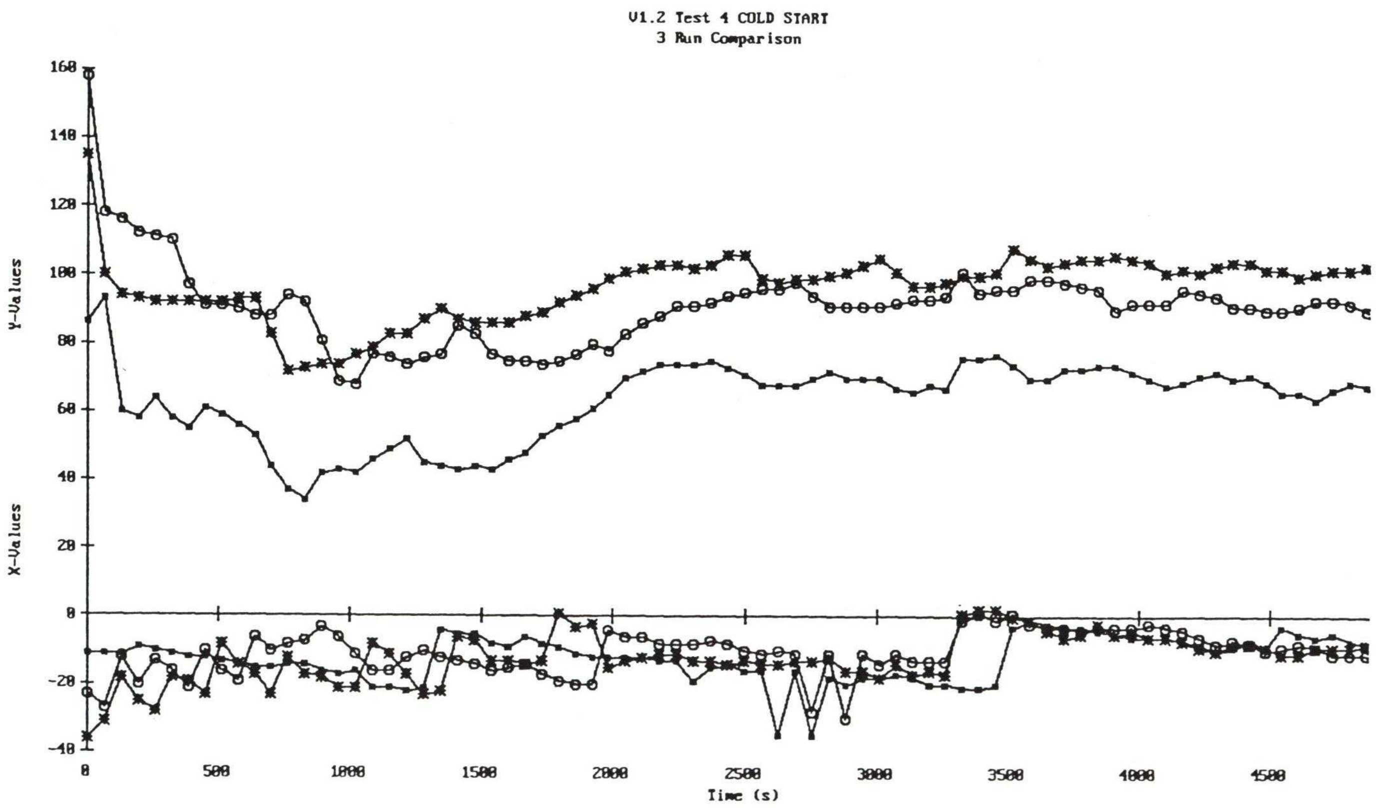

Fig. 10. DX and DY values plotted against time. Note how the positioning stabilizes after approximately 3500 s.

CONCLUSIONS

The experiment proved very successful in teaching students about robot systems and how they should be treated as an integral part of manufacturing. The need for standard performance evaluation and use of process control was emphasized to gain a better understanding of errors and limitations in robot systems. An inexpensive and relatively easy to use repeatability-measuring instrument was introduced to demonstrate and allow for a hands-on approach of how the performance of a robot can be quantified and how the information gained can be used. It was demonstrated that the monitoring of manufacturing systems, as well as their products, must be performed to ensure the acceptability of a process.

Finally, the results obtained with the RMI are quite acceptable. The success of the RMI in capturing the warm-up characteristics of a Cincinnati Milacron T3 industrial robot show that an exercise period of up to one hour may be necessary to exploit its full capability. The limitations of the RMI (i.e. contact-type instrumentation, 2D capability only, etc.) are not believed to be very significant in evaluating the basic performance characteristics used by industries in surveying robots for simple manufacturing-based tasks.

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