encased in plaster so that it could not be moved, most tasks would be much more difficult. When operating a keyboard, for example, the wrists allow your hands to move up and down as you strike the keys — this is known as 'pitch', and without it, you would have to move the whole forearm up and down when typing.

Your wrists also move from side to side as you press the different keys — this is 'yaw', and the absence of this would entail elbow movement. Once you have finished typing, you can turn your wrists so that your hands rest, thumbs upwards, at the side of the keyboard. This is known as 'roll' and would require a complicated set of shoulder movements if wrist movement was not available.

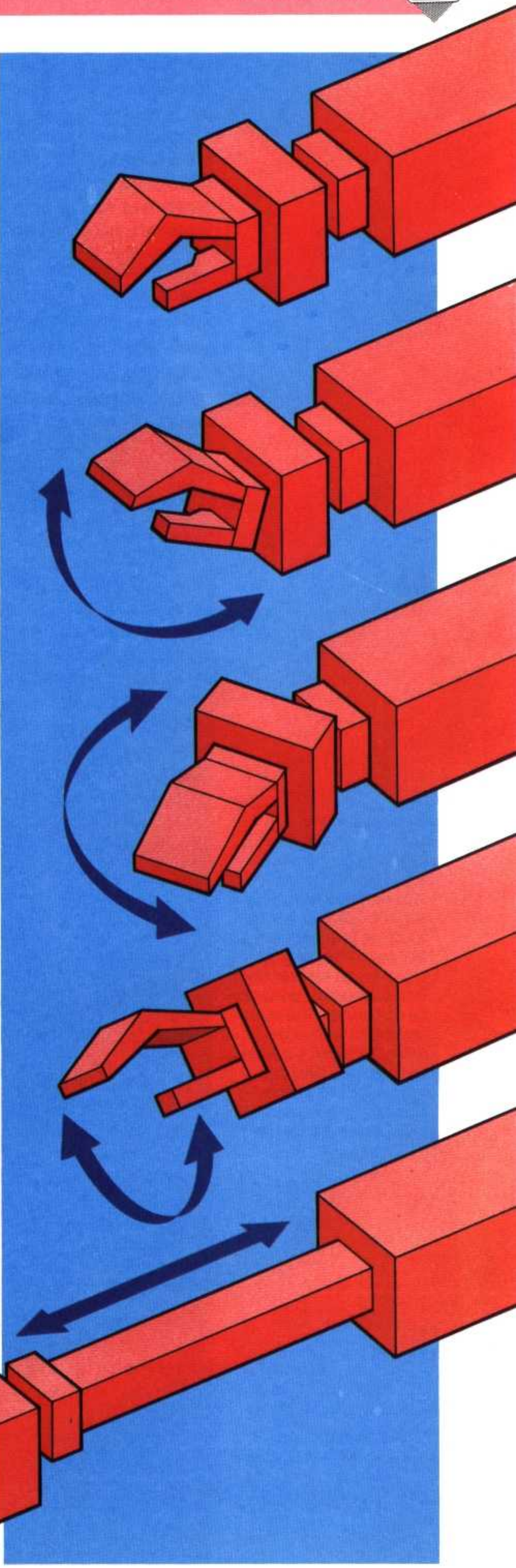
Ideally, then, these three different movements should all be built into the robot wrist. Each of the movements — pitch, yaw and roll — can act in two directions (up/down, left/right, clockwise/anticlockwise) and each of these is called a 'degree of freedom'. So a robot that incorporates pitch, yaw and roll can be said to have six degrees of freedom. Robots are built with lesser degrees of freedom — perhaps four or five — but for each reduction in wrist movement there is a corresponding increase in the movements that must be made by other, larger parts of the arm.

THE ROBOT HAND

We must now consider the design of the hand itself. The ideal configuration would be a human-like hand at the end of a human-like arm, and some robot hands do approach this definition. The most common form of robot hand is a three-fingered gripper — consisting of two fingers plus an opposing 'thumb' — which enables the robot to grasp objects in much the same way as a human hand would.

The power used to drive the hand can be any of the three types already mentioned, and will depend on the task the robot is to perform. If the hand must move large objects weighing several hundred pounds, hydraulics will probably be necessary. But for many applications, simple electrical or pneumatic power will suffice because the hand will need only to grip an object and release it when desired — if the arm and wrist have positioned the hand correctly, this will not require any great accuracy; a simple opening and closing movement will be enough.

In many cases, though, the robot arm will not be fitted with a hand. We have already used the phrase 'end effector' to describe a hand, but this can just as easily refer to many other things. A robot that is used for welding does not require a hand at all — a welding gun may be fastened directly to the wrist. In fact, some robots are capable of choosing the correct end effector for the task they are carrying out; they can discard one end effector (a screwdriver, say) and insert another (a spray gun, for example) into a standard socket at the wrist. This may not be a particularly human-like action, but it serves to make robots extremely adaptable.



Robot Wrist
If the simple two-axis arm illustrated is equipped with a flexible wrist, then its access space is greatly increased in volume; the complexity of the co-ordinate transformations increases with the wrist articulation, but the mathematics are trivial compared with the engineering problems of lightness, strength, accuracy and flexibility. The real software problem is in 'deciding' which of the many possible gripper orientations best suits the object to be gripped

Pitch And Yaw
The human wrist's capability for pitch and yaw (up-down and left-right movement) is limited by precisely those constraints that affect robot designers; i.e. the problem of reconciling strong, compact joints with the need for flexibility and lightness. These joints do not add much to the access space, but they do greatly increase the arm's ability to manipulate real objects

Roll And Extension
These are simpler joints to construct, and contribute far more to the arm's access space than do the pitch and yaw joints. Arms equipped with only roll and extension capabilities are adequate for the majority of industrial applications