# CELL CALIBRATION AND ROBOT TRACKING

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Introduction: When considering off-line programming of Industrial robots, it is important that the simulated model of the robot and its environment is calibrated against the real hardware. It is well known that industrial robots have relatively good position repeatability characteristics but suffer from a lack of precision in terms of absolute accuracy. When programmed on-line, this is not apparent since the programmer intuitively moves the robot to location points which are relative to the workpiece and other elements within the cell. However, when considering off-line programming using simulation software to represent the robot and its environment, the absolute accuracy of the system becomes a critical issue. The effectiveness of off-line programming is only apparent if there is a true correspondence between the "virtual" simulation system and the "real" hardware system.

In order to provide cell calibration, it is important to be able to measure the absolute position of the robot and other strategic locations within the cell. This paper presents details of a measuring system for recording tool point absolute positions and path trajectories. It is intended that this data is then used to improve the correlation between the simulated and the real kinematics of the robot cell.

System Design Concept: The robot tracking system (ROBOTRAK) used for providing absolute position measurement is based on the principle of triangulation. The system utilises three wires, the lengths of which are continually measured over a fast time base using three measuring units placed at known locations in space. Calibration datum points fixed to the measuring units are used to set the location of these relative to each other and provide a cartesian coordinate reference framework for the absolute measurements. Through a transformation algorithm, these measurements can be referred to the world coordinates of the robot or any other reference framework if desired.

Knowing the relative positions of the measuring units and the instantaneous wire lengths, the instantaneous absolute position of the robot tool point can be calculated, (Fig 1). The calculations are based on the following system equations derived by considering the geometry of the three wires, describing three spheres, the centres of which are located at the exit points of the three measuring units. The intersection of these spheres give the absolute instantaneous coordinates as follows:

$$Px = \frac{Bx^2 + Ra^2 - Rb^2}{2\,Bx}$$

$$Py = \frac{Cy^2 + Ra^2 - Rc^2}{2\,Cy}$$

$$Pz^2 = Ra^2 - Px^2 - Py^2$$

Digital signals from encoders in the three measuring units are fed to an Enconding Interface Card located in a single expansion slot of a Personal Computer. The computer system provides data reduction, graphical analysis of results and hard copy output as well as providing a framework for test measurement control. The software provides for the data logging of absolute cartesian coordinates and their transformation to any reference frame together with time dependent data for path plotting.

The principal components of the Robotrak system may be considered to consist of three basic sub systems; the measuring units, the encoder interface card and the computer hardware / software system.

Measuring Units & Encoder Interface Card: The three measuring units consists of a storage drum, a pulley fitted with an incremental encoder and a wire guide. All three parts are mounted on a single plate.

The storage drum is used as a take spool for a constant tension “tensator” spring, which is supported on deep groove ball races to minimise torsional friction.

The main pulley and encoder unit is assembled on a single turned component which bolts onto the mounting plate. A shaft bolts directly onto the encoder and a ball race at the pulley end of the shaft. The tensator spring is bolted onto this pulley to supply the drive. Dracon cord is wrapped around the pulley and fed out through the wire guide. It is terminated using an aluminium coupling assembly.

Fig. 2 shows an assembly design drawing of the measuring units used.

The Encoder Interface Card is a three channel device used to produce a 16 bit up / down count of the measuring unit encoder values and includes interface electronics for decoding and buffering to the IBM PC Bus. The 16 bit up / down counting function is provided by three LS 2000 direction discriminator IC’s and channel decoding is done by a single LS 138 IC.

Computer System: The hardware configuration is based on a “486” PC having 4MB of random access memory a 150MB hard disk and a SVGA colour screen. The software system is written both in the “C” programming language and as a Windows application using the Visual Basic programming language.

The primary function of the software system is to provide data reduction and data logging of the absolute cartesian coordinates measured by the Robotrak system. In its simplest form, this consists of recording current tool position coordinates against a reference node number. A file is created consisting of x, y, z coordinates for particular reference locations in the robot cell. Facilities exist for providing transformation of these coordinates to any user defined cartesian coordinate system including the World coordinate system of the robot.

A more advanced feature of the software is toolpath measurement and dynamic analysis. Data is recorded over a time base to give time histories along the x, y and z axes of the measuring system. Velocity and acceleration measurement either as a resultant tool point trajectory value or resolved values in the x, y or z directions can be recorded and presented in graphical format. Also locus plots of the tool path in any of the three orthogonal planes can be given.

Performance Specification and Test Examples: In order to validate the output results from ROBOTRAK, performance trials were conducted. Particular trajectories of known velocity and acceleration profiles were set up under laboratory conditions and the ROBOTRAK system used to measure these. The output from ROBOTRAK was then compared against these known values. From these trials ROBOTRAK was found to conform to the following performance specification:

Static repeatability
Better than ± 0.2 mm within 2m x 2m x 1.2m
Variable path ± 0.32mm within 2m x 2m x 0.7m
Absolute accuracy ± 0.5mm within 2m x 2m x 0.7m

Dynamic repeatability
Same path same speed ± 0.5mm with 2m x 2m x 2m
Same path variable velocity ± 0.7mm within 2m x 2m x 2m

Maximum allowable tracking velocity = 4m / s
Maximum allowable acceleration = 10m / s$^2$

Representative test data obtained during trials on a Unimation Puma 560 industrial robot are shown in Figures 3 to 6. A simple rectangular path was programmed by teaching the Puma Robot four points. The plane of the rectangle was set perpendicular to the x-y plane of ROBOTRAK, and at an angle to the x axis. The Puma program was set at the taught points, with the exception of the start / stop point. This was chosen to show the effect of tracking around smooth corner radii. Plots of x against z and x against y are shown in Figs 3 and 4 respectively.

Both velocity and acceleration profile plots were produced and are shown in Figs 5 and 6. These plots represent the components of resolved velocity and acceleration in the x and z directions respectively.

Curret Developments and Offline Programming: In the past the system has been used for a variety of robot performance assessment tasks and can give an indication of the absolute position of the robot tool point. In this mode, the system is simply monitoring the actions of the robot. Its true benefit however is for use in improving the absolute accuracy of industrial robots by cell calibration. Significant advances have been made in recent years in the development of Robot Simulations and offline programming systems and current developments with the Robotrak system are in the integration of this system with “Workspace 3”, a PC based robot simulator. The philosophy here is to provide an integrated Cell calibration, offline programming and simulation system on an affordable PC platform. Both Robotrak and Workspace 3 have a common synergy of low cost and applicability to industrial applications such as Spot Welding, Arc Welding and other industrial processes where a positional inaccuracy in the region of ½ mm can be tolerated and where “one shot” offline programming has operational advantages. One calibration technique which appears particularly feasible for kinematic calibration involves measuring the absolute location of a series of points throughout the working envelope of the robot and mapping these to the inaccurate robot coordinates. From this data a “look-up table” is generated which through interpolation between points, gives a correction to be applied to the simulation coordinates. In this way, simulation coordinates are transformed to robot coordinates taking into account the inherent inaccuracies of the real robot system. This technique is currently being developed for use with both Robotrak and Workspace sysytems in addition to other calibration approaches.

## References

1. Baudouin, J-P. The Development and Evaluation of a Coordinate Measuring Machine based on a Triangulation Measuring Approach. M Sc. Thesis, Cranfield University, 1993
2. Newman, W. S. & Osborn, D. W. A New Method For Kinematic Parameter Calibration Via Laser Line Tracking. IEEE International Conference on Robotics and Automation, Vol 1 pp. 160-165, May 1993
3. Tang, G-R. & Mooring, B. W. Plane-Motion Approach to Manipulator Calibration. Intemational Journal of Advanced Manufacturing Technology, pp. 21-28, 1992
4. McMaster, R. S. A Low Cost, High Performance, Dynamic Testing Device for Tracking the Tool Point of Industrial Robots. Robots between Science and Technology National Conference, Milan, Italy, March 1988
5. MacArthur, G. M. The Evaluation and Development of a Dynamic Robot Testing Device. M Sc. Thesis, Cranfield University, 1988

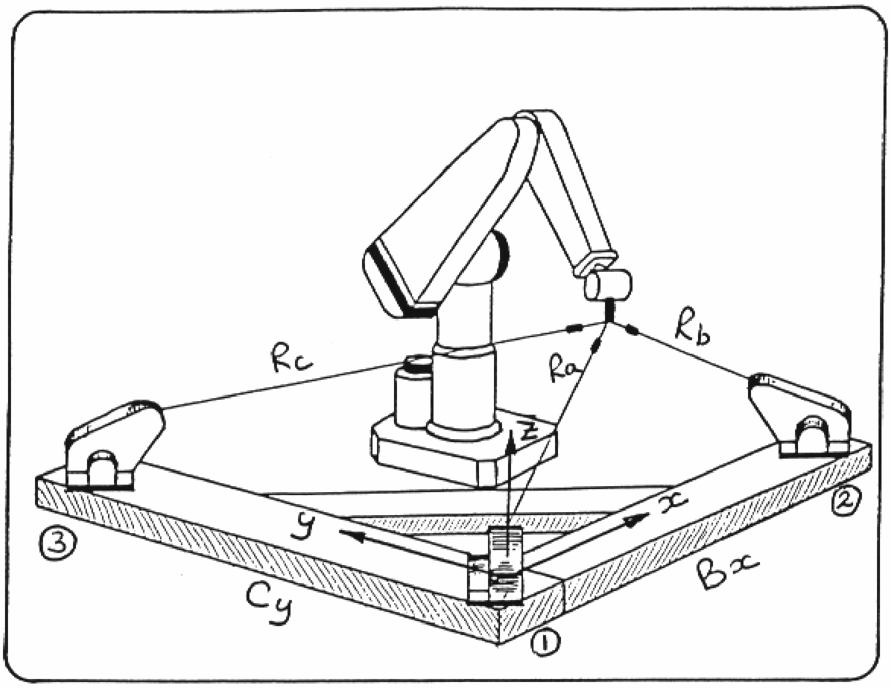

Figure 1. Diagram of ROBOTRAK Measuring System

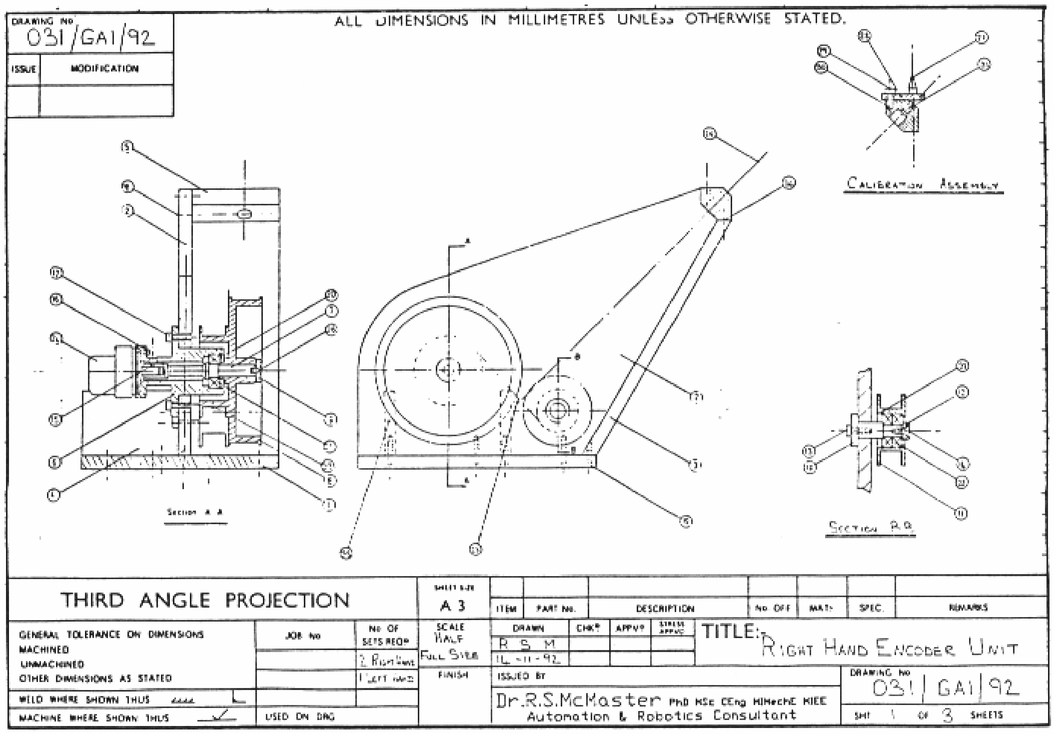

Figure 2. Measuring Unit Design Drawing

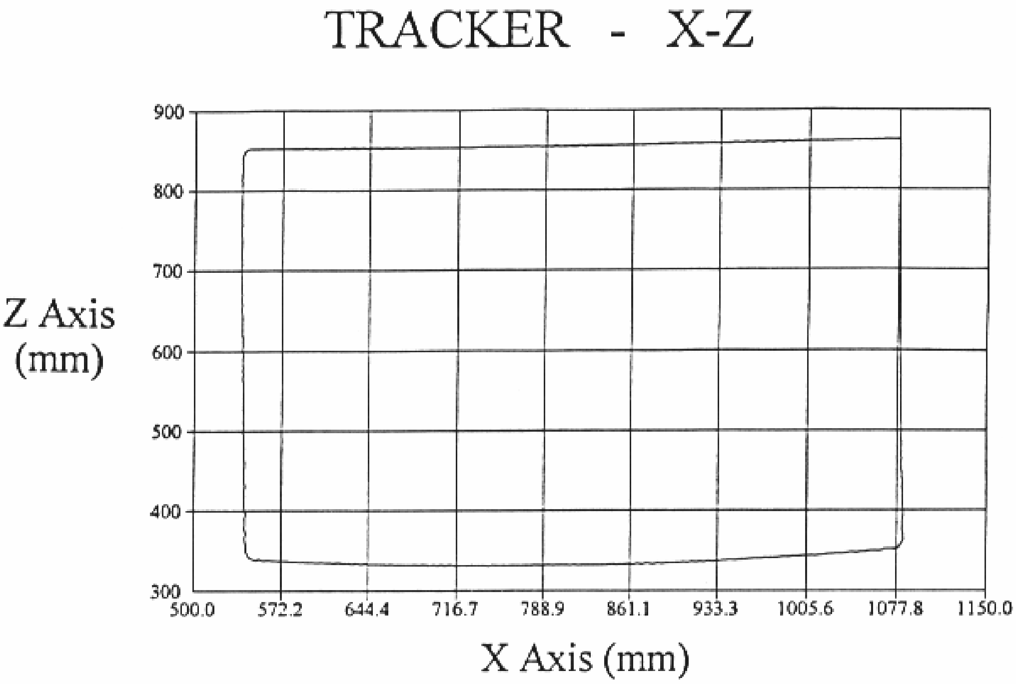

Figure 3. Locus Position Plot on the X-Z Plane

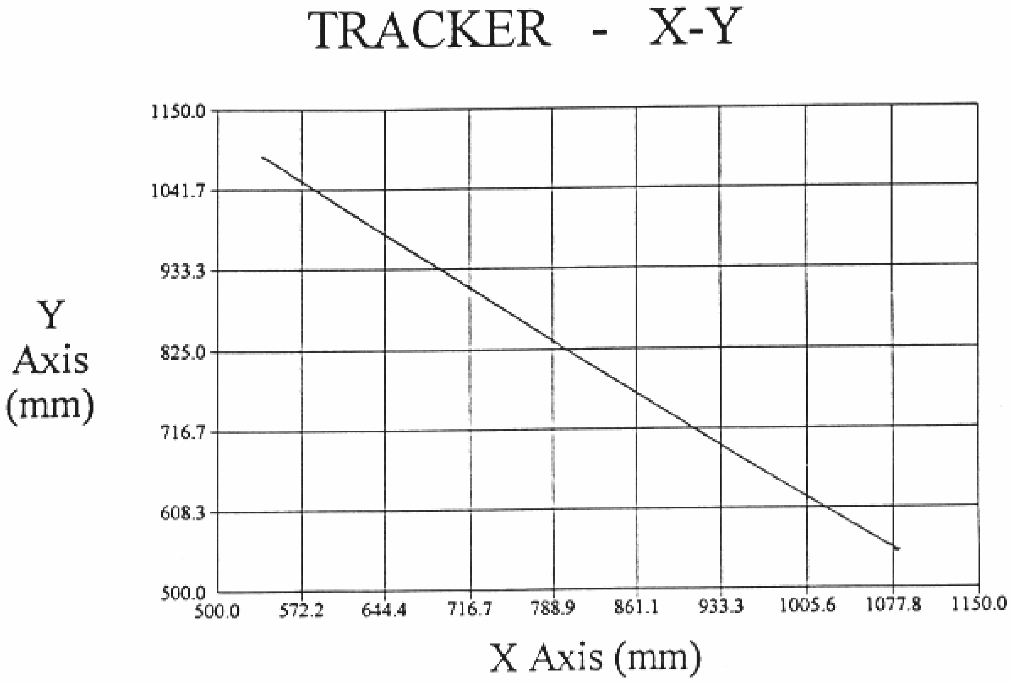

Figure 4. Locus Position Plot on the X-Y Plane

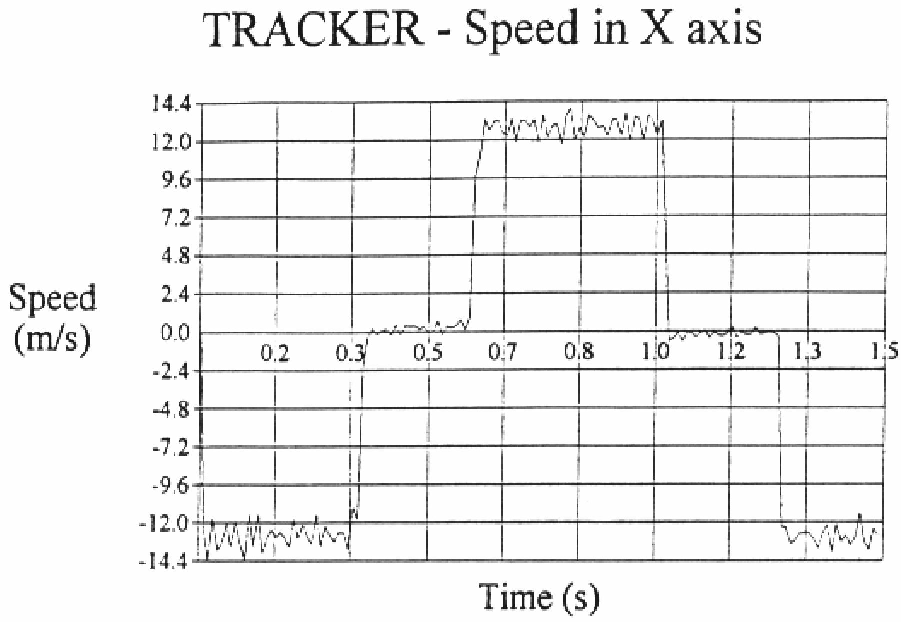

Figure 5. Resolved velocity Plot in the X direction

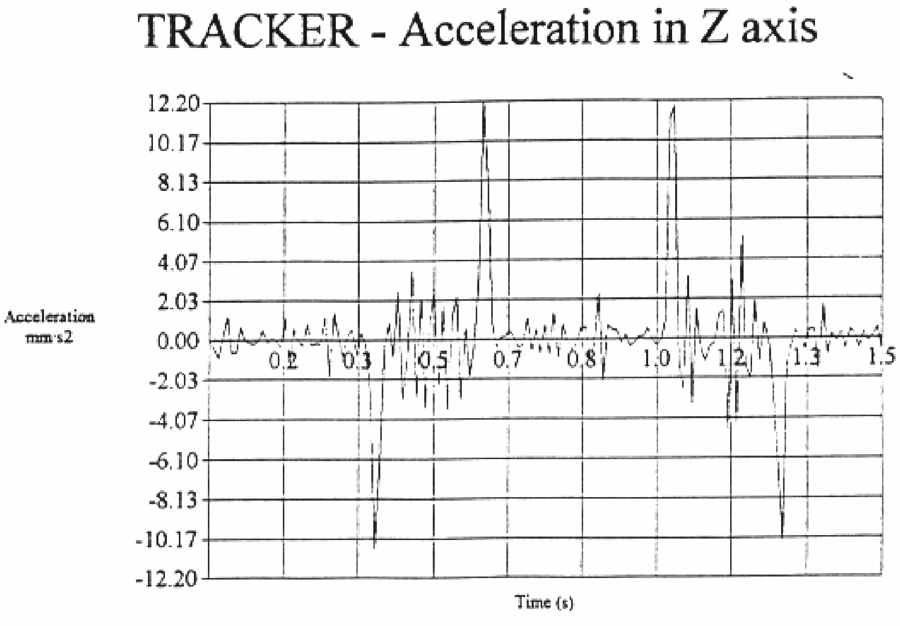

Figure 6. Resolved acceleration Plot in the Z direction

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