hands around in an unfamiliar three-dimensional world. Once it has learned to do this, such movements will seem to become automatic, requiring no conscious thought, and we would then cease to think of them as needing intelligence.

The robot arm is in the same position as the human toddler — it has the equipment to perform tasks, but it must 'learn' how to perform these tasks automatically.

The simplest method is to train the arm to perform specific tasks merely by leading it through a sequence of movements and, in effect, telling it to 'remember this'. This method is used with a large number of industrial robots. An operator literally takes the robot by the hand and leads it through the steps that it must follow. This has the big advantage that the person needs to know nothing about how the robot arm actually works — all he must know is the sequence of actions that the arm must follow. In turn, the robot does not need to 'know' what it is doing — it simply has to 'remember' the actions it must carry out.

## TRAINING METHODS

There are two types of 'training' used with robot arms — point-to-point training and continuous path training. In point-to-point training, the operator moves the arm to a certain position and then presses a button to signal to the robot that this position must be 'remembered'. The arm is then moved to the next position and the button pressed again. This sequence is continued until a whole sequence of actions has been stored in the robot's memory. Once the training session is over, the robot may be switched into 'playback' mode, and it will then move from point to point in exactly the way it was 'taught'. In continuous path training, the operator simply leads the robot through the complete sequence, and the robot remembers each and every position in the sequence. On playback, the robot will follow the sequence in the same way as before.

Returning to the example of a person sitting at a table and moving an object from one side of it to another, we can use the point-to-point method to 'train' a robot to duplicate this action. This method is often used with robots that must carry out 'pick and place' tasks — moving an object from one location to another. By contrast, a robot that is used for spray painting will need to be taught by the continuous path method to ensure that it covers the whole object evenly with paint, just as a person would do.

We now need to consider how the robot 'remembers' the sequence of movements that it should follow. The answer is that the robot uses its internal sensors to record the position of each of its joints during the training mode. This is often done by taking the output from the shaft encoders in the robot joints and recording the movements made, either directly into memory or, for more permanent storage, on tape or disk. When playback mode is selected, the robot can then recall all the relevant data and convert it into joint movement — a relatively complex task.

Surprisingly, it is easier for the robot to 'remember' continuous path movement — it has only to follow the exact route it has been taught. However, a very large amount of data needs to be stored — often several thousand positions are needed to define a continuous path, rather than the very few positions that are involved in point-to-point movement. The second difficulty arises from the fact that, if the arm is to follow the sequence smoothly and exactly, all of its joints must be activated simultaneously. A spray-painting robot may have to make a sweep of the arm along all three axes, while manoeuvring its three wrist joints to position the spray correctly. This means that the computer controlling the robot must work very fast in order to manipulate each joint in turn with no appreciable delay; alternatively, the robot may use as many as six separate processors, each directing the movement of one joint, to achieve truly simultaneous movement.

## CALCULATED MOVE

A point-to-point robot has a harder task because, although it knows where it should move to, it has not been 'told' how it should get there. It could simply move each joint until it was at the required position, but this would be wasteful of both time and energy. It would be much better if the robot could calculate a direct route for its hand from one point to another; it could then make the required movement in one sweep, just as a person does. But the calculations required to do this are again complex, as Cartesian co-ordinates must be used to move the hand in a straight line between two defined points, while the arm positions themselves are defined in a different co-ordinate system

**Two-Joint Geometry**

In moving from point to point, the two-joint robot arm must rotate about its pivot (angle R), and it must change the shoulder (S) and elbow (E) angles. If the Cartesian co-ordinates of the current and destination points are (X1,Y1,Z1) and (X2,Y2,Z2) then the changes are calculated as follows:

```
    A1=SQR(X1^2+Y1^2+Z1^2)
    A2=SQR(X2^2+Y2^2+Z2^2)
Pivot:
    R1=ARCTAN(Y1/X1)
    R2=ARCTAN(Y2/X2)
    Change=(R2-R1)

Shoulder:
S1=ARCCOS(Z1/A1)+ARCCOS
        ((A1^2+U^2-L^2)/
        (2*A1*U))

S2=ARCCOS(Z2/A2)+ARCCOS
        ((A2^2+U^2-L^2)/
        (2*A2*U))
Change=(S2-S1)

Elbow:
E1=ARCCOS((U^2+L^2-
A1^2)/(2*U*L))
E2=ARCCOS((U^2+L^2-A2^2)/
        (2*U*L))
Change=(E1-E2)
```

where U and L are the lengths of the upper- and lower-arm respectively