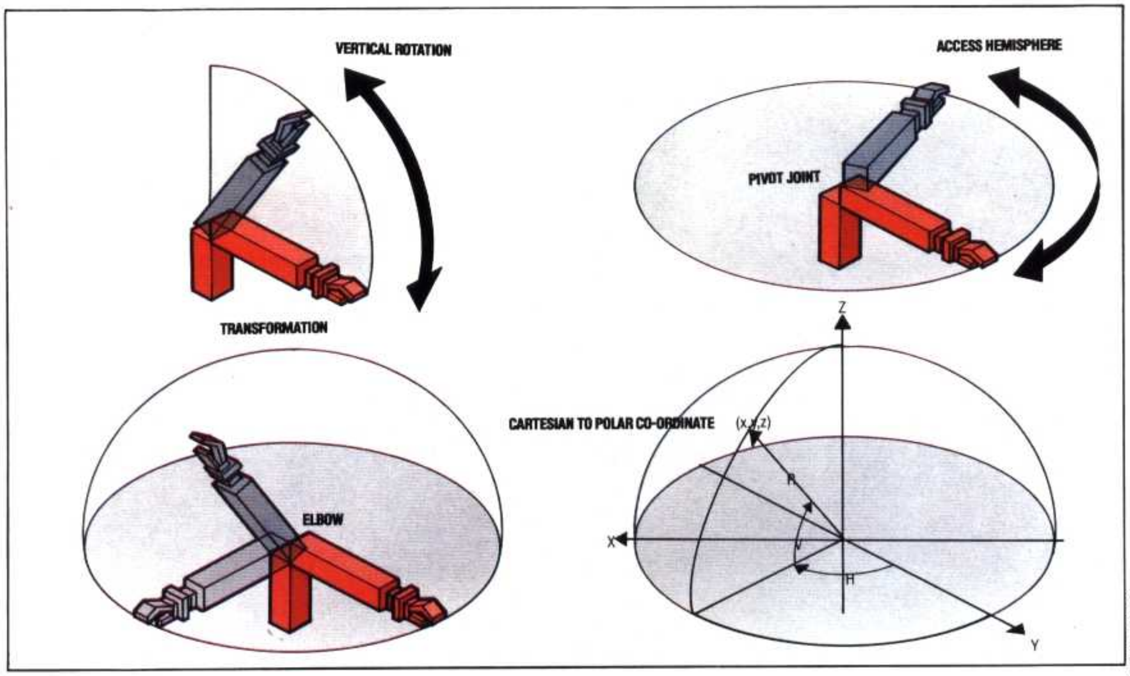
Robotic Rotations
The simplest arm, consisting of a gripper and a two-axis elbow joint, is capable of precise positioning in a very large volume of space as these illustrations show.

The elbow is hinged, permitting semi-circular vertical movement, and pivoted, which allows horizontal circular movement. The arm moves to any point on the access hemisphere by rotations at the pivot and hinge. These can be derived by trigonometry from the Cartesian (x,y and z) co-ordinates of the point as shown: H, the pivot rotation, is equal to ARCTAN(x/y), while V, the hinge rotation, is ARCSIN(z/R). The arm is programmed with the Cartesian locations of objects; it transforms each set of co-ordinates into two rotations which it sends to its two servomotors, thus effecting movement



another distance variable, z). So by using cylindrical co-ordinates it would be very easy to develop a system that could pick out any object from a specified position inside the can.

Arms that use spherical co-ordinates take this process one step further by specifying a position in terms of two angles and one distance. In this case, 'distance' is the length of the arm, and the two angles are the amount by which the base rotates and the angle of elevation of the arm. Arms such as these are very much like a gun turret, in which the length of the gun barrel may be varied. Spherical co-ordinates are usually described as r, θ, and ∅. For the robot engineer, it is simple enough to design an arm that can move in and out telescopically, possibly driven by hydraulic power.

The final, and most common, method of describing the position of an arm is by using revolute co-ordinates. This is a system that is specifically designed to control robot arms by imitating the actions of the human arm. As before, three variables are needed to specify the arm's position; this time they are all angles and could be described as θ, ∅ and γ co-ordinates. θ (theta) refers to the angle through which the base is rotated; ∅ (phi) refers to the angle of elevation of the arm; and γ (gamma) describes the angle of a second arm joint.

BUILDING UP MUSCLE

The chosen co-ordinate system will dictate the type of 'skeleton' a robot arm requires. All that is needed now is some 'muscle' to power the arm's movement. In general, there are three types of robot muscle used — electrical, hydraulic and pneumatic. Let's look at these in turn.

We have already discussed electrical power in connection with robot movement. The same electrical stepper motors may be used to power robot arms. For example, they can do so directly, by having a powerful motor at each arm joint and letting this rotate by a small amount for each joint movement, or indirectly, by means of gears, pulleys or levers.

However, a better system would involve making the robot 'muscles' work in much the same way as our own — by expanding and contracting so as to act on the skeleton of the arm directly. This is done by arranging a series of pistons to act on each arm joint. These pistons may be hydraulic (using fluid) or pneumatic (using air). For use with massive industrial robots, hydraulic power is preferred as this can provide much higher pressure (giving more force to the arm) and because fluid does not compress or expand to the same extent as air does.

This means that when a piston is moved along a cylinder by hydraulic pressure it does not 'bounce', but stops at precisely the desired point. Air, by contrast, does not allow such precise positioning. No matter which system is used, single or double action pistons may be utilised to produce motion in the arm. This type of motive power is called a *linear actuator.*

A further refinement is possible. Instead of using pistons that move backwards and forwards and then translating this movement into a rotation at the joint, a *rotary actuator* may be used. This produces direct rotation in the joints by means of pressure on a vane inside a circular housing. This is a similar process to the use of an electrical stepper motor, but the hydraulic pressure means that far more power may be exerted. Pneumatic pressure is unsuitable for this type of application.

Once the mechanics of the robot arm have been decided upon, all that is needed is a 'hand' (or *end effector*) so that, once the arm is correctly positioned, it can actually do something. Here, it is instructive to think about the way a human hand works. Consider the human wrist — if this was