thorough record-keeping a snap).

One may program the robot using coordinates and its own control language, or one can teach it, by moving the hand through a series of control points which the software is then instructed to remember. There is some drift in the robot's precision over time, and it may be necessary to reteach the machine at fairly widely spaced intervals—or if someone blunders into the setup and shifts the relative positions.

The user must remember, though, that the robot is dumb and blind—depending instead on very precise positioning of everything it touches. And a number of factors can influence the robot's precision. Positioning accuracy, for example, is inversely proportional to the moments on the robot's arm. Thus, the heavier the robot (or its payload) and the faster it moves, the harder it is to maintain a given level of precision and the more power the robot demands.

In general, laboratory robots are rated on two kinds of precision: accuracy, the ability to find a pre-programmed position; and repeatability, the ability to return to the same position on each cycle. Accuracy is typically within 2–3 mm and repeatability, 1–2 mm.

Robomation can also make special demands on laboratory design. Though smaller than people, robots demand more room. A robot for sterile work must fit entirely within the protected environment, necessitating a clean space larger that the glove box a human would find convenient. And the automata in general need more workspace that humans. Zenie estimates that 80 percent of his customers need benchtops 3 × 6 ft or larger.

Robot Senses

Right now, laboratory robots need, at most, but rudimentary senses—feedback from resistance in their actuators to tell them whether they have indeed picked up a test tube, or whether a microplate is jamming as the robot attempts to feed it into a reader. Or perhaps a simple optical cell to confirm that the sample has

IMAGE UNAVAILABLE FOR COPYRIGHT REASONS

Top-down programming. An elegant robotic program, like an elegant computer program, is an economical hierarchy of nested procedures. (S. S. Jones, et al., Genetics Institute)

WHAT IS A ROBOT?

The essence of a robot is programmability and dexterity—the brains and brawn to do many different tasks. As Zymark president Francis H. Zenie puts it, laboratory robotics is the extension of programmable computers which allows computers to do the physical work as well as process the data. Thus there is, as Perkin-Elmer's Lawrence Haff points out, a big difference between automation and robotics.

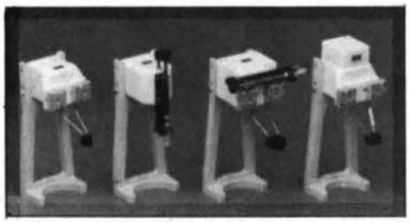
So, too, the robot's capabilities are determined by its electronics—the sophistication of its programming language, the suppleness of its interfaces—and its mechanics—its power, precision, and basic design.

The workspace shape is determined by the robot's geometry, and so are some of the machine's dynamic characteristics (see figure). For example, a Cartesian robot (the scheme favored for dedicated pipettors or X-Y plotters, for example) must move its entire mass in left-right moves—that will slow it down and decrease accuracy in moving along the bench, but suits it for working on a flat workpiece. Cylindrical (e.g., Zymark's Zymate), revolute (e.g., Perkin-Elmer's MasterLab), or spherical robots may be able to cover less flat surface for the same total reach, but they have some advantages of their own. Most of their mass is usually near the first axis of rotation, which decreases their resistance to large-scale movements. Thus, when the robot moves to its left or right—"slews" is the term—it expends relatively little effort to move its own bulk. And the straight-armed radial stroke of the cylindrical robot is well suited to loading machines. (*Design Engineering*, **53 (1)**:50, Jan. '82)

Once the hand is in position, the robot's wrist determines how the sample will be oriented—to pour a reagent into a vial or slide a test-tube into a centrifuge rotor.

For very tight fits, compensators like remote center compliance links allow the sample to adjust to small misalignments while the robot keeps them in a firm grip.

Laboratory hands. Specialized grippers for (left to right) gripping small vials, pipetting, combination gripping and pipetting, and large vials. (Zymark)



A robot's body determines the shape of its workspace and many of its performance characteristics. The most common forms for laboratory robots are the cylindrical (Zymate) and the revolute (MasterLab). The construction of the robot's wrist governs the sample's orientation—roll, yaw, and pitch—though most robot wrists allow roll only, or roll and pitch.